Smoke plume from fire lagrangian simulation: dependence on drag coefficient and resolution

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Introduction

A numerical simulation of the plume dispersed from a fire is performed using the Lagrangian stochastic particle model SPRAYWEB and the results are compared to a field experiment, carried out in August 2013 in Idaho (USA). Here we want to assess the dependence of the plume rise scheme on the values chosen for the drag coefficient and the cell size.

The plume rise scheme

The plume rise scheme (Alessandrini et al., 2013) is based on the Lagrangian description of the plume evolution in terms of particle trajectories, while the temperature and momentum differences, which are responsible for the plume buoyancy, are calculated on a fixed grid. At each time step $\Delta t = t_1 - t_0$ temperature and momentum differences (ΔT and w_c respectively) between each grid cubic cell and the surrounding environment are computed using the following equations

$$\Delta T(t_1) = \Delta T(t_0) + \Gamma(z_c) w_c(t_0)\Delta t + 0.0098 w_c(t_0)\Delta t$$

$$w_c(t_1) = w_c(t_0) + \frac{\Delta T_c(t_1)}{\Delta T_c + T_a(z_c)} g\Delta t - \frac{0.5 C_D S w_c^2(t_0)\rho_a}{\rho_p V_c}\Delta t$$

where z_c is the cell height, T_a the ambient temperature, g the gravity, C_D the drag coefficient, S and V_c the cell section and volume, ρ_a and ρ_p the ambient and plume density. This plume rise scheme is not based on an analytical model and the only two assumptions required are the drag coefficient value and the cell size.

Drag coefficient models

There is not a generally accepted value in the literature for the drag coefficient. Four drag coefficient expressions which depend on the Reynolds number of the cells ($Re_c = \phi\frac{|U_c|}{\nu}$, where ϕ is the equivalent cell diameter, U_c is the cell vertical velocity and ν is the kinematic viscosity of air), are tested.

Table: Drag coefficient expressions

Author	C_D expression
Turton and Levenspiel (1986)	$C_D = \frac{24}{Re_c}(1 + 0.173 Re_c^{0.657}) + \frac{0.413}{1+16300 Re_c^{-1.09}}$, if $Re_c < 2 * 10^5$
Brown and Lawler (2003)	$C_D = \frac{24}{Re_c}(1 + 0.15 Re_c^{0.681}) + \frac{0.407}{1+8710 Re_c^{-1}}$, if $Re_c < 2 * 10^5$
Cheng (2009)	$C_D = \frac{24}{Re_c}(1 + 0.27 Re_c)^{0.43} + 0.47(1 - exp(-0.04 Re_c^{0.38}))$
Mikhailov and Silva Freire (2013)	$C_D = \frac{777((\frac{669806}{875}) + (\frac{114976}{1155})Re_c + (\frac{707}{1380})Re_c^2)}{646 Re_c((\frac{32869}{952}) + (\frac{924}{643})Re_c + (\frac{1}{385718})Re_c^2)}$

The first three expressions presented in the table above are similar, as a sort of Stokes' law extended for higher Reynolds numbers, but with different constants derived by fitting experimental data. The latter is derived from the Shanks transformation of Goldstein series (Goldstein, 1929, Shanks, 1955) improved by fitting its coefficients directly to experimental data.

Taylor diagram

The two most faithful models are those of Cheng (2009) and Brown and Lawler (2003) since their points are closest to that of the observations.

