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A simplified physical propagation model for surface fires designed for an implementation into fire decision making tools

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Abstract

Nowadays, the needs for decision making tools useful for people involved in firefighting and/or in landscape management becomes more and more crucial, especially with the dramatic increase of the fire dangerousness and fire severity. These tools have to be accurate enough and faster than real time. Up to now, simulators and other tools are mainly based on empirical or semi-empirical models but the lack of physics in their formulation is a major limitation. The Balbi model is a simplified physical propagation model for surface fires which explicitly depends on the topography, the wind velocity and several fuel characteristics. It is a set of algebraic equations built from usual physical conservation laws (mass, momentum etc.) with some strong assumptions. This work aims at providing a new version of the Balbi model in which the resolution of the rate of spread (ROS) does not need any iterative method any more. This simplification is helpful in implementing the equations set into a fire propagation simulator or a coupled fire-atmosphere simulator. It needs a complete change in the structure of the model and the predicted ROS was tested at the field scale against 179 shrubland fires (burnt in Australia, South Africa, Turkey, Portugal, Spain, New Zealand) and 178 Australian grassland fires with a very good agreement with the observed ROS. Two statistical tools are used to check this agreement (Normalized Mean Square Error, NMSE and Mean Absolute Percentage Error, MAPE) and the Fractional Bias (FB) aims at understanding when the model over-predicts or under-predicts the ROS. The proposed model is accurate and its model parameters are calibrated against a small training dataset which makes it fully predictive whatever the environmental and topographic conditions and the fuel bed characteristics. Its more simple structure allows it to be a good candidate for the heart of a simulation or land management decision making tool.

1. Introduction

Climate change is one of the reason that increases the number of severe wildfires or extreme fire events (European Science & Technology Advisory Group, 2020). The response found by the firefighters to this new type of high intensity fires has to be fast and reliable. Another response consists in shifting from suppression to prevention with efficient fuel mitigation policies or an increase of safety zones and fuel breaks for instance. In both cases, the use of decision making tools is crucial for people involved in firefighting and in landscape management.

The fire behaviour modelling has been considerably improved for the last fifty years. Three main approaches in fire modelling have been emphasized by several authors (Weber, 1991; Perry, 1998; Pastor *et al.* 2003; Sullivan 2009a,b,c): (1) empirical models, (2) semi-empirical models and (3) physical models.

Empirical models are very simple and usually defined thanks to a correlation between ROS and the main parameters influencing the propagation (wind speed, fuel moisture content, fuel height, etc.). They are constructed over a large set of experimental fires (Anderson *et al*. 2015 for instance). Semi-empirical models are based on very simple physics principles but they don't differentiate the heat transfer mechanisms. Because of their simplicity and quickness, both empirical and semi-empirical models were the best candidates to be incorporated into fire simulators. For instance the semi-empirical Rothermel's model (Rothermel, 1972) is the core of the FARSITE simulator (Finney 1998) or of the coupled fire-atmosphere WRF-SFIRE simulator (Mandel *et al.* 2011). The main limitation of these models is the lack in the physics of the phenomenon and the high cost of the large campaign of experimental burnings.

Detailed physical models — e.g. Firestar 2D (Morvan *et al.* 2009) and 3D (Frangieh *et al*. 2018), Firetec (Linn and Cunningham, 2005), WFDS (Mell *et al.* 2007), are based on multiphase formulations which consists in solving the partial differential equations obtained from the gaseous and solid phases. The main interest of these models lies in improving the comprehension of the fire dynamics but because of their high computational cost, they can't be used to perform numerical simulations in real time situations.

Simplified physical models (Pagni and Peterson, 1973; Albini, 1985; Balbi *et al*. 2010) combines the advantages of the three previous categories. The Balbi model (Balbi *et al.* 2020; Chatelon *et al.* 2022) is a simplified physical propagation model for surface fires at the field scale. It consists in a set of non-linear algebraic equations depending on the triangle of fire (fuel, wind and slope) and built over three heat transfer mechanisms: (1) radiation from the flame base, (2) radiation from the free flame and (3) convection inside the vegetal stratum. The model parameters are calibrated upon a small training dataset of experimental fires found in the literature. The Balbi model is physics-based, fully predictive and faster than real time; it is then designed for an implementation in decision making tools for people involved in firefighting or in fire management.

