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Evaluation of the smoke injection height from wild-land fires using remote sensing data

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Abstract

A new methodology for estimation of the smoke injection height from wild-land fires is suggested and evaluated. It is demonstrated that the approaches developed for estimating the plume rise from stacks can be formally written in terms characterising the wild-land fires: fire energy, size and temperature. However, these semi-empirical methods still perform quite poorly because the physical processes behind the uplift of the wildfire plumes strongly differ from those controlling the plume rise from stacks. The suggested new methodology considers wildfire plumes in a way similar to the Convective Available Potential Energy (CAPE) computations. The new formulations are applied to the dataset collected within the MISR Plume Height Project for about 2000 fire plumes in Northern America and Siberia. It is shown that the new method performs significantly better than the stack-oriented formulations. For two-thirds of the cases, its predictions deviated from the MISR observations by less than 500 m, which is the uncertainty of the observations themselves. It is shown that the fraction of "good" predictions is much higher (> 80 %) for the plumes reaching the free troposphere.

1 Introduction

Biomass burning is one of the major contributors of trace gases and aerosols to the atmosphere significantly affecting its chemical and physical properties. In addition to solid and gaseous material, fires release large amount of heat. The resulting buoyancy generates strong updrafts above the fire, which control the tracer distribution through rapid transport to the upper part of the atmospheric boundary layer (ABL) and the free troposphere (FT) (Freitas et al., 2007; Labonne et al., 2007), sometimes reaching the stratosphere (Fromm et al., 2000; Luderer et al., 2006).

Bulk of the atmospheric models considering the fire emissions distribute the emitted smoke plumes homogeneously starting from the ground up to some height H_p, which is prescribed, sometimes as region-dependent. For global chemistry-transport models, (Davison, 2004; Forster et al., 2001; Liousse et al., 1996) set it to about 2 km, whereas (Westphal and Toon, 1991) used 5–8 km for regional simulations of smoke from intense Canadian fires. On the basis of observations from different field experiments, (Lavoué et al., 2000) found a linear relationship between the plume height and the fire-line intensity with correlation coefficient of 0.95 and proportionality constant of 0.23 $m^2\,kW^{-1}$. They further showed that H_p is usually about 2–3 km for fires in the northern latitudes, but can reach 7–8 km for intensive crown fires. The biomass burning in Central America is usually less intensive, so that $H_p \sim 0.9$–1.5 km was suggested by (Kaufman et al., 2003). Following this estimation, (Wang et al., 2006) used 1.2 km (8th model layer) for their mesoscale simulations and conducted sensitivity studies showing 15 % variation of the near-surface concentrations if H_p is varied plus-minus one model layer (a few hundreds of metres).

Despite the apparent nearly-consensus among the modellers in using prescribed fire injection height, H_p is strongly dependent on meteorological conditions and fire intensity, which are both highly dynamic. In particular, favourable meteorological conditions are necessary for the smoke to reach the stratosphere (Labonne et al., 2007; Luderer et al., 2006; Trentmann et al., 2006).

Recently, remote-sensing observations of the plume heights became available from the Multi-angle Imaging SpectroRadiometer (MISR) instrument onboard NASA Terra satellite (Mazzoni et al., 2007, http://www-misr.jpl.nasa.gov). Using the database of the MISR Plume Height Project, (Sofiev et al., 2009) showed that more than 80 % of fires observed in 2007–2008 over the US injected their smoke within ABL. This estimate was supported by the extensive analysis of (Val Martin et al., 2010).

One of the widely known approaches to dynamic evaluation of the injection height was developed by (Freitas et al., 2007), who embedded a 1-D plume-rise model into a 3-D atmospheric dispersion model and demonstrated the importance of the water condensation heat for the plume rise estimations. The module was included into WRF-Chem model and used in studies related to biomass burning (Pfister et al., 2011). However, the system requires integration of a set of 1-D differential equations for each

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fire and model time step, which may be expensive for large-scale applications. Also, (Pfister et al., 2011) pointed out that about 50 % of the fire emission were attributed to the free troposphere, which is in apparent contradiction with the MISR set statistics, where only ∼ 15 % of the plumes reach FT.

A specific problem of the fire plumes is that the characteristics of this type of source differ from the parameters considered by the existing plume-rise formulations. In particular, all such approaches require diameter of the buoyant plume at the stack top (considered to have circular cross-section), temperature and velocity of the outgoing gases, their density, etc. (Briggs, 1984; Freitas et al., 2007; Nikmo et al., 1999; Weil, 1988). These quantities are hard to define for wild-land fires, which have strongly non-circular shape (rather a bow- or kidney-shaped), wide overheated surface area with strongly varying temperature in different parts of the burn, no stack or defined release height, and strongly varying initial fumes velocity in different parts the fire. Therefore, the necessity of development of an approach adapted to the specifics of the wild-land fires is evident.

The objective of the current study is to develop and evaluate an approach for computing the plume injection height for wild-land fires and to compare its performance with existing approaches. The development is aimed for the 3-D chemistry transport models.

The paper is organised as follows. The next section summarises the existing plume-rise formulations used for the comparison. Section 3 outlines the datasets used by this study for the development. The new algorithm is derived in Sect. 4. Section 5 presents the comparison of the new methodology with the existing approaches. Finally, Sect. 6 considers peculiarities of the new formulations.

