Numerical Modeling of Firebrand Transport

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Introduction

Wildfire ember attacks, also known as firebrand showers, are the fastest and most complex form of wildfire spread. This project seeks to answer what aspects of turbulence affect firebrand landing distribution. The hypothesis is that turbulence intensity affects firebrand landing distribution. The following work uses a firebrand particle dynamics solver to calculate transport in a turbulent boundary layer at various turbulence intensities. Velocity data of a high-fidelity computational fluid dynamics solver is used for small-scale turbulence and WRF-SFIRE (wildfire simulation) for large-scale wildfire turbulence at various wind speeds.

Firebrand Model

Key features:

- 6 DOF particle dynamics model for plate and rod shapes
- Dynamically solves linear and angular momentum
- Utilizes experimental drag and moment coefficients
- Singularity free by quaternions for rotation calculations

Governing equations of the firebrand model,

$$^{I}\frac{d}{dt}(m^{I}\vec{V}_c) = {}^{I}\vec{F}_D + {}^{I}\vec{F}_G$$

$$^{I}\vec{M}_G = {}^{B}\frac{d}{dt}({}^{I}h_G) + {}^{I}\vec{\omega}^{B} \times {}^{I}h_G$$

solve for linear and angular momentum [1], [2], [3]. Firebrands translate and rotate on a body-fixed frame (B) with respect to a fixed inertial frame (I).

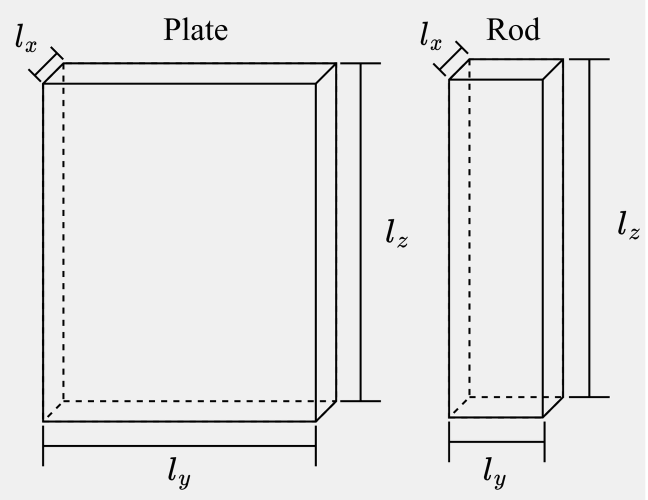

Figure 1. Diagram of plate and rod firebrand geometry where $l_x < l_y < l_z$

Turbulent Boundary Layer Simulation

Large eddy simulations (LES) were created for small-scale high-resolution turbulent boundary layers. LES simulations were validated with experimental wind tunnel data, seen in Figure 2.

LES Parameters:

- Re = 284,000
- v = 2.23 m/s
- L = 2 m
- $\nu = 1.568 \times 10^{-5}$

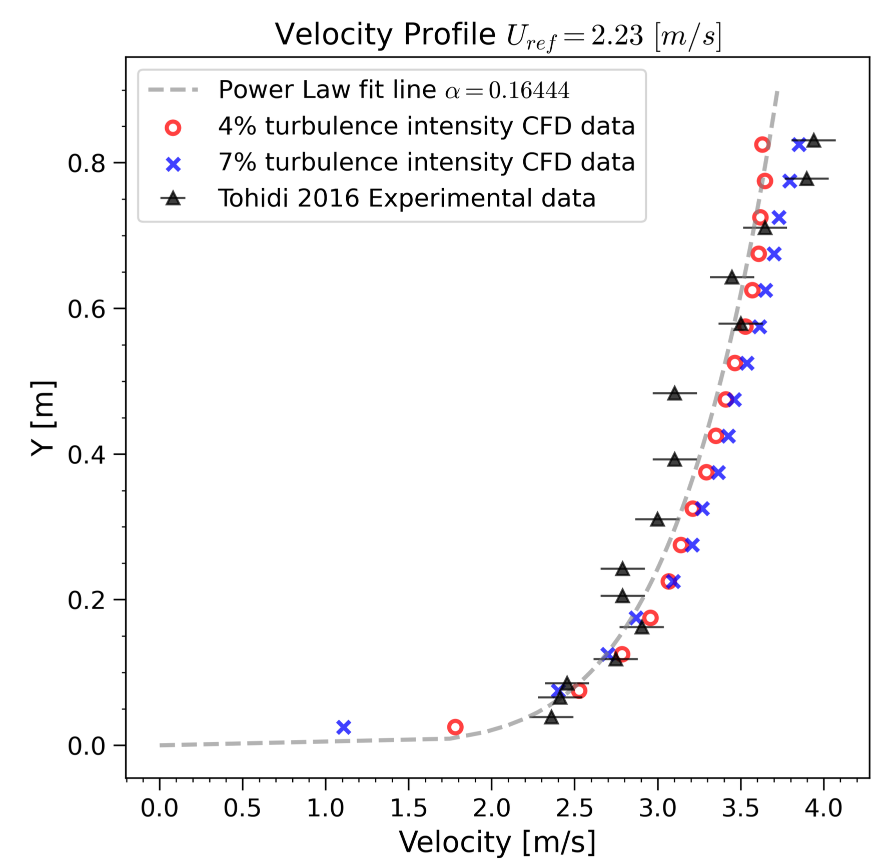

Figure 2. Validation of LES results with experimental data from Tohidi et. al. [4].

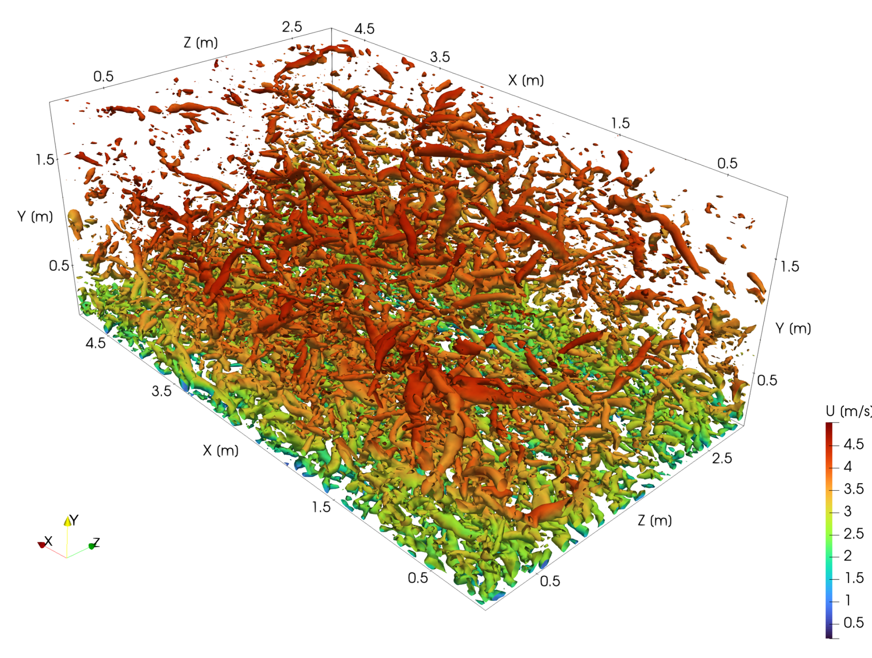

Figure 3. Q-Criterion of 4% turbulence intensity case

Figure 3 shows high resolution turbulence structures. This was important because current wildfire simulations with firebrand transport use large/coarse domains and mesh sizes, leaving a gap in knowledge on the influence of small-scale turbulence on firebrand transport. CFD simulations of 4% and 7% turbulence intensities were created for experimental test cases.

Small-scale Transport

A series of 32 tests were conducted for plate and rod firebrands to compare transport in 4% and 7% turbulence intensity, instantaneous and time-averaged velocity fields, and at 4 different release heights.