This work deals with a change in the structure of the Balbi model in order to obtain a brand-new version which aims at simplifying the resolution method for an easier implementation. The predicted ROS is compared to the ROS measured in 179 shrubland fires and 178 grassland fires using some usual statistical tools: (1) Normalized Mean Square Error (NMSE) and Mean Absolute Percentage Error (MAPE) to measure the model's accuracy and (2) Fractional Bias (FB) to check if the observed ROS is overestimated or underestimated.

2. Changes in the structure of the Balbi model

The main equation of the Balbi model presented by Chatelon *et al.* (2022) concerns the calculation of the ROS as the sum of three components derived from: (1) the radiative heat flux from the free flame F1 (see fig.1) on the unburnt fuel (R_r), (2) the radiative heat flux from the flame base (R_b) and (3) the convective heat flux inside the vegetal stratum (R_c) which involves the flame F2. The main equation of the model is then the following:

$$R = R_b + R_c + R_r \quad (1)$$

All details and nomenclature can be found in (Chatelon *et al.* 2022).

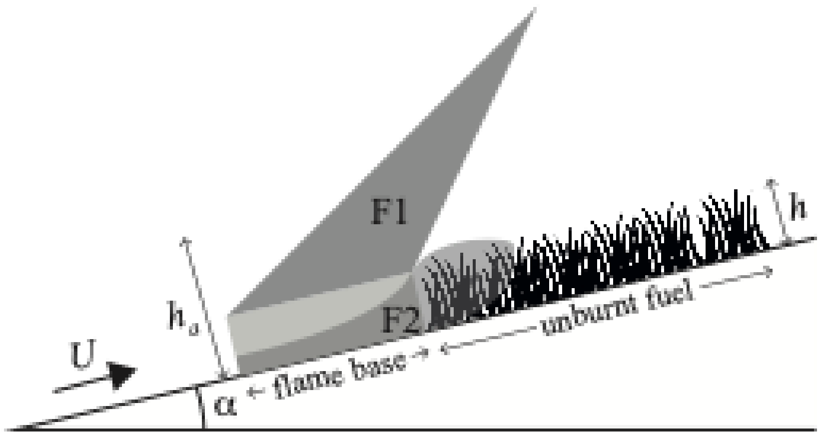

Figure 1- An idealized representation of the flaming zone combustion profile

Both terms R_c and R_r depend on the ROS R and thus, eq. 1 is an implicit algebraic equation that must be solved using an iterative method, which could be difficult to implement in fire simulators. In order to obtain an explicit equation, eq. 1 is changed by the following

$$R = \max(R_b \; ; \; R_c \; ; \; R_r) \quad (2)$$

The term R_b is defined thanks to a usual Stefan-Boltzman modelling that does not depend on the wind speed (Chatelon *et al*. 2022) and:

$$R_c = \frac{b\,U}{1+K\,b\,U} \tag{3}$$

$$R_r = s\,\frac{r_{00}}{u_0}\,(2A-1)(U - u_0\frac{A}{2A-1}) \tag{4}$$

Where b is a convective coefficient and K represents the drag forces law that are assumed to linearly depend on the total packing ratio. These coefficients (and R_b) mainly depend on fuel characteristics:

$$b = d\ \min\left(\frac{W}{W_0};1\right)\frac{\Delta H}{q\,\tau_0}\ s\sqrt{h} \tag{5}$$

$$K\ = 5\,\beta_t \tag{6}$$

The expressions of the radiative coefficient A and the upward gas velocity u_0 are the same as in (Chatelon *et al*. 2022).

The convective coefficient b depends on the fuel bed arrangement through the scaling factor d. Indeed, at the field scale two different type of fuel arrangement are considered: (1) isotropic (shrub species) and (2) vertical (grass). The expression of this scaling factor is the following:

$$d = d_0 * \begin{cases} 1\ (isotropic\ fuel) \\ 1+\frac{0.3}{h}\ (vertical\ fuel) \end{cases} \tag{7}$$

Finally, all the three components of the ROS (eq. 2) does not depend on the ROS anymore. So eq. 2 has become an algebraic explicit equation.

The value of the radiative coefficient A defines the fire regime expressed by eq. 2. Indeed two different regimes can be found:

(1) If A < ½, the component Rr (obtained from the free flame radiative heat flux) is a negative term and then:

$$R = \max(R_b\ ;\ R_c) \tag{8}$$

The fire turns into a radiative regime for weak wind values (when $U < U_{bc}$, see fig. 2) and into a convective regime otherwise.

