CWE-8
June 7-11, 2026
London, ON, Canada

A Multi-Level Framework for Modeling Wildfires at the Wildland-Urban Interface: Case Study of the 2025 Eaton Fire

Tanmay Vora[a], Seymour M.J. Spence[a], Ann Jeffers[a]

[a]University of Michigan, Ann Arbor, Michigan, USA

Summary

The recent Eaton and Palisades fires caused massive structural destruction. In response, this paper introduces a multi-level framework for modeling wildfires at the wildland-urban interface (WUI). The WUI is divided into four nested domains–wildland, buffer, surrounding communities, and communities of interest–each treated with increasing modeling fidelity. In the wildland domain, the fire front propagates through convection. Within the buffer domain, convection and firebrand spotting are responsible for fire spread. Fire spread in the surrounding communities is simulated empirically via thermal radiation and firebrand spotting. For the communities of interest, on the other hand, a computational fluid dynamics (CFD) approach using an Euler-Euler multiphase model is employed. Results from this CFD method applied to a smaller representative community are presented. The proposed framework shows promise for developing a community-scale wildfire model capable of predicting fire spread. These predictions could support decision-making by authorities during wildfires and aid in designing wildfire-resilient communities.

Keywords: *Wildland-Urban Interface, Computational Fluid Dynamics, Fire Spread Modeling, Euler-Euler Model*

1 INTRODUCTION

Over 15000 structures have been reported destroyed, according to the California Department of Forestry and Fire Protection (CAL FIRE). Fire spread modeling in the context of wildlfires can be categorized as urban fire spread models, wildland fire spread models, and wildland-urban interface (WUI) fire spread models depending on the domain being considered. There are three mechanisms of wildfire spread, i.e., flame convection, thermal radiation, and firebrand spotting. Firebrands are burning embers made of ignitable material such as wood, that are ejected out from burning vegetation and structures. Firebrand spotting refers to ignition of flammable fuel ahead of the fire front due to deposition of firebrands.

Community scale wildfire models either neglect certain parts of the fire spread or approximate them using empirical models. Using computational fluid dynamics (CFD) to model fire spread on a large scale, while being accurate, is computationally infeasible. However, CFD can be used to model fire spread inside smaller domains such as for a selection of neighborhoods that are of most interest. CFD models are sensitive to boundary conditions and hence defining appropriate boundary conditions is very necessary. Additionally, the simulation approach needs to account for disparate time and length scales associated with the governing physics. To address this, a multi-level framework is required that has the ability to provide accurate time-varying boundary conditions for the CFD domain.

The aim of the current research study is to develop a framework that models wildfire spread involving all three mechanisms with multiple levels of resolution. To achieve that, the WUI area is divided into four nested domains, namely, wildland, buffer, surrounding communities, and region/s of interest (ROI), each with varying time and length scales. Furthermore, a novel (CFD)-based approach is proposed to model fire spread in the ROI, which emphasizes an Eulerian multiphase model for firebrand transport that was validated in prior research. This paper details the modeling procedure and presents results from the CFD approach on a smaller model community.

2 METHODOLOGY

The multi-level framework used in this study is depicted in Fig. 1. Red boundary represents the wildland domain, blue boundary represents the buffer and the surrounding communities domain, and the black boundary represents the ROI for the case of Eaton Fire which occurred in January 2025. The framework is similar to the one presented in Szasdi-Bardales et al. (2025) with the addition of a fourth CFD-based domain and modifications in firebrand generation.