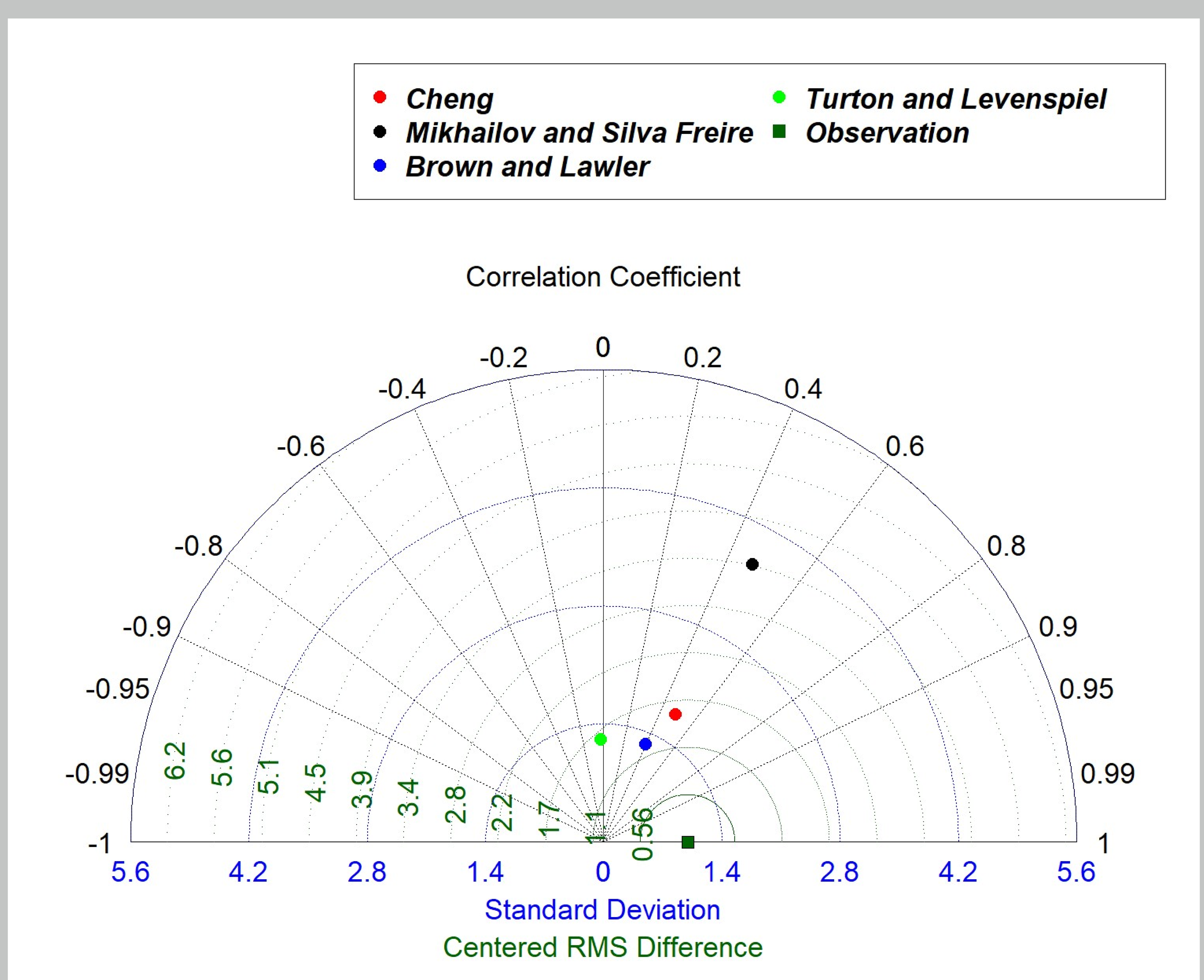

Figure: Taylor diagram for the four drag coefficient expressions

Maximum height

We estimated maximum plume height considering two vertical standard deviation of the plume distribution above the mean particles height.