2 Existing plume-rise formulations

The most widely known formulations of the plume height from buoyant sources belong to G.Briggs. In the middle of the previous century he compared nine formulas of this

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type using data from sixteen different sources and concluded that the best fit to the data was obtained using the "2/3 law" with a certain termination distance. The 2/3 law states that plume rise is directly proportional to the power 2/3 of the downwind distance from the source x^*. Originally, it was formulated in the following form (Briggs, 1969; Guldberg, 1975):

$$H_C = \begin{bmatrix} 1.6F^{1/3}(3.5x^*)^{2/3}U^{-1} \\ 2.4(F/Us)^{1/3} \\ 5F^{1/4}s^{-3/8} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} 21.4F^{3/4}U^{-1}, & F < 55\,\mathrm{m^4\,s^{-3}} \\ 38.7F^{3/5}U^{-1}, & F \geq 55\,\mathrm{m^4\,s^{-3}} \end{bmatrix} & \text{neutral, unstable} \\ 2.4(F/Us)^{1/3}, & \text{stable}, \quad U > 0.5\,\mathrm{ms^{-1}} \\ 5F^{1/4}s^{-3/8}, & \text{stable}, \quad U \leq 0.5\,\mathrm{ms^{-1}} \end{bmatrix}, \tag{1}$$

where H_C is final rise of the plume centerline from the stack top, $F = gv_s r^2(1-\rho_p/\rho_a)$ is buoyancy flux parameter, g is gravity acceleration, v_s is stack gas exit velocity, r is stack exit radius, ρ_a is ambient air density, ρ_p is plume gas density, x^* is distance at which atmospheric turbulence begins to dominate over the entrainment, U is mean speed from the top of the stack to the top of the plume, $s = \frac{g}{T_a}\frac{\partial\theta}{\partial z}$ is buoyancy parameter, θ is potential air temperature. Hereinafter, the set of (Eq. 1) is referred to as B69.

Numerous subsequent refinements were mainly aiming at better reflection of the details of meteorological conditions and, to some extent, more detailed source description. By middle-80s a set of more sophisticated formulations had emerged (Briggs,

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1984; Weil, 1988):

$$H_C = \begin{bmatrix} 2.1\left(\frac{rv_s^3}{N^2\Phi^2 U}\right)^{1/3}, & \text{stable} \\ 0.76\left(\frac{rv_s^3}{u_*^2\Phi^2 U}\right), & \text{neutral} \\ 4.5\left(\frac{rv_s^3 z_i^{2/3}}{4w_*^2\Phi^2 U}\right)^{3/5}, & \text{unstable} \end{bmatrix} \quad (2)$$

Here N is Brunt-Vaisala frequency, u_* is friction velocity, w_* is convection scale velocity, z_i is the height of the inversion layer, $\Phi = v_s/\sqrt{gr(1-\rho_p/\rho_a)}$ is Froude number. This version is further referred to as B84.

These and other formulations (e.g. Berlyand, 1975) have a common weak point: they assume vertically homogeneous atmosphere, which can be described via some parameters taken (in practice) at the top of the stack. This can be acceptable only if both stack top and the plume injection height are within ABL or both are in the FT. The assumption is evidently wrong if the stack is inside ABL whereas the plume buoyancy is sufficient to reach the FT. More discussion and a list of limitations can be found in (Briggs, 1984).

A more sophisticated approach is taken by 1-D plume-rise models, such as BUOYANT (Martin et al., 1997), BUO-FMI (Nikmo et al., 1999), FEPS (Fire Emission Production Simulator), FIREPLUME, VSMOKE (Freitas et al., 2007), and others. These systems still assume the horizontal symmetry of the plume and use the formulations integrated across it. However, they explicitly integrate a system of 1-D equations for energy, mass, and momentum of the buoyant plume along the trajectory of the plume centreline. The centreline position and the plume width are computed as functions of time and/or horizontal distance from the source point. This approach allows for direct consideration of the vertical structure of the atmosphere, which is usually simplified by considering only two layers – ABL and FT – with prescribed temperature and wind speed gradients in each of them.

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3 Input data for plume-rise computations

The input information needed for any plume-rise approach consists of the data on the buoyant source and on the meteorological conditions at the place.

For the current study, the information on the wild-land fires is obtained from the active-fire observations by MODIS instrument onboard Aqua and Terra satellites (http://modis.gsfc.nasa.gov). The MODIS collection of the active fire characteristics includes the following parameters: (i) radiative temperatures of the overheated pixel and the surrounding background pixels; (ii) emission rate of the radiative energy from the pixel, the Fire Radiative Power (FRP, (W)). The inter-relations of these parameters were considered by (Sofiev et al., 2009). This dataset is practically the only existing collection that covers the whole globe over more than a decade (the Terra satellite was launched in 2000, Aqua – in 2002) and observes the actual on-going fires rather than the burnt area.

The only source of the meteorological information, which would cover the whole globe and could be co-located with the fire observations, is atmospheric modelling by a global Numerical Weather Prediction (NWP) system. For the current study, we used the operational archives of the European Centre for Medium-Range Weather Forecast (ECMWF). Since the data required post-processing before using them in the plume-rise computations, we involved the dry-parcel method of ABL height estimation after (Sofiev et al., 2006).

The observations of the injection height were taken from the database of the MISR Plume Height Project (Kahn et al., 2008; Mazzoni et al., 2007). For the current study we used all information available to-date, which included injection heights for about 2000 fires that took place in the US, Canada, and Siberia during 2007–2008 fire seasons. These datasets were arbitrarily split into "learning" and "control" subsets in proportion 70–30 %.

Importantly, MISR is onboard of the same satellite Terra as one of the MODIS devices, which provides a perfect co-location in space and time between the active-fire observations by MODIS and the fire plume height measurements by MISR.

4 Methodology for injection height estimation adapted to wild-land fires

An estimate of the plume rise from a wild-land fire can be obtained by assuming that the heat energy of the fire is spent to work against buoyancy forces and friction. Such approach neglects the momentum of the uplifting plume, which is acceptable for most fires (the uplift is comparatively slow). It also changes the criterion for the end of the rise: the plume comes to equilibrium with the surrounding air when the energy excess pumped into it by the fire is fully spent to the uplift. This approach has common features with the CAPE (Convective Available Potential Energy) formulations used for describing deep convection and thunderstorms (see Moncrieff and Miller, 1976, and Barry and Chorley, 1998, p. 80–81). Importantly, it is totally different from the criterion for the stack plume-rise where the wind-induced bending is the key factor.

For qualitative analysis of the dependencies let's consider only two processes: the uplift against the atmospheric stratification and the plume widening due to involvement of the surrounding air.