- 1000 particles
- Release location (X, Y, Z) : $2.5, 1.5, 0.25 - 1.75\ m$
- Release angle: $^{B}\theta_0 \sim \mathcal{U}(0, 2\pi)$

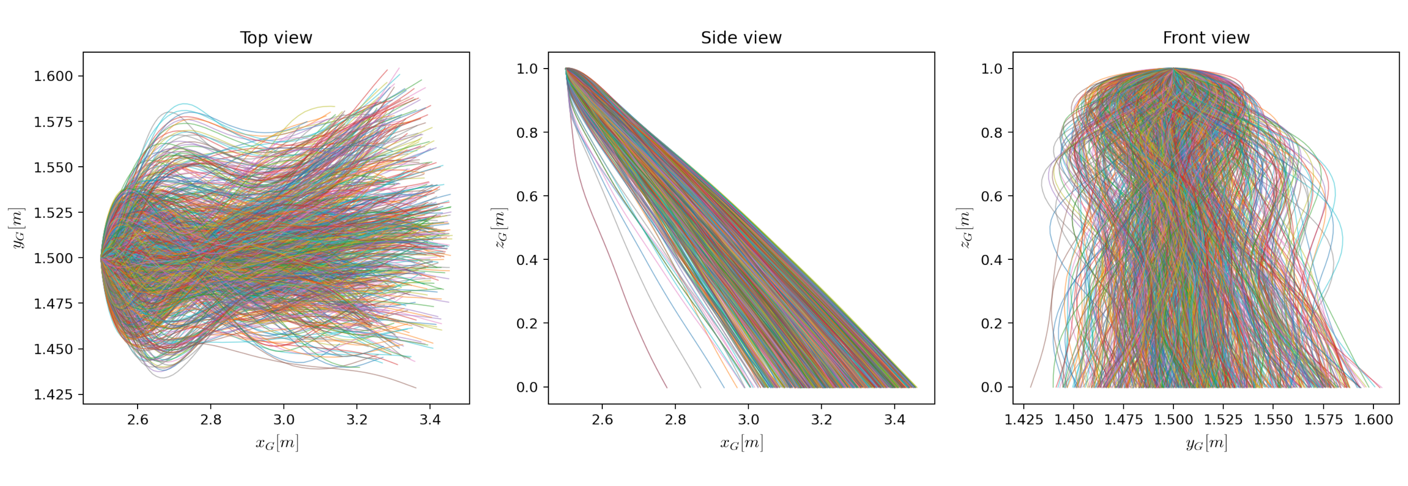

Figure 4. Plates trajectories, fixed size: $l_x = 3\ mm$, $l_y = 15\ mm$, $l_z = 25\ mm$