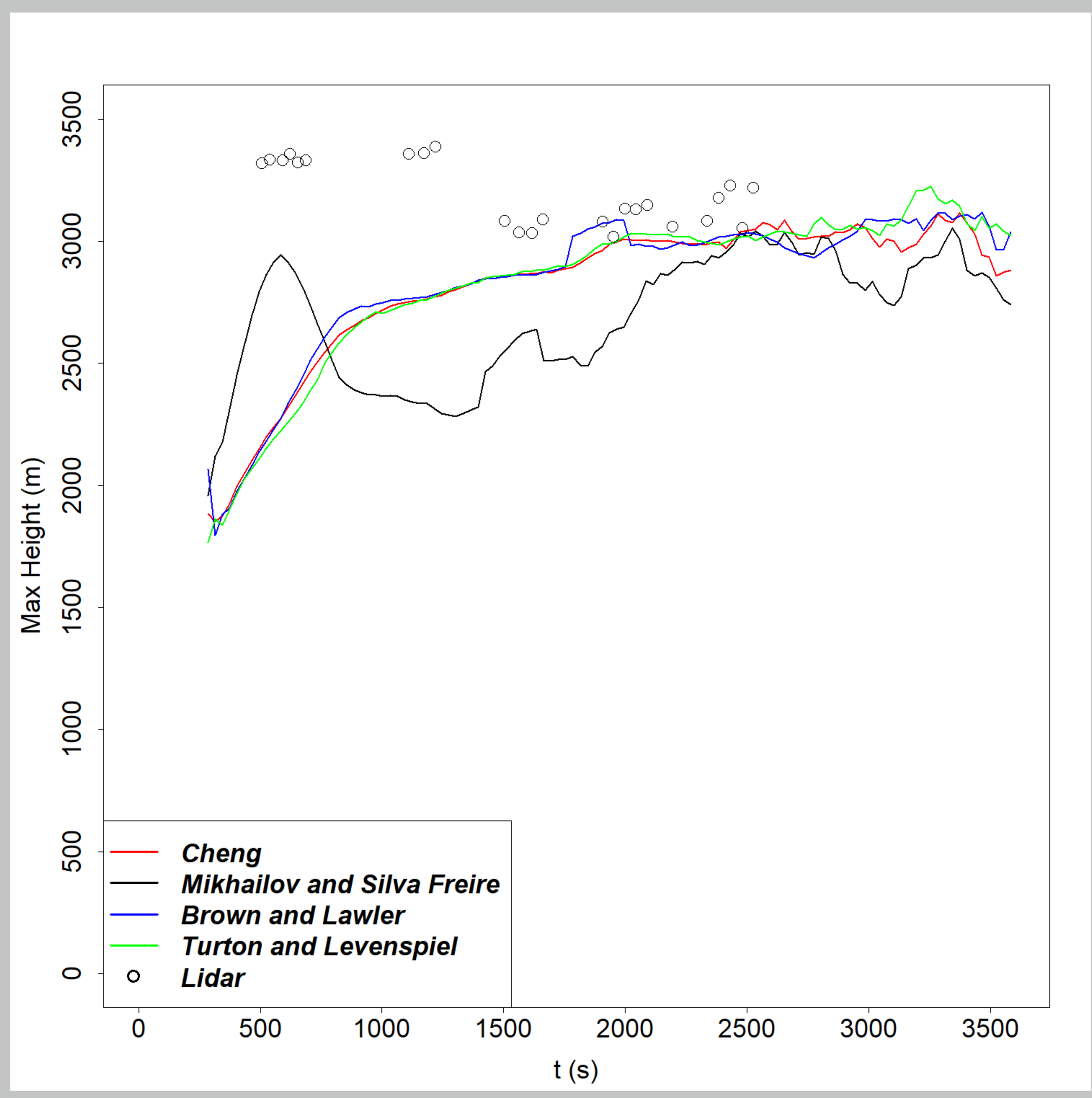

Figure: Maximum plume height trend

QQ-plots

QQ-plot of the models deriving from the Stokes law is shown on the left; the one of the model from the Shanks transformation of Goldstein series is shown on the right.