Let the fire energy E_0 be pumped into an air volume V while it is in contact with the flames. Then the density of the energy excess e_0 in comparison with the undisturbed surrounding air will be:

$$e_0 = \frac{E_0}{V} = \frac{E_0}{S_f w \tau} = \frac{P_f}{S_f w} \tag{3}$$

Here w is the initial mean vertical velocity of the plume, τ is the time period during which the volume is in contact with flames, S_f is the fire area (of any shape), and P_f is the fire power released into the air as both sensible and latent heat energy.

The change of the energy excess $e(z)$ during the uplift can be written as:

$$\frac{de}{dz} = -c_p \rho_a \frac{d\theta}{dz} - \frac{E_0}{V^2}\frac{dV}{dz} \tag{4}$$

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Here θ is potential temperature of ambient air, c_p is air heat capacity at constant pressure. The first term describes the work against the buoyancy forces whereas the second one reflects the plume widening. Assuming constant cross-plume horizontal diffusivity K_{hor}, and constant speed of the uplift w, one obtains linear growth of the plume cross-section area S with height (see Sects. 18.4–18.6 and p. 845 of Seinfeld and Pandis, 2006):

$$\frac{d\sigma^2}{dz} = \frac{2K_{\mathrm{hor}}}{w}, \quad \Rightarrow \quad S = \pi r^2 \sim 3\pi\sigma^2 = \frac{6\pi K_{\mathrm{hor}}}{w} z + S_{\mathrm{f}} \tag{5}$$

Here r is plume radius and S_{f} is fire area. Introducing Brunt-Vaisala frequency N instead of $d\theta/dz$ and noticing that for constant w, $dV/dz = w\tau dS/dz$, the Eq. (4) can be written as:

$$\frac{de}{dz} = -\frac{c_p \rho_{\mathrm{a}} \theta}{g} N^2 - \frac{6\pi K_{\mathrm{hor}}/w}{(S_{\mathrm{f}} + 6\pi z K_{\mathrm{hor}}/w)^2} P_{\mathrm{f}} \tag{6}$$

This equation should be integrated with the boundary condition $e(0) = e_0$. The final plume top height H_{p} is then determined via $e(H_{\mathrm{p}}) = 0$.

If all parameters in Eq. (6) are assumed to be constant, the change of the variables from height z to normalised plume cross-section area $\xi = S/S_{\mathrm{f}}$ followed by integration renders quadratic equation for $\xi_{\mathrm{p}}(z = H_{\mathrm{p}})$:

$$\begin{aligned} &-\frac{c_p \rho_{\mathrm{a}} \theta S_{\mathrm{f}}^2 w N^2}{6\pi g K_{\mathrm{hor}}} \xi_{\mathrm{p}}^2 + \frac{P_{\mathrm{f}}}{w} \xi_{\mathrm{p}} + \frac{P_{\mathrm{f}}}{w} = 0 \\ &\xi_{\mathrm{p}} = 1 + \frac{6\pi H_{\mathrm{p}} K_{\mathrm{hor}}}{S_{\mathrm{f}} w} \end{aligned} \tag{7}$$

Its solution is:

$$\xi_{\mathrm{p}} = \frac{P_{\mathrm{f}}}{AN^2} \left(1 + \sqrt{1 + \frac{2AN^2}{P_{\mathrm{f}}}} \right), \quad A = \frac{c_p \rho_{\mathrm{a}} \theta w^2 S_{\mathrm{f}}^2}{3\pi g K_{\mathrm{hor}}} \tag{8}$$

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It can be turned into a generic formula for $H_p = f(P_f, N, \ldots)$ with a few unknown constants to be determined empirically.

Firstly, the variable A has to be taken as a normalising constant. It incorporates poorly known parameters, which cannot be evaluated with the information available in real-life cases. Its value can be roughly estimated taking $S_f \sim 10^3\,\mathrm{m}^2$, $w \sim 1\,\mathrm{ms}^{-1}$, $K_{hor} \sim 1\,\mathrm{m}^2\mathrm{s}^{-1}$. Then $A \sim 4 \times 10^9\,\mathrm{J\,s}$. This normalization can formally be written as a ratio of reference fire power P_{f0} and Brunt-Vaisala frequency N_0:

$$A = \frac{P_{f0}}{N_0^2}, \quad P_{f0} = 10^6\,\mathrm{W}, \quad N_0^2 = 2.5 \times 10^{-4}\,\mathrm{s}^{-2} \tag{9}$$

Secondly, the fire energy P_f spent on the air heating and the FRP observed from space are linearly related to the consumed biomass and close to each other (Kaufman et al., 1998; Sukhinin et al., 2005), thus allowing the switch $P_f \rightarrow \mathrm{FRP}$.

Thirdly, for typical values of atmospheric and fire parameters, AN^2/FRP varies from 1 to 100. From the corresponding asymptote of the solution (Eq. 8), one can see that the injection height will be proportional to FRP taken to the power of 0.5. This, however, is the upper limit of H_p because additional losses to friction and changing atmospheric and plume parameters (e.g. gradual slowing down of the rise and faster-than-linear widening of the plume with height) will result in a smaller power $\gamma < 0.5$.

Fourthly, Brunt-Vaisala frequency is an external parameter with regard to fire and varies strongly with altitude. Therefore, the ratio P_f/N^2 in Eq. (8) cannot be expected to stay as a unique descriptor of the case. Therefore, we shall consider these variables independently. To avoid problems with $N^2 <> 0$ inside the ABL, we shall take its FT value $N = N_{FT}(z \approx 2H_{abl})$ but allow for some part of the ABL passed "freely" by adding a fraction of H_{abl} to H_p. In addition, instead of N_0^2/N^2 we shall use $\exp(-N^2/N_0^2)$, which for small N^2 limits the H_p growth by replacing $1/N_0^2$ with $1/(1+N^2/N_0^2)$. For large N^2 it quickly approaches zero, as one would expect for very stable stratification.