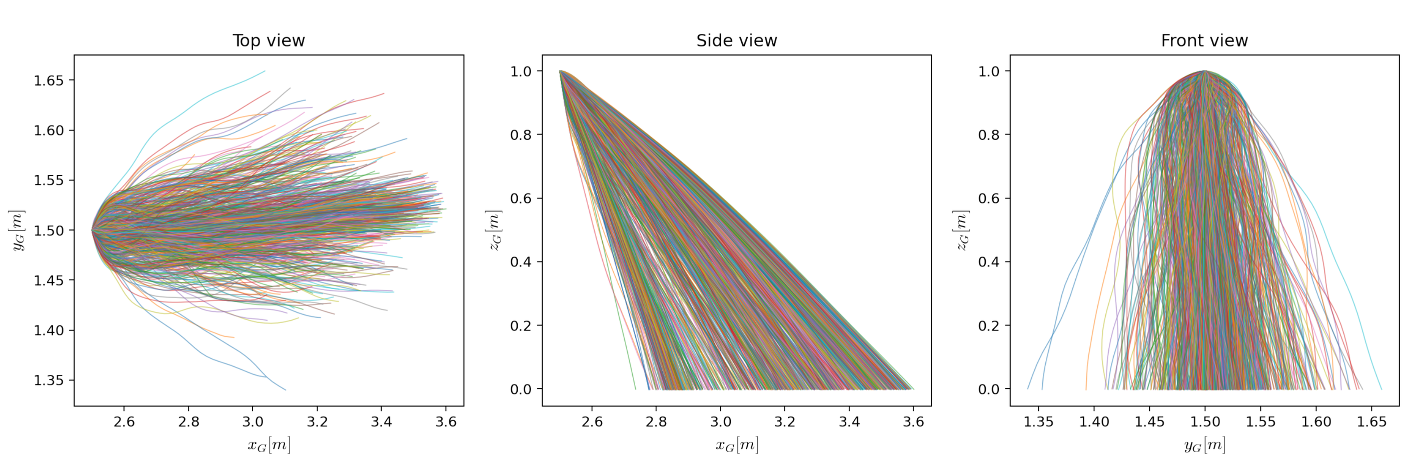

Figure 5. Rods trajectories, fixed size: $l_x = 3\ mm$, $l_y = 5\ mm$, $l_z = 25\ mm$

Large-scale Transport

The firebrand transport code was coupled with wildfire simulation software WRF-SFIRE to simulate transport in large-scale domains. Firebrands were simulated in high velocity/low fluctuation (Manning Creek) and low velocity/high fluctuation (Creek Fire) wildfire simulations.

