EXECUTIVE SUMMARY

Improving Parameterization of Combustion Processes in Coupled Fire-Atmosphere Models through Infrared Remote Sensing

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SERDP Project RC-2643

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Project: RC-2643

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

ACRONYMS AND ABBREVIATIONS

CFD computational fluid dynamics

DoD Department of Defense

PDF probability distribution function
PIV particle image velocimetry

1.0 INTRODUCTION

Wildfire behavior and spread are influenced by complex processes involving interactions between the fire and its surroundings. These interactions depend heavily on dynamic and heterogeneous turbulent flow fields that connect the fire to the fire environment, surrounding atmosphere, fuels, and topography. Computational fluid dynamic (CFD) techniques are used in physics-based fire behavior models to represent the coupled fire-atmosphere interaction using partial differential equations. These formulations describe the exchange of mass, momentum, and energy through non-linear processes such as convective and radiative heating and cooling, drag, turbulence, combustion, and evaporation. However, since wildland fires occur at large spatial scales and involve complex non-linear processes occurring at a wide variety of scales, it is not feasible to resolve all important phenomena over all relevant scales. Thus, sub-models or parameterizations must be developed to capture the net effects of these sub-grid phenomena. The focus on the lower end of the fire intensity scale will benefit Department of Defense (DoD) land managers by improving model performance in conditions consistent with a wide range of prescribed fire applications.

Recent CFD-based wildfire studies have focused on understanding the behavior of intense wildfire scenarios, which are the most challenging to manage and pose significant risks to people, communities, and infrastructure. The characteristic length scales of dominant fire phenomena and fire geometry typically increase with the intensity of the fire, while the sensitivity of fires to fine-scale variations in the ambient environment and the significance of fine-scale variations in fire conditions decrease with the increase in the characteristic length scales. When conditions are extreme and fires are intense, existing physics-based wildfire behavior models typically perform well. However, the spatial scales of fire behavior are smaller and the importance of finer scale variations in fire activity and fire environment is greater during lower-intensity fires. As the relevant length scales of the fire decrease relative to feasible model resolution, many physical wildfire behavior models struggle in this regime.

Physics-based coupled fire atmosphere models use a series of coupled partial differential equations to track the evolution of mass, momentum, energy, turbulence, and species of the gases moving around a fire and the mass, moisture content, and temperature of the fuel. These models are typically solved numerically on a three-dimensional grid, and the temperature and moisture variations that govern some ignition and drying processes can be explicitly resolved on meter scales. However, even at the sub-meter scale, there can be distributions of temperatures and moisture conditions. Currently, these models employ the notion of a probability distribution function (PDF) of temperatures within each grid cell to determine the moisture evaporation and combustion rates. Using this approach, they avoid having a step function in the rate of evaporation or combustion associated with the mean temperatures reaching critical values. However, the current formulation still presents challenges for low-intensity fire scenarios, where the moisture and temperature heterogeneity scales are even more poorly resolved. As the importance of fine-scale variations increases with decreasing physical scales of the fires, the need for a more dynamic and scenario-dependent representation of sub-grid distributions becomes more apparent.

The overall goal of this project is to improve the representation of subgrid-scale processes in coupled fire-atmosphere models operating at the landscape level through the use of fine-scale infrared remote sensing at the plot level. Infrared remote sensing, along with some additional measurements of the ambient environment, allows tracking the temporal evolution of fuel temperature and fuel moisture flux in heterogeneous fuel beds at a sub-meter scale, ideal for evaluating subgrid scale combustion processes in the coupled model. The measurements need to be amenable to similar averaging, as the governing equations for these models describe changes in model variables averaged over a grid volume.

The current FIRETEC model formulation explicitly tracks a mean solid fuel temperature and allows an assumed temperature variance. The combination is used to determine how much of the fuel is hot enough to evaporate water and to begin combusting as the temperature of the mean fuel increases. However, this approach suffers when conditions are less extreme and the length scales are small. In such cases, a parameterization needs to be flexible to account for multiple physical processes occurring at a given cell temperature based on variations in the environment. The aim of the work described here is to improve the overall performance of models like FIRETEC, particularly during lower-intensity fires where the sub-grid spatial and temporal variations have significant impacts on fire behavior.