(2) If A > ½, the radiation from the flame base is still the dominant heat transfer mechanism for weak wind speeds ($U < U_{bc}$, see fig. 2). Beyond the threshold wind speed U_{bc}, the convective effects are dominating up to a second threshold wind speed U_{cr}. For greater wind speed values, the role of the free flame radiation as heat transfer mechanism on the fire propagation highly increases.

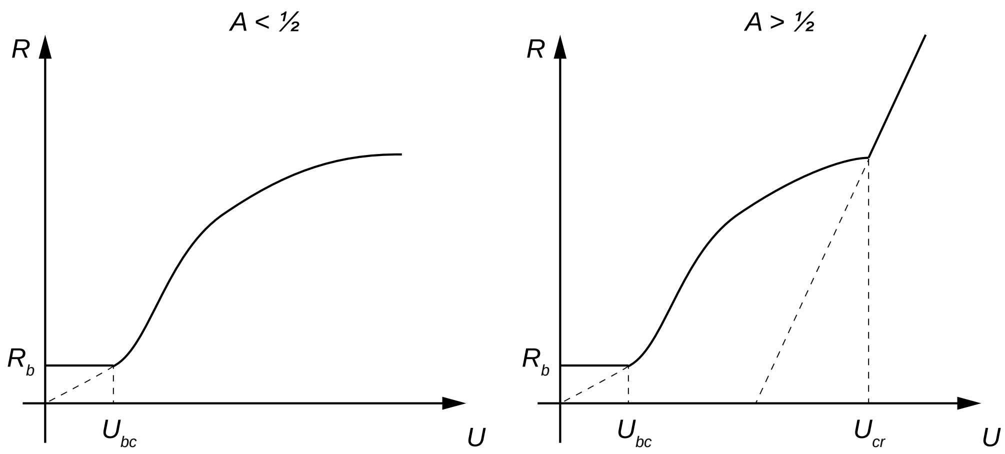

Figure 2- A qualitative representation of the two fire regimes exhibited by the proposed model.

The proposed model is composed of several equations for the calculation of the main physical characteristics of the fire front (flame tilt angle, flame height, flame length, upward gas velocity, flame temperature etc.) and the main equation for the ROS in combining all the previous equations:

$$R = \max\left(R_b \, ; \, \frac{b\,U}{1+K\,b\,U} \, ; \, s\,\frac{r_{00}}{u_0}\,(2A-1)(U-\,u_0\,\frac{A}{2A-1})\right) \quad (9)$$

As the proposed model is a strong simplification of the Balbi model presented by Chatelon *et al.* (2022), an increase in the overall deviations is expected considering that only the main heat transfer mechanism is taken into account.

The proposed model is fully predictive because its model parameters, especially d_0 (see eq. 7) is fitted once against a small set of experiments. Indeed, this coefficient was derived from the set of 25 fire experiments carried out by Bilgili and Saglam (2003) for shrubland fires and from a subset of 10 grassland fires (location: Ballarat) proposed by Cruz *et al*. (2018).

3. Numerical results and discussion

The proposed model is tested against a large set of fire experiments at the field scale. This set picked up in the literature is composed of 179 shrubland fires (Anderson *et al.* 2015; Bilgili and Saglam, 2003; Marsden-Smedley and Catchpole, 1995; van Wilgen *et al.* 1985) and 178 grassland fires (Cheney *et al.* 1998; Cruz *et al.* 2018) burnt in several regions of the world (Australia, New Zealand, Spain, Portugal, South Africa, Turkey). This set can be distinguished by a wide range of fuel characteristics and wind velocities. Some fires (van Wilgen *et al.* 1985) spread on sloped terrains.

The agreement between observed and predicted rate of spread is assessed using three statistical tools. Both Normalized Mean Square Error (NMSE) and Mean Absolute Percentage Error (MAPE) are useful for estimating the overall deviations and the Fractional Bias (FB) allows to understand if a model shows under-predictions or over-predictions. An ideal model is obtained for a zero NMSE, MAPE and FB.