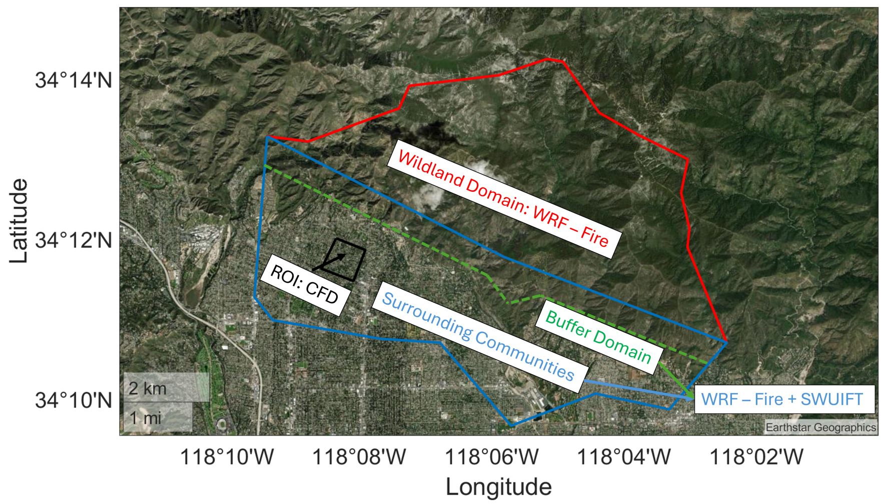


Figure 1: The proposed multi-level framework in the Eaton fire area

2.1 Wildland Domain

The wildland domain consists of vegetation far from the community. Weather research and forecasting fire model (WRF-Fire) (Coen et al. 2013) which is a coupled fire-atmosphere numerical weather prediction model is used to model the fire propagation in this domain. The fire front location determined from the WRF-Fire model and the resolved wind fields provide inputs to the subsequent domains.

2.2 Buffer Domain and the Surrounding Communities

These domains represent the vegetation and structures surrounding the domain of interest. In these domains WRF-Fire coupled with a semi-physical SWUIFT (Streamlined Wildland-Urban Interface Fire Tracing) model developed by Masoudvaziri et al. (2021) is run to model fire spread and structural ignitions. The firebrand distribution (mass and size) at the boundaries of the ROI is calculated and used as an input to the next domain.

2.3 ROI Domain

The ROI is where the highest fidelity of fire spread simulation is required. To tackle this, a novel CFD-based approach leveraging an Euler-Euler multiphase model is proposed similar to the one outlined in Vora et al. (2025). Multiple continuum phases are assumed for firebrand particles to obtain an accurate size and mass distribution. The turbulent gases (wind and fire) are modeled using unsteady Reynolds' averaged Navier-Stokes (URANS) equations. The computational domain for a community located in Altadena is shown in Fig. 2. The inlet for the wind is farther upstream following the recommendations outlined by Franke et al. (2011). The yellow buildings in Fig. 2 are surrounding buildings to the neighborhood of interest modeled to minimize the effects of the boundary conditions.

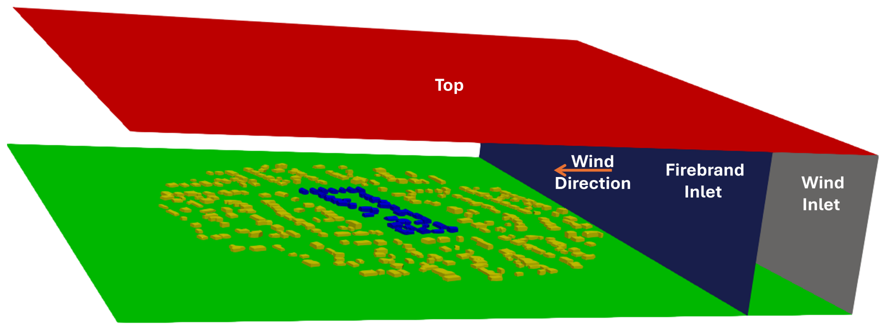


Figure 2: Computational Domain for CFD simulation inside the community of interest.