2.0 OBJECTIVES

The overall goal of this project is to improve the representation of combustion processes in coupled fire-atmosphere models operating at the landscape level. Models intended to be used for landscape-scale fires (hundreds of meters to 10s of kilometers), typically divide the simulation domain up into a mesh of grid cells and these grid cells typically range in size from 1–30 meters on a side. As the processes governing combustion occur on considerably smaller scales, models require a means of describing these processes that is capable of dealing with heterogeneity within a cell and must also be scalable if the cell size is changed. A detailed examination of these combustion processes will improve the understanding of fine-fuel heat exchange, ignition, and fire spread and how fire behavior may be affected by fuel conditions. The specific objectives of the project are to:

- Track real-time high-resolution fuel moisture dynamics and fuel consumption at sub-meter scale in natural fuel beds containing both live and dead fuels.
- Evaluate the subgrid-scale parameterization of solid-phase combustion used in coupled fire-atmosphere models.
- Examine how model resolution affects the level of detail required in subgrid-scale models of combustion processes.
- Examine interactions among fuel heterogeneity, in both arrangement and load that influences fire spread, principally through fire-atmosphere interactions.
- Use knowledge gained in pursuit of the first four objectives to advance a new parameterization for fuel consumption in FIRETEC that is better capable of responding to fine-scale variation in the fire environment.

3.0 TECHNICAL APPROACH

The focus of this study was to improve the understanding of how subgrid processes influence the combustion process in FIRETEC. In each burning cell, the local rate of combustion was described in terms of the change in bulk density of fine fuel particles with time, which is a function of the local bulk densities of fuel and oxygen, turbulent mixing, along with the fraction of the computational cell that was actively burning. Currently, in FIRETEC, the burning fraction of the computational cell is defined as a PDF that determines the fraction based on the temperature of the cell, and this fraction is used to determine both the moisture evaporation and combustion rates for the cell. Assessing how well this PDF performed required fine-scale estimates of temperature to be able to estimate a measured analog to the model's PDF. Additionally, to guide any refinement of the parameterization, the project team also obtained additional fine-scale measurements to help understand the system. These additional measurements included estimates of the reaction rate, fluxes of moisture, and flow field measurements to provide estimates of the turbulent mixing term in the reaction rate. Understanding these fine-scale processes will guide improvements to the parameterization of the reaction rate.

Measurements for this study were collected using both infrared and visual cameras mounted on tall tripods within the burn units. The height of the nadir-view tripod system (8.2m) provided a 4.8x6.4m field of view for the infrared camera with a pixel size on the order of a square centimeter, providing sufficient resolution to allow scaling of quantities to the square meter and larger sizes to represent model cell sizes. The infrared camera was used to directly estimate the fraction of a model grid cell equivalent area burning, as well as to provide additional estimates of fuel consumption and fuel drying to aid in assessing the relative role of different subgrid processes. For estimating the fractional area burning, the fraction of pixels above the Draper point (525°C) within an analysis block was used. The size of analysis blocks was varied from 1 cm^2 up to 4 m^2 to assess possible model resolution influences on subgrid phenomena.

It has been demonstrated that fire radiative energy is linearly related to the total amount of fuel consumed, and that fire radiative power is linearly related to the rate of fuel consumption in a statistically significant manner (Wooster, 2002; Wooster et al., 2005). Freeborn et al (2008) utilized infrared remote sensing in a laboratory setting to evaluate relationships between energy release, fuel mass loss, and emissions with good success. Loudermilk et al (2012) employed infrared thermography to explore links between fuel structure and fire behavior at fine scales in natural fuel beds. As expected, a linear relationship was found between energy release and fuel consumption.

To assess fuel drying with infrared imagery, a new methodology was developed based on solving a coupled set of surface energy budgets for the fuel and a set of targets of known radiative properties inserted in the fuel bed. The targets streamlined the calculation process by removing the need for additional measurements such as a pyranometer for estimating solar radiation and fine-scale estimates of the flow field. The targets were designed to have similar aerodynamic properties as the vegetation but each target had a different known albedo. Since the targets lacked moisture, their energy budgets lacked the latent heat flux term, and the aerodynamic similarity resulted in a system of three equations with three unknowns: incoming solar radiation, sensible heat flux, and latent heat flux for the fuels.