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Finally, introducing the empirical calibration constants, we obtain the generic formula:

$$H_\mathrm{p} = \alpha H_\mathrm{abl} + \beta \left(\frac{\mathrm{FRP}}{P_\mathrm{f0}} \right)^{\gamma} \exp\left(-\delta N_\mathrm{FT}^2 / N_0^2 \right) \tag{10}$$

Here the constants are: α is the part of ABL passed freely, β weights the contribution of the fire intensity, γ determines the power-law dependence on FRP, δ defines the dependence on stability in the FT. Their ranges follow from the above considerations:

$$\alpha < 1\,; \quad \beta > 0m\,; \quad \gamma < 0.5\,; \quad \delta \geq 0 \tag{11}$$

4.1 Identification and evaluation of parameters of Eq. (10)

Identification of the constants in the Eq. (10) was based on the learning sub-set of the MISR fire observations (70 % of the MISR collection, 1278 fires).

Since both FRP and H_p observations have a noticeable fraction of outliers, utilization of the standard L_2 (least-squares) fitting criterion is not advisable (Huber, 1981). Instead, the ranking sum J_R was used:

$$J_\mathrm{R} = \sum_{i=1}^{N_\mathrm{fires}} \Theta\left(\left| H_\mathrm{p}^\mathrm{obs}(i) - H_\mathrm{p}^\mathrm{mdl}(i) \right| - \Delta h \right), \quad \Theta(x) = \begin{bmatrix} 0, & x \leq 0 \\ 1, & x > 0 \end{bmatrix} \tag{12}$$

Here Δh is the desired accuracy of the prediction, (m), N_fires is the number of fires in the subset, $H_\mathrm{p}^\mathrm{obs}(i)$ and $H_\mathrm{p}^\mathrm{mdl}(i)$ are the observed and predicted plume top heights of the i-th fire.

Following (Kahn et al., 2007), the MISR actual accuracy was taken to be 500 m, which was used as the Δh value. As a result, only the predictions indistinguishable from the MISR estimates were considered as "good" by the cost function (Eq. 12), whereas those falling outside the MISR uncertainty range were penalised.

The fitting ended up with the following parameters:

$$\alpha = 0.24\,; \quad \beta = 170m\,; \quad \gamma = 0.35\,; \quad \delta = 0.01 \tag{13}$$

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The quality of the fit is demonstrated in Fig. 1a, which shows that the formula (10) with the parameters (Eq. 13) predicts about two thirds of the learning-set cases within 500 m of the MISR observations. These values are for the whole learning subset but the difference between the North American and Siberian cases did not exceed 5 %.

The formulation (Eqs. 10, 13) was evaluated using the control MISR subset (Fig. 1b). Comparing the scatter plots in panels a and b, one can see that the performance of the suggested procedure over the control dataset is essentially the same as that over the learning subset. The scores for American and Siberian control-set fires differed by less than 10 % (not shown). Therefore, we conclude that the identified parameters (Eq. 13) and the approach (Eq. 10) are stable with regard to the input dataset. The heights of the top of the plumes predicted with this method are within uncertainty of the MISR observations in two-thirds of the cases.

For the above fit calibration and evaluation, we used all MISR observations without filtering out the data with “fair” and “poor” confidence. Their exclusion brings about 10 % of the scores improvement ($>$ 70 % of predictions appear within 500 m from the observations) but also reduces the size of the datasets by three times, thus raising doubts in the statistical significance and stability of the obtained coefficients.

5 Comparison with other approaches

In this section, we compare the four approaches (B69, B84, BUOYANT model, and the new formula (10) using the whole MISR dataset (1913 fires). The comparison required two pre-processing steps: (i) extra characteristics of the fires and meteorological variables were calculated to satisfy the input requirements of BUOYANT; (ii) B69 and B84 formulas were rewritten using the variables available from MODIS and MISR.

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5.1 Extra parameters describing wildfire

MODIS observations of temperature and FRP of the burning pixel at several wave lengths enable estimating the area of the fire S_f and its radiative temperature T_f. Let's consider the burning pixel seen by the satellite with radiative temperature T_rad as a combination of two parts: the fire and the undisturbed background with areas S_f and S_b, and temperatures T_f and T_b, respectively. These two sub-areas emit radiative energy recorded by the satellite at two frequencies v_1 and v_2. Using Planck's law, one can write:

$$\frac{2hv_i^3(S_\mathrm{f}+S_\mathrm{b})}{c^2(\exp(hv_i/kT_\mathrm{rad}))}=\frac{2hv_i^3 S_\mathrm{f}}{c^2(\exp(hv_i/kT_\mathrm{f}))}+\frac{2hv_i^3 S_\mathrm{b}}{c^2(\exp(hv_i/kT_\mathrm{b}))}, \quad i=1,2 \tag{14}$$

The system (Eq. 14) contains two equations for two frequencies and two unknowns: the ratio $S_\mathrm{f}/S_\mathrm{b}$ and T_f. The total pixel area $S_\mathrm{f}+S_\mathrm{b}$ is determined from the MODIS frame geometry, and the background environment temperature T_b is found from the neighbouring pixels. The system has to be solved numerically resulting in the fire radiative temperature T_f and its area S_f. Due to noise in the data, the solution does not always converge or may lead to unpredictable results if $T_\mathrm{f} \sim T_\mathrm{b}$. Such cases (a few % of the total dataset) were filtered out.