3 RESULTS

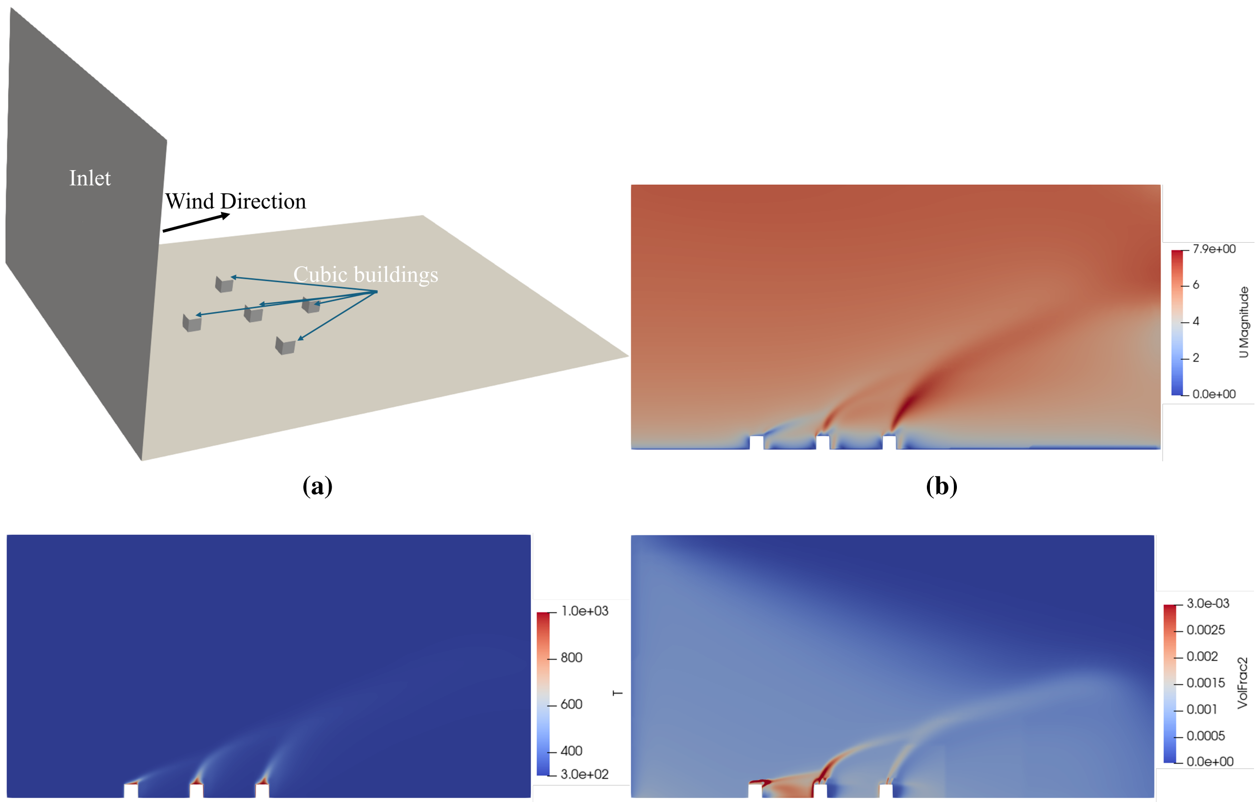
To demonstrate the novel CFD approach, a model problem (see Fig. 3a) is set up to simulate the fire spread inside a community. The firebrands and the wind inlet are the same for this simulation and thermal radiation is neglected. Three firebrand phases with different diameters were prescribed at the inlet and the cubes. The results from the model community simulation after a 80 second firebrand shower are presented in Fig. 3. The results are presented on the center-plane along the wind direction. Fig. 3b represents the wind velocity magnitude at the end of the simulation. Fig 3c shows the temperature of the gas while Fig. 3d shows the volume fraction occupied by the 1 mm diameter firebrands.

4 DISCUSSION

From Fig. 3d firebrand accumulation can be observed on the first two buildings. This can be attributed to the lower wind speeds (see Fig. 3b) in the vicinity of these two buildings whereas a higher wind speed due to the fire plume is observed on the third block leading to the lofting of the firebrands. The slower wind speeds on the first two blocks could be due to the presence of obstacles downstream causing the wind to slow down. The temperature profile in Fig. 3c shows the fire plume being tilted in the wind direction causing updrafts in the wind profile. The fire spread along with the firebrand transport was well captured using the Euler-Euler multiphase approach.

5 CONCLUSIONS

From the above discussion and results, it can be concluded that there is a need for modeling fire spread using high-fidelity physics-based models inside of communities situated in the WUI. The multi-level framework proposed in this paper has the capability to provide a first step in developing accurate physical models to predict the fire spread in WUI communities. A novel CFD-based multiphase approach has been developed and tested on a smaller representative community. This approach can provide a much better resolution for fire spread and ignition locations for targeted communities or neighborhoods of interest. The results from these simulations can assist in providing valuable insights in designing resilient communities, help authorities plan evacuation, and support firefighting.



(a) **(b)** **(c)** **(d)**

Figure 3: Results from the model community simulation: (a) Perspective View of the domain; (b) Wind velocity; (c) Temperature of gas; (d) Volume fraction occupied by 1 mm diameter firebrands.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation (NSF) grant number CMMI-2227315.

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