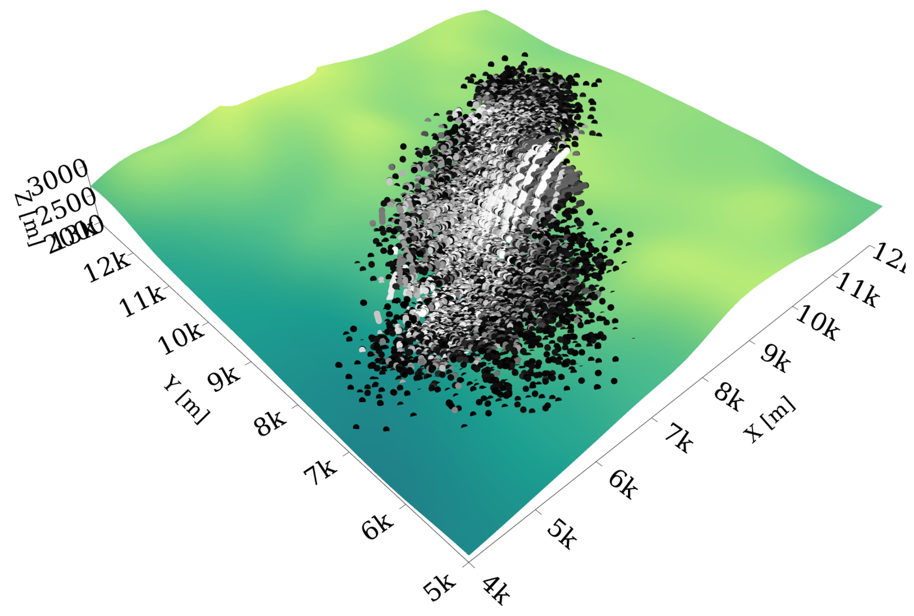

Figure 6. Manning Creek fire, 10k plate firebrand trajectories

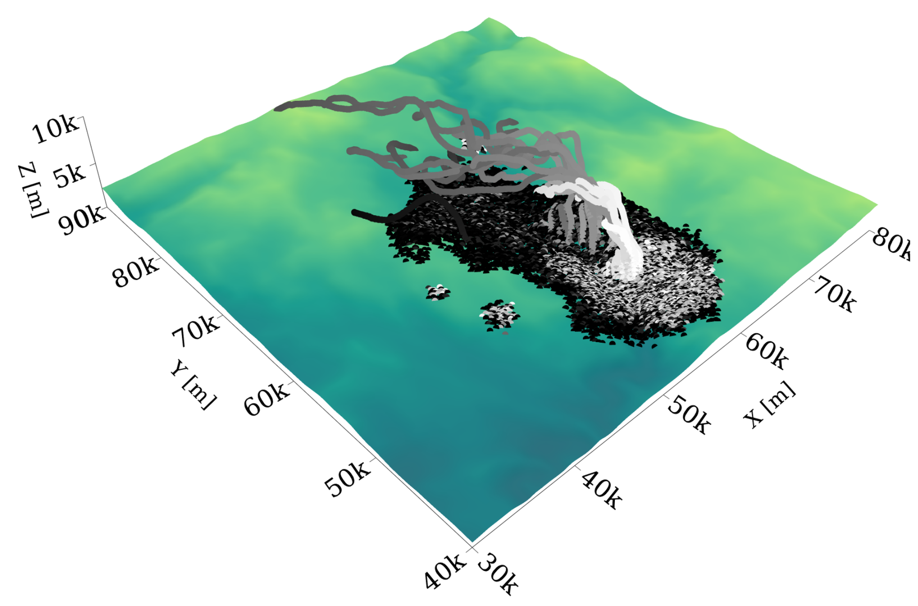

Figure 7. Creek Fire, 10k plate firebrand trajectories

Results

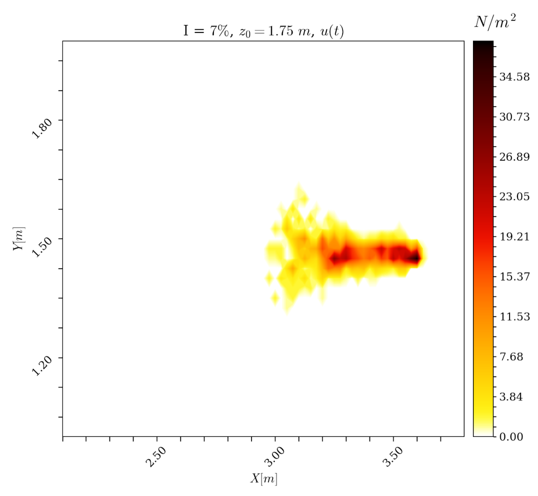

Figure 8. Plate landing distribution

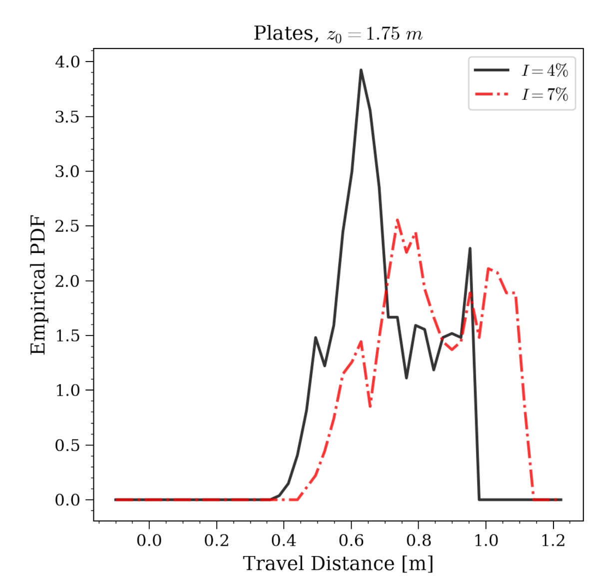

Figure 10. Plate travel distance

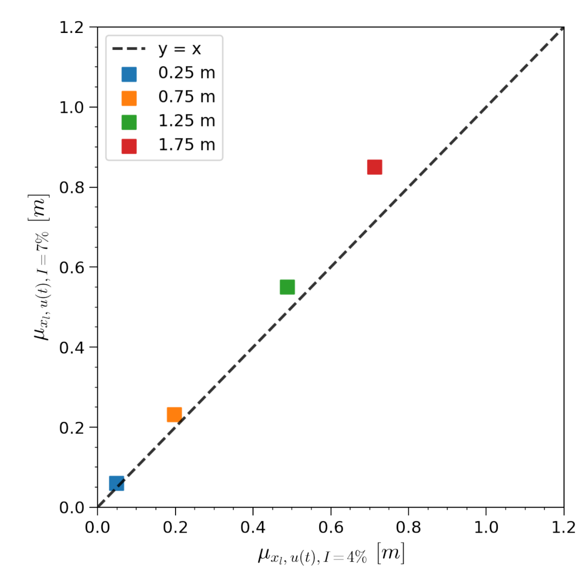

Figure 12. Plate μ_{x_f}

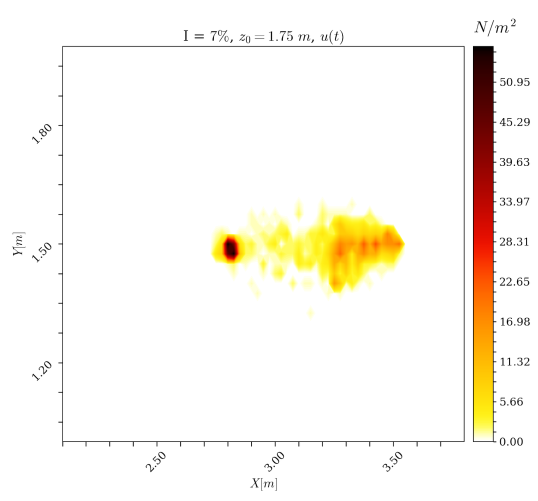

Figure 9. Rod landing distribution

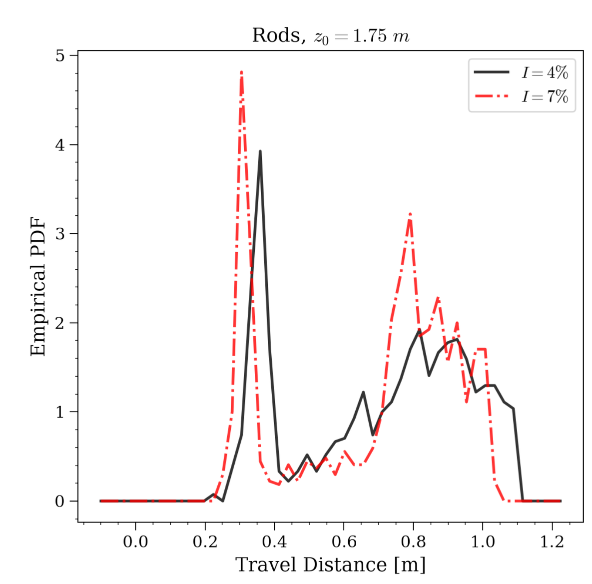

Figure 11. Rod travel distance

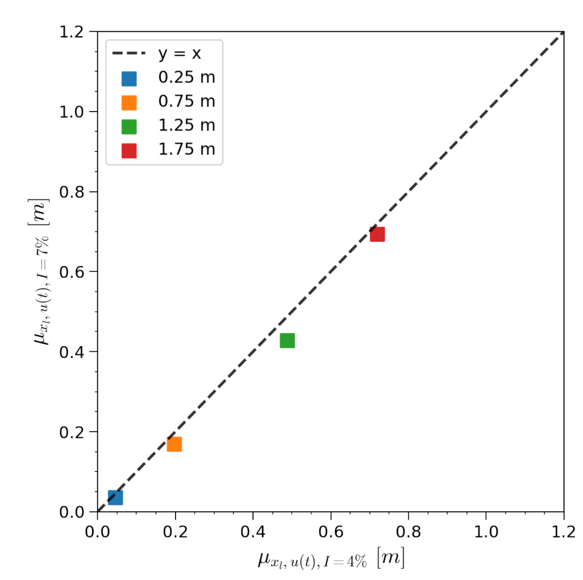

Figure 13. Rod μ_{x_f}

Statistical analysis of small-scale transport for plate and rod firebrands. Landing distribution of aggregate firebrand count over 1x1 m^2 area (left), empirical PDF of travel distance in X direction (middle), and average travel distance at 0.25, 0.75, 1.25, 1.75 m release heights of firebrands in 4% and 7% turbulence intensities (right).

Conclusions

- The turbulence intensity affects the landing distribution of firebrands
- Plates have higher travel distances at 7% turbulence intensities, and rods have slightly higher travel distances at 4%
- Firebrand shape is significant because of their different aerodynamic drag forces
- The presence of turbulence leads to shorter travel distances, time-averaged velocity fields with no fluctuations overpredict the travel distance
- Firebrands in large-scale domains have greater travel distances in low wind-speed wildfires

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