5.2 Adaptation of B69 and B84 for wild-land fires

In the equations B69 and B84, the buoyancy flux F has to be expressed in energy and temperature terms in order to be applied to MISR set. Applying the gas state equation and taking into account that the plume molar mass is close to that of air, we obtain:

$$F=gv_\mathrm{s}r^2\frac{1/T_\mathrm{a}-1/T_\mathrm{p}}{1/T_\mathrm{a}}=\frac{g}{T_\mathrm{p}}v_\mathrm{s}r^2(T_\mathrm{p}-T_\mathrm{a})=\frac{g}{\pi T_\mathrm{p}}\frac{P_\mathrm{f}}{c_p\rho_\mathrm{a}}=\frac{g}{\pi T_\mathrm{p}}\frac{\mathrm{FRP}}{c_p\rho_\mathrm{a}} \tag{15}$$

The plume temperature T_p is the analogy to the stack-top temperature but, since there is no "top" of the wildfire, its exact definition is hardly possible. The actual temperature

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of outgoing gases varies from 700–1000 K (Lim et al., 2001) down to 350–400 K within short distance along the vertical (Gostintsev et al., 1991). Fortunately, T_p almost always (except for B84 neutral case) is taken to the power of 0.25–0.5, which reduces the impact of its uncertainty. As a rough estimation, we linked it to the fire radiative temperature T_f obtained from Eq. (14):

$$T_\mathrm{p} = T_\mathrm{a}\,\mathrm{const}\,(T_\mathrm{f} - T_\mathrm{a}) \tag{16}$$

The value const = 0.1 was selected to obtain the best estimates of B69 and B84 for the learning MISR dataset.

Since both B69 and B84 predict the centerline height H_C, conversion to the plume top height H_p has to be made. Following (Briggs, 1975), the plume thickness is taken equal to H_C, hence $H_\mathrm{p} = 1.5H_\mathrm{C}$.

Taking into account that for fires $\mathrm{FRP}/T_\mathrm{p} > 55\,\mathrm{m^4\,s^{-1}}$ almost always, for B69 we obtain:

$$H_\mathrm{p} = \left[\begin{array}{lll} 5.7\left(\dfrac{g\,\mathrm{FRP}}{N^3 T_\mathrm{p} c_p \rho}\right)^{1/4}, & \text{stable}, & U \le 0.5\,\mathrm{ms^{-1}} \\ 2.4\left(\dfrac{g\,\mathrm{FRP}}{N^2 U T_\mathrm{p} c_p \rho}\right)^{1/3}, & \text{stable}, & U > 0.5\,\mathrm{ms^{-1}} \\ 29\left(\dfrac{g\,\mathrm{FRP}}{T_\mathrm{p} c_p \rho}\right)^{3/5} U^{-1};, & \text{neutral, unstable} & \end{array}\right. \tag{17}$$

The B84 equations will read:

$$H_\mathrm{p} = \left[\begin{array}{ll} 2.7\left(\dfrac{g\,\mathrm{FRP}}{N^2 U c_p \rho T_\mathrm{p}}\right)^{1/3}, & \text{stable} \\ 0.72\left(\dfrac{g\,\mathrm{FRP}}{u_*^2 U c_p \rho T_\mathrm{p}}\right), & \text{neutral} \\ 1.1\left(\dfrac{g\,\mathrm{FRP} H_\mathrm{ABL}^{2/3}}{w_*^2 U c_p \rho T_\mathrm{p}}\right)^{3/5}, & \text{unstable} \end{array}\right. \tag{18}$$

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5.3 Inter-comparison results

The scatter plots for all approaches applied to the whole MISR dataset are presented in Fig. 2 and the corresponding statistics are summarised in Table 1. Table 1 also includes the statistics for the persistency-based approach, which appoints the same value to all fires: 1289 m, the mean height of the learning MISR set. As one can see, the suggested formula performs better than any other approach and much better than other semi-empirical formulas. Comparable quality was demonstrated only by the BUOYANT model, which was directly solving the 1-D budget equations along the plume trajectory. Intriguingly, B69 and B84 scored even worse than the persistency method. From one side, it provides certain justification for the prescribed plume distribution accepted by many atmospheric models. From another side, it raises questions about reasons for failure of the well-recognised methods in applications to wild-land fires.

The root-cause of the low scores of B69 and B84 is that they are based on numerous simplifications and empirical coefficients, which were selected for stacks rather than for wildfires. The poor quality of predictions originates from the inadequacy of these assumptions and, in particular, the wrong sets of governing parameters. For example, wind speed is unimportant for the wild-fire plume height – but it is the primary parameter for all approaches related to stacks.

From Fig. 2, one can also notice the tendency towards the under-estimation of the BUOYANT model, which did not allow any single plume to rise above 3000 m. This is probably due to the missing latent heat contribution, which, according to (Freitas et al., 2007), can nearly double the injection height. However, its direct inclusion may lead to over-estimation of the number of plumes reaching the FT (Pfister et al., 2011). The new approach is free from this caveat: the effect of both sensible and latent heat is automatically taken into account during the calibration step.

6 Discussion

Comparison of the relative importance of the atmospheric and fire characteristics in Eq. (13) makes it evident that the success of the prediction strongly depends on quality of the boundary layer height predicted by an the NWP model and on the FRP observation by the satellite. The Brunt-Vaisala frequency contributes only marginally: in most cases $|\delta N^2/N_0^2| < 0.1$. One can expect, however, that the FT stability is partly reflected by the boundary layer height – following the arguments of (Zilitinkevich et al., 2007).

The added value of the combination of H_{ABL} and FRP is demonstrated in Fig. 3, which presents scatter-plots of the observed injection height with regard to these parameters taken independently. As one can see, neither deep H_{ABL} nor high FRP taken separately can explain the actual injection height of the plume. This tendency was also noticed by (Labonne et al., 2007; Luderer et al., 2006; Trentmann et al., 2006) for stratosphere-reaching plumes: it is the combination of favourable meteorological conditions and strong fire that results in high plumes.

6.1 Prediction of free-troposphere plumes

One can argue that prediction of the plume heights inside the boundary layer is quite uncertain and less important than those above ABL. Indeed, intensive turbulent mixing quickly distributes the smoke over the whole ABL, thus making the question about the plume height rather academic. Prediction of the FT plumes seems to be more important since the vertical profiles of the smoke concentration would survive longer under stable stratification.

