Numerical investigations of 3D aspects of fire/atmosphere interactions

R.R. Linn[a], J.M. Canfield[a], J. Sauer[a], M. Finney[b], J. Frothofer[b], J.L. Winterkamp[a], C.H. Sieg[g], F. Pimont[c], JL Dupuy[c]

[a] *Los Alamos National Laboratory, Los Alamos, NM, USA.* rrl@lanl.gov, jessec@lanl.gov, jsauer@lanl.gov, judyw@lanl.gov
[b] *USDA FS Rocky Mountain research Station, Missoula, MT, USA.* mfinney@fs.fed.us, jaforthofer@fs.fed.us, csieg@fs.fed.us
[c] Institut National pour la Recherche Agronomique, Avignon, France. pimont@avignon.inra.fr, dupuy@avignon.inra.fr

Abstract
Idealized FIRETEC grassfire simulations were used to study some of the roles that three-dimensional aspects of coupled atmosphere/fire interactions play on fire behavior. Domains of various widths that were periodic in the cross-stream direction, simulating an infinite-length fireline, were used to isolate local fireline-scale three-dimensional effects. Two-dimensional vertical plane (zero width) simulations were performed for comparison. Idealized finite-length fire simulations were used to study the larger fire-scale three-dimensional effects.
In the infinitely long simulations the fireline remains fairly straight on a macroscale while significant heterogeneities develop along the fireline at fireline-scales. These simulations suggest that the nature of atmosphere–fire coupling and these heterogeneities are influenced by wind speed. At low wind speed, the spread rate is not significantly affected by the width of the domain (for domains greater than 10 m wide). For higher wind speeds, the flank of the simulated firelines is fingered and the front of the fireline exhibits lobes. The average spread rates vary by approximately 20% for the different domain widths.
In the finite-length fireline simulations, the fireline shape was fairly parabolic and the headfire rate of spread (ROS) increased with wind speed and length of ignition line. The curvature of the fire was also influenced by the length of the ignition line. The indrafts of the headfire and flanking fire lines compete for upstream wind. For wider fires, the separation between the flanking fire lines is larger and more of the upstream wind is able to reach the headfire. These finite-length simulations also suggest that there might be an overall negative pressure gradient from upwind of the fireline to downwind of the fireline near the ground. This pressure gradient is believed to be tied to the penetration of wind through the fireline and the convective heating of unburned fuel.
Streamwise-vorticity pairs contribute to the heterogeneous appearance of the fire front by feeding upward momentum in the location where towers are seen on the fireline and thrusting hot gases through the fireline and down to the unburned fuel in the troughs between the firelines. These streamwise vorticies have also been recognized in the periodic infinite length and finite-length simulated firelines as well as laboratory tests.
In the two-dimensional simulations with wind speeds above 3 m/s, one major effect of the two-dimensional restrictions is to preclude the nominally streamwise-vorticity structures from forming upstream of the fireline. This thus diminishes the ability of the wind to mix through the heated plume and entrain hot gases down into the fuels ahead of the fire.
These simulations suggest that caution should be used when attempting to use one or two-dimensional models to simulate wildland fires. These simulations also suggest the significant value of experiments in which details of both flow and fire dynamics can be studied at scales ranging from fireline scale to overall fire geometry scales in order to better understand fire behavior. The hypothesis generated here can help provide insight in support of experimental design and analysis.

Keywords: *coupled fire/atmosphere, FIRETEC, grassfire, wildfire behaviour, vorticity, vortex*