Information on fine-scale fire-induced flows was obtained using visual imagery and applying cross-correlation particle image velocimetry (PIV). As an unseeded PIV measurement technique, the project team relied on patterns generated by the fire: flames, smoke, and ash particles as unseeded tracers. These fine-scale flow fields were used to improve understanding of subgrid turbulence being produced by subgrid combustion and how this turbulence could sustain the combustion process in the absence of turbulent mixing driven by larger-scale motions.

The project team's goal with these measurements was to develop and demonstrate techniques for collecting sub-meter scale measurements suitable for investigating the subgrid parameterization of a range of physical processes within a coupled fire-atmosphere model such as FIRETEC. While the focus in this study was the parameterization of the combustion process and specifically the form of a PDF used in that parameterization, measurements extended beyond what was needed to investigate that specific parameterization by including estimates of moisture fluxes and turbulent flow dynamics to foster a more holistic understanding of subgrid processes that will lead to further investigations.

4.0 RESULTS AND DISCUSSION

Using the Draper point as the transition point between burning and not burning, the pixels of each infrared image could be transformed into a binary image of pixels burning or not burning. Various size averaging windows could then be applied to both images to determine the mean temperature within the averaging window and the fraction of pixels within that window that were burning (Figure ES-1).

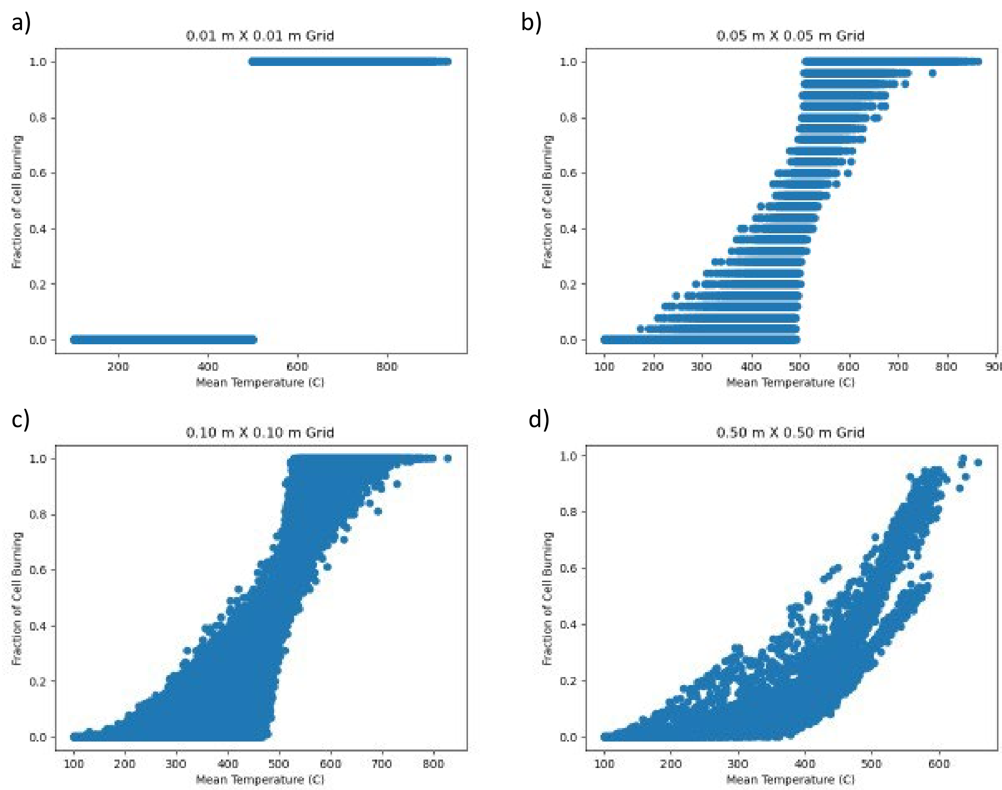

Figure ES-1. Fraction of Computational Cell Burning as a Function of Mean Temperature Derived from FLIR Imagery for Grid Sizes of a) 0.01m, b) 0.05m, c) 0.10m, and d) 0.50m.