To investigate the possibility of predicting the height of the FT plumes, they were picked from the MISR learning subset (204 cases). The fitting procedure was then repeated repeated for these fires only resulting in the following parameter values:

$$\alpha = 0.95\,; \quad \beta = 190m\,; \quad \gamma = 0.19\,; \quad \delta = 0.01 \tag{19}$$

They are substantially different from Eq. (13). In particular, the ABL is always passed

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"almost for free". However, the FRP power has been reduced down to 1/5 reflecting the necessity of the plume to rise against the FT stable stratification. Noteworthy, an attempt to refit the ABL-only fires does not lead to significant changes in the optimal coefficient values (Eq. 12). The generic fit is also optimal for ABL-only fires.

The performance of the formula with the coefficients (19) for the FT cases this fit for the FT cases from both learning and control sets is comparatively similar and outstandingly good: 92 and 82 % of the fires appear within 500 m from the observations (Fig. 4), respectively. The 10 % difference is due to limited size of the sets.

There is, however, one peculiarity: in Fig. 4 the fit (Eq. 19) was applied to the plumes, which were known to reach FT: this information came from the MISR observations. In general case such hint is not available, which raises the problem of identifying the above-ABL plumes. A seemingly evident solution to compute H_p with the generic fit (Eq. 12) and then compare it to H_{ABL} unfortunately leads to unequivocal outcome. From one side, the scatter plot of Fig. 5 demonstrates that the method performs comparatively well: the bulk of the cases are correctly recognised to be inside ABL or to reach FT. But since the fraction of the FT plumes is barely 15 % and the fit is optimised for the bulk assessment, only 85 out of 204 FT plumes are recognised correctly. Apart from that, 50 ABL plumes are erroneously marked as the FT ones.

To improve the detection of the FT fires, the third fitting exercise was performed with the modified quality criterion:

$$J_R = \sum_{i=1}^{N_{fires}} \Theta(-\Delta H_{obs}) \cdot \Theta(\Delta H_{mdl}) - 1.2 \sum_{i=1}^{N_{fires}} \Theta(\Delta H_{obs}) \cdot \Theta(\Delta H_{mdl}) \tag{20}$$

Here $\Delta H_{obs} = H_p^{obs}(i) - H_{ABL}(i)$, $\Delta H_{mdl} = H_p^{mdl}(i) - H_{ABL}(i)$. Minimisation of this function corresponds to the minimum fraction of the ABL-plumes misinterpreted as FT-ones (the first term) and the maximum fraction of the FT-plumes recognised correctly (the second term). The scaling of 1.2 sets the priority to correct recognition of the FT cases over the misinterpretation of the ones inside the ABL.

The optimization with the cost function (Eq. 20) results in the following parameter values:

$$\alpha = 0.15; \quad \beta = 102m; \quad \gamma = 0.49; \quad \delta = 0 \tag{21}$$

It is well seen that for accurate positioning of the plume regarding the ABL height, the FT stratification is unimportant, whereas the FRP is taken to power of 1/2, which is much larger than in all other fits.

Detection skills of this fit are better than those of the generic one: 110 out of 204 FT plumes are recognised correctly, with the rate of mis-located ABL plumes still being small: 70 out of ~ 1000.

As a result, the following two-step procedure can be considered:

1. The injection height is evaluated using the formula (10) with parameters (Eq. 21).
2. The result is compared to H_{ABL} and, depending on $H_p < H_{abl}$, or $H_p > H_{abl}$, the final height is evaluated using the parameters (Eqs. 13 or 19), respectively.

Application of this procedure to the whole MISR set leads to slightly lower but still similar quality scores as the single-step computations: ~ 64 % of the plumes are predicted within 500 m from the observations. This is not surprising because the bulk of the dataset is still the ABL cases where little has changed.

For the FT plumes, however, the situation changes. As seen from Fig. 6a, the plumes observed and/or detected as the FT ones, fall to three clearly distinguishable groups: (i) the FT-plumes, which are correctly treated with FT-specific fit (Eq. 19) and predicted well (green dots in Fig. 6a), (ii) FT-plumes, which are wrongly treated with the ABL fit (Eq. 13) and under-estimated (blue dots); (iii) the ABL-plumes, which are erroneously treated with the FT fit (Eq. 19) and over-estimated (red dots).

The trade-off between the one- and two-step estimations becomes clear from the comparison of the panels in Fig. 6. They both show the predictions for the same subset of fires but the panel b shows the outcome of the single-step procedure using the generic coefficients (Eq. 13). As one can see, single-step predictions are practically

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free from the over-estimated cases but the fraction of the under-estimated plumes is large. However, the formal quality criteria (RMS, fraction of good predictions, etc.) are better for the one-step procedure. Therefore, the choice between the one- and two-step approaches would depend on goals of the specific application.

7 Conclusions

The suggested methodology (Eq. 10) with parameters (Eqs. 13 and 19) and the selection fit (Eq. 21) are based on three input parameters: boundary layer height, fire radiative power, and Brunt-Vaisala frequency.

The inside-ABL injection heights are predicted within the uncertainty range of the MISR observations (500 m) for about two thirds of the cases if all MISR data are considered and for > 70 % of the cases if only "good" MISR data are taken. The existing parameterizations show much lower scores if similar level of complexity of the approach is considered (e.g., Briggs formulas). Comparable but still lower scores were demonstrated only by 1-D plume rise model – but at much higher input information and computational demands.

The FT-plumes comprise about 15 % of all cases and thus have low impact on the optimal parameters if all fires are considered. However, the fraction of well-predicted plume heights exceeds 80 % if the free-troposphere plumes are pre-selected.

The formula with parameters adapted for detection of the FT cases is capable of catching about 60 % of the free-troposphere plumes but it also mis-detects a few plumes as belonging to the FT. Until this detection procedure is improved, selection of the single-formula approach or the two-step computations should go on the case-by-case basis.