The comparison between predicted and observed ROS against shrubland fires is presented in Fig. 3. The solid line and the dotted lines are the line of perfect agreement and the ±35% error threshold lines, respectively. As expected, the overall deviations (NMSE = 0.163) are barely higher than the value (NMSE = 0.132) found by Chatelon *et al.* (2022). This increase in the error is kept under control and is mainly due to the fires carried out in Australia where the radiation was found slightly higher than the convective effects. In this case, the NMSE changed from 0.213 (Chatelon *et al.* 2022) to 0.321 (see table 1). Moreover the relative error is equal to 35% which constitutes an acceptable error for ROS models (Cruz and Alexander, 2013). In spite of it, the proposed model provides high NMSE and MAPE for the Portugal fires group (see table 1). Although this fires group was used by Anderson *et al.* (2015) to build their empirical model, both the Anderson's model and the Balbi model (Chatelon *et al.* 2022) generated a poor agreement between predicted and observed ROS. So, it does not seem to be a specific limitation of the proposed model.

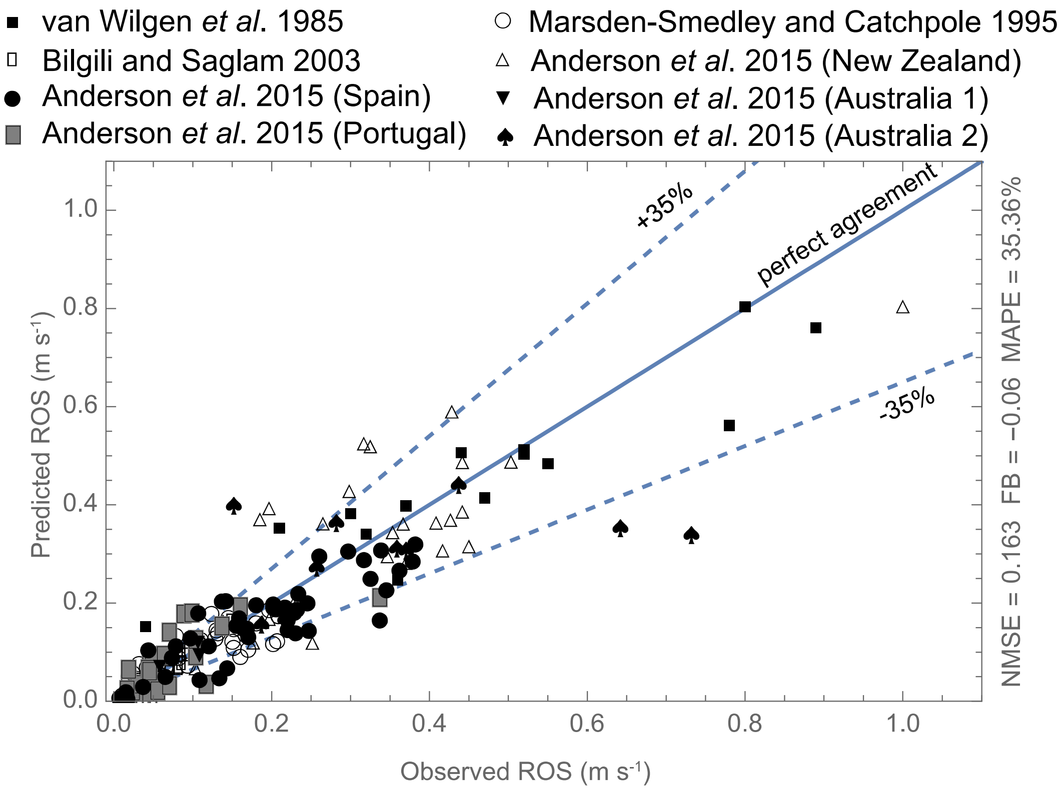

Figure 3- Comparison of predicted ROS vs ROS observed in the shrubland fires dataset.