The finest scale used in Figure ES-1a was at the pixel resolution of the camera, which yielded a step function as cells were either burning or not burning but increasing the resolution by a factor of 5 (Figure ES-1b) yielded a broad range of mean temperatures that could correspond to a given fraction of a cell burning. The banded nature of the plot in Figure ES-1b was due to the small averaging window size that was using only 25 pixels, which led to 25 discrete possibilities for the fraction of a cell that could be burning. As the grid cell size increased (Figures ES-1c and d), fewer instances of the entire cell burning were observed as the ignition patterns for the prescribed fires favored more backing and flanking fire behavior leading to the depth of the flaming front often being below the resolution of the computational grid. As the grid cell size increased, so did the likelihood that multiple processes were occurring below the model's ability to resolve them. One such process would be the drying of fuel prior to its ignition.

Currently in FIRETEC, subgrid processes such as combustion and fuel drying are tightly coupled through the PDF for fraction of a cell burning. This tight coupling limits the range of potential responses of the model to varying conditions. To relieve this limitation, the two processes were coupled through a new set of equations describing the evolution of the variation of gas temperatures and both wet and dry solid temperatures. This new set of equations incorporated conservations of mass and energy for the dry and wet fuels, individually, to ensure the model could better represent sub-grid combustion and evaporation processes simultaneously.

The new equations were incorporated in a simulation and compared to observations (Figure ES-2), where the dashed lines are the mean temperatures of the various burning observations within the 1x1m cell, the red solid line with squares indicates modeled mean dry temperature, the blue solid line with circles is mean wet fuel temperature, the grey line is gas temperature and shading indicates one standard deviation above and below the mean based on the dry and wet modeled variances. While the observed fuel temperatures were significantly hotter than the modeled mean temperatures, if the simulation data was truncated (from the modeled mean temperature and variance) to values in the distribution greater than 773 K, a significant improvement was observed in the alignment between modeled and observed temperature, especially after the peak temperature as shown by the solid black line. Distinct differences included a more rapid modeled rise in temperature during the initial combustion phase with a slightly premature drop in temperature as fuel was being consumed and a slower reaction rate.

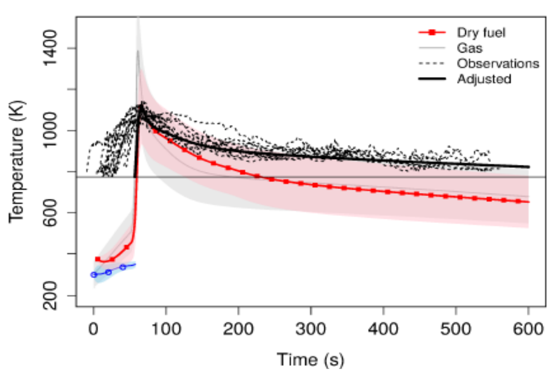

Figure ES-2. Simulation Results for the Mean Wet Solid Fuel, Dry Fuel and Gas Temperatures (Blue, Red, Grey Solid Lines) Compared with Observations (Dashed Lines) of Mean Solid Temperature Evolution in a 1 m x 1 m Cell.

The horizontal line is at 773 K (500 C) which is the minimum observed FLIR temperature. The adjusted dry fuel temperature (thick solid black line) is the recalculated mean temperature for temperatures above 773 K.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

The focus of this project was improving the parameterization of the combustion process in coupled fire-atmosphere models by better describing the governing equations for wet and dry fuels and their temperature evolution. The project team's future plan (currently ongoing) is to focus on the development of equations describing the evolution of the temperature variations for the gas phase based on a similar approach as described here. These new equations for the gas phase will then be coupled to the set of equations for the wet and dry fuels, which should improve the modeled energy exchange between wet and dry fuel and surrounding gas. This has a significant influence on fire behavior as was previously shown. This energy exchange is one of the essential components contributing to the self-determining nature of FIRETEC.

The majority of fire model validation studies focus on comparing simulated fire perimeters to what was observed, most often for wildfires. While this may serve as a first cut at validation, it raises the question of whether the model is getting the right answer for the right reason. This study examined fuel moisture and temperature dynamics at the sub-meter scale to facilitate improved representations of combustion in fire spread models for lower-intensity fires where the heat transfer process is poorly resolved by the model grid. This focus on the lower end of the fire intensity scale will benefit DoD land managers by improving model performance in conditions consistent with a wide range of prescribed fire applications.

6.0 REFERENCES

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