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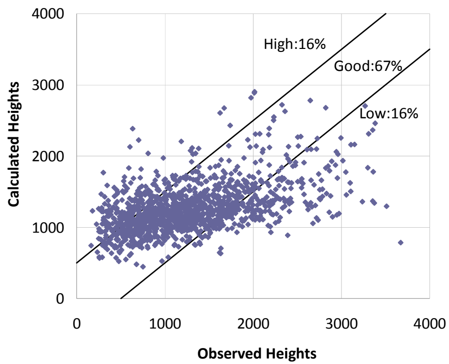
Table 1. Performance of B69, B84, Buoyant and formula (10) approaches for the MISR dataset.

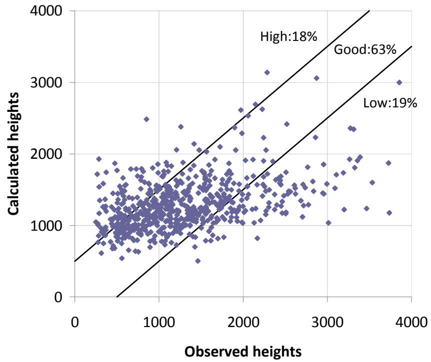
	B69	B84	BUOYANT	Persistence	Formula (10)
Prediction within observation accuracy, %	42	37	51	55	65
Low predictions, %	36	43	17	21	17
High predictions, %	14	12	14	24	18
Failed analysis, %	8	8	18	–	–
Correlation coefficient	0.15	0.03	0.44	0	0.45
Range representation	2.6	8.0	0.54	0	0.48
RMSE, (m)	1764	5555	604	716	646

Parameters:

Prediction within observational accuracy: a fraction (in %) of the predicted plume top heights deviating from the MISR observation by less than the MISR uncertainty of 500 m.
Low prediction: fraction (in %) of the predicted plume top heights lower than the MISR observation by more than 500 m.
High prediction: fraction (in %) of the predicted plume top heights higher than the MISR observation by more than 500 m.
Failed analysis: fraction (in %) of cases where computations have not converged.
Correlation coefficient: Pearson's sample correlation coefficient taken over the MISR dataset.
Range representation: a ratio of the observed and predicted sample standard deviations of the heights: $\sigma_{mdl}/\sigma_{obs}$.
RMSE: root mean square error of the predicted heights, (m).
Note: large fraction of failed cases by BUOYANT is related to the model applicability range (computations failed for too low surface pressure in mountains, too high wind speed, too high T_f, etc.).



a) Learning subset, eq (10), (13)



b) Control subset, eq (10), (13)

Fig. 1. Comparison of predictions of the formula (10) with the observed H_p for the learning **(a)** and control **(b)** subsets. Parameter values Eq. (13). Unit = (m).

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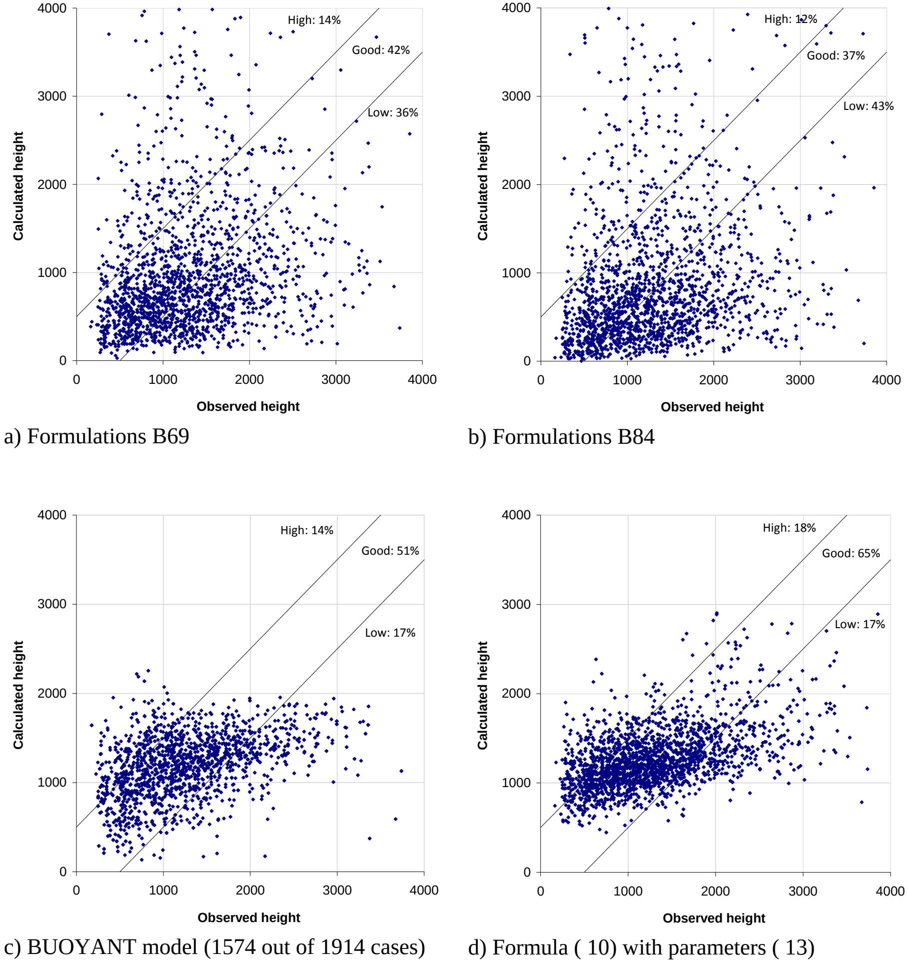

Fig. 2. Comparison of B69, B84, BUOYANT, and formula (10) for the whole MISR set.