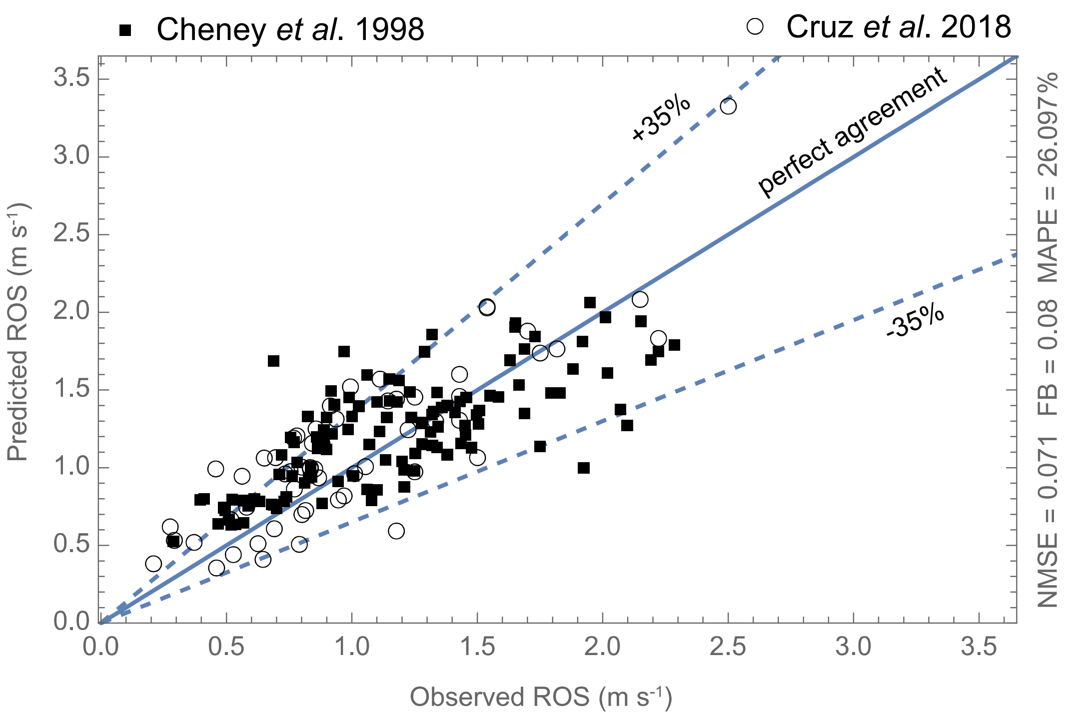

Figure 4- Comparison of predicted ROS vs ROS observed in the grassland fires dataset.

Fig. 4 shows the predicted ROS vs observed ROS in grassland fires. The numerical results provided by the proposed model are very good with small NMSE (0.071) and MAPE (26%). Note that contrary to the shrubland fires group, the confrontation of the proposed model to grassland fires produces a slight overestimation of the ROS (FB = 0.08).

Table 1- Agreement between observed and predicted rate of spread estimated with three statistical tools (NMSE, Normalized Mean Square Error, MAPE, Mean Absolute Percentage Error and FB, Fractional Bias)

Fuel (location)	Reference	NMSE	MAPE	FB
Shrubs (South Africa)	Van Wilgen *et al.* 1985	0.045	35%	0.06
Shrubs (Turkey)	Bilgili and Saglam 2003	0.046	25%	0.11
Shrubs (Australia)	Marsden-Smedley and Catchpole 1995	0.123	37%	-0.03
Shrubs (New Zealand)	Anderson *et al.* 2015	0.109	29%	-0.02
Shrubs (Portugal)	Anderson *et al.* 2015	0.425	63%	-0.16
Shrubs (Spain)	Anderson *et al.* 2015	0.115	29%	-0.18
Shrubs (Australia)	Anderson *et al.* 2015	0.321	31%	-0.07
Shrubland fires		**0.163**	**35%**	**-0.06**
Grass	Cheney *et al.* 1998	0.068	24%	0.06
Grass	Cruz *et al.* 2018	0.079	30%	0.12
Grassland fires		**0.071**	**26%**	**0.08**

4. Conclusion

This work deals with a simplification of the simplified physical propagation model for surface fires called Balbi model in order to make its incorporation into decision making tools easier. In order to obtain an explicit formula for the ROS, several assumptions are made. The major assumption consists in considering only the main heat transfer mechanism as the mainspring of the propagation. Because of this simplification, the deviations provided by the proposed model are expected to be higher than the ones obtained by Chatelon *et al.* (2022). The numerical results against shrubland fires show a slight increase of the error which remains controlled. The predicted ROS against grassland fires is in a good agreement with the observed ROS. These good results and the characteristics of the proposed model (more simple, accurate, physics-based, fully predictive) confirm that the proposed model can be easily incorporated into decision making tools for operational people (firefighters, landscape managers etc.)

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