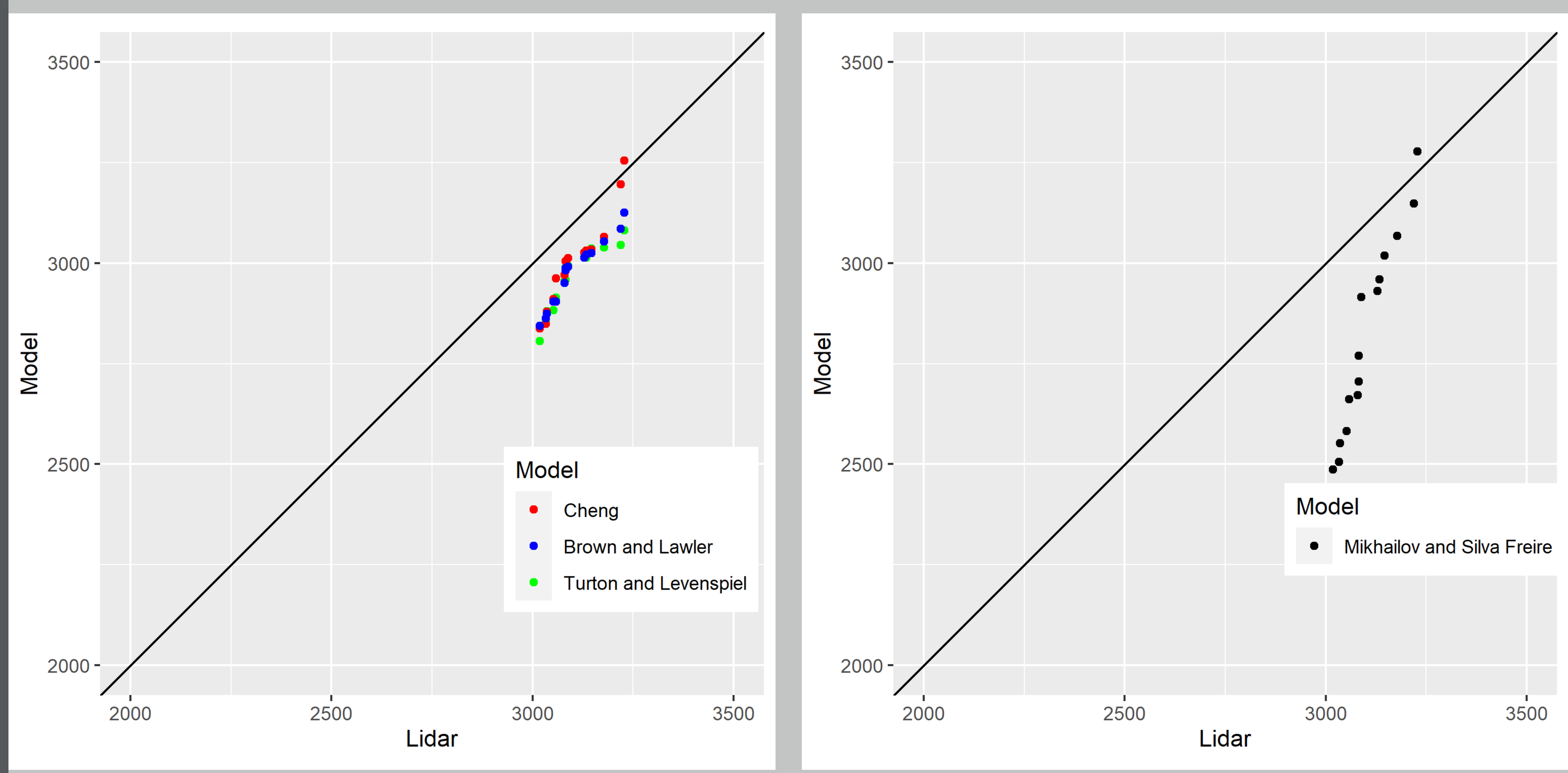

Figure: Models qq-plots

Conclusions

For this type of application the models deriving from the Stokes law have a better performance. In particular, the models of Cheng (2009) and Brown and Lawler (2003) give results that better agree with the observations. The model of Brown and Lawler (2003) can only be applied in case of Reynolds numbers less than 2×10^5, while the one of Cheng (2009) has no restrictions and this makes it the best choice for our purposes. We are now working on other case studies to consolidate these results. Regarding the horizontal resolution we did not find a strong dependence of the results in case of small prescribed fires

Acknowledgments

Part of the activities were carried out in the framework of SAPERI Project, funded by Aethia Srl and Regione Piemonte (POR FESR 2014/2020 - Asse I - Azione I.1b.1.2 - Bando PRISM-E)

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