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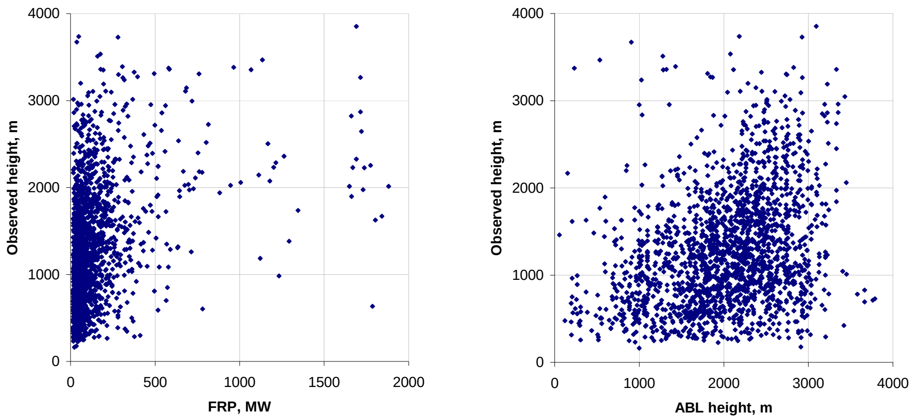

Fig. 3. Correlation of the observed plume height and individual components of the formula (10): boundary layer height and FRP.

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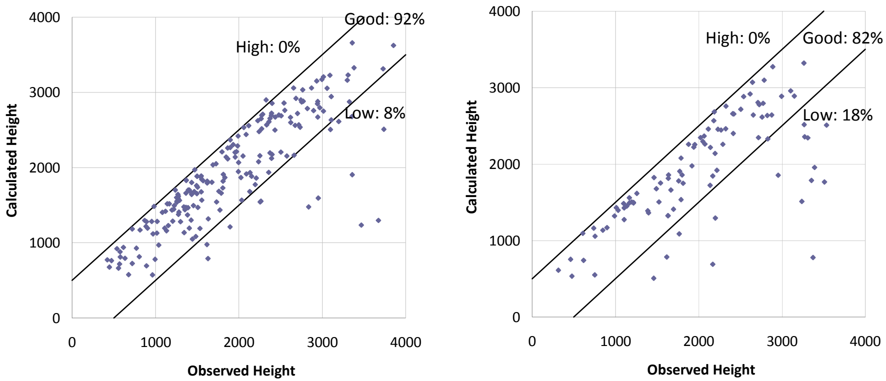

a) Learning dataset b) Control dataset

Fig. 4. Performance of the algorithm (Eqs. 10, 19) for the FT plumes extracted from the learning **(a)** and control **(b)** MISR datasets. Unit = (m).

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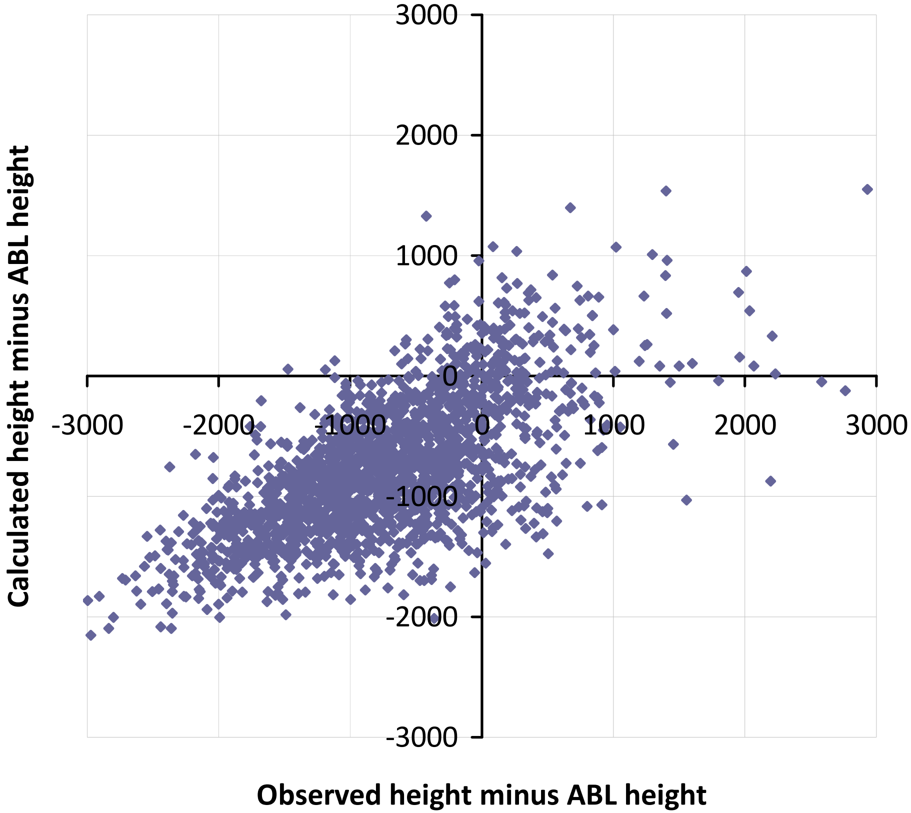

Fig. 5. Comparison of difference between the H_{abl} and the predicted and observed fire plume heights.

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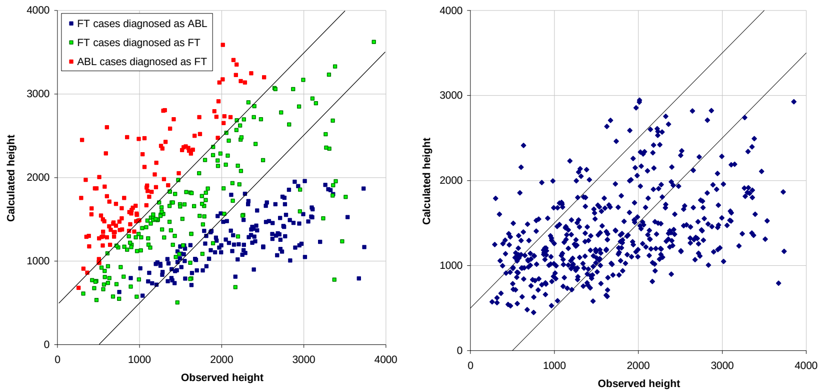

a) Prediction with selection of ABL-FT cases

b) Prediction with the generic formula (10) and parameters (13)

Fig. 6. Performance of the formula (10) for cases detected as FT using the fit parameters selection and the general fit Eq. (13).

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