1. Introduction

A variety of wildfire models have been developed in recent years to predict wildfire behavior, assess wildfire risk or simply gain insight into cause and effect relationships and the sensitivity of wildfires to their environment. Some of the models are empirical-based, while others are process-model based so they can be used to explicitly simulate some of the processes that control wildfire behavior. In order to reduce complexity or save computational cost, some researchers have tried to develop wildfire behavior models using one- or two-dimensional formulations. In the case of empirical models, local fire-line scale three-dimensional effects can be inherently represented through extensive data collection in ensembles of experiments. However, without a good understanding of the phenomenology driving multi-scale fire dynamics, it is very difficult for these types of models to capture the larger fire-scale three-dimensional effects caused by fireline shape or end effects due to the complexity and number of experiments and/or field observations required to parameterize these effects over the possible size and shape of fires in various weather and topographic conditions. Some researchers have attempted to use computational fluid dynamics techniques to explore fire behavior using a two-dimensional x–z plane, where x is the direction of the wind and spread and z is the vertical direction. Unfortunately, these approaches inherently neglect three-dimensional features of wildfire behavior due to the combination of the two-dimensional formulation and process-based approach.

While the potential benefits of physics-based modeling includes the ability to look at the interplay between processes and explore various cause and effect relationships in fire, this approach has the downside of omitting those processes that are not resolved or explicitly modeled as unresolved processes. In two-dimensional approaches, fluctuations in the third direction are omitted unless explicitly modeled by sub-grid parameterizations. However, such parameterizations have not yet been adequately developed for wildfire behavior. Better understanding of three-dimensional aspects of coupled fire/atmosphere interactions could suggest new ways to represent the effects of three-dimensionality without explicitly resolving them by providing insight into the relative sensitivity of fire behavior to key variables, suggesting functional forms and reducing the number of parameters that must be obtained from experiments. Canfield *et al*. (2014) considered this three-dimensionality in two size-based categories: local fireline-scale aspects such as fireline undulations, which were the main focus of Linn *et al*. (2012), and larger fire-scale aspects such as fire shape.

In order to understand the implications of omitting these aspects of fire behavior, a three-dimensional physics-based simulation tool was used to explore the significance of local fireline-scale heterogeneities (Linn *et al*. 2012) as well as larger fire-scale three-dimensionality (Canfield *et al*. 2014) of coupled fire/atmosphere fireline dynamics. These explorations are intended to compliment experiments by feeding the development of new hypotheses and additional mechanistic perspectives that are very difficult to isolate in experiments.

2. Methods

Idealized simulations with a physics-based fire/atmosphere model, FIRETEC, were used to explore the impacts of the local three-dimensionality of coupled fire/atmosphere interactions on fire behavior (Linn *et al*. 2012). FIRETEC (Linn, 1997; Linn, 2002, Linn and Cunningham, 2005) was developed as an attempt to represent multi-phase chemistry and physics in a bulk sense by resolving quantities at approximately meter-scale. FIRETEC is coupled to a fully compressible, non-hydrostatic, atmospheric-dynamics model, HIGRAD (Reisner *et al*., 2000), that was specifically designed to operate at higher resolution as compared to traditional mesoscale models.

In all of the simulations described in this paper, the grid spacing in both of the horizontal directions is uniform and equal to 2 m. The grid spacing in the vertical direction is nonuniform, with a value of approximately 1.5 m near the ground increasing to about 30 m at the top of the domain (z = 615 m). The fuel bed load is specified to be similar to tall grass of height 0.7 m, with a load of 0.7 kg m^{-2}, contained within the first grid cell above the ground. Within the fuel bed, the surface area per unit volume is specified as 4000 m^{-1}.

In order to isolate local fireline-scale three-dimensionality from larger three-dimensionality such as fireline curvature and end effects, a series of simulations were performed using periodic boundary conditions in the cross-stream direction (Figure 1) (Linn *et al*, 2012). Fires were uniformly ignited over the cross-stream width of several domain sizes: 10, 20, 40, 80, and 160 m. Since the domains were periodic in the cross-stream direction, these fires could be considered infinite in length with some periodic restrictions on them. In order to further isolate the effects of fire/atmosphere coupling from ambient upstream turbulence or the effects of eterogeneous vegetation, these idealized scenarios included homogeneous grass fuels with no cross-stream or time-dependent ambient wind variations at the domain boundary 100 m upwind of the fire. Two-dimensional, vertical plane (zero crossstream width) simulations were performed with the same model for comparison. Simulations with six different ambient wind speeds - 1 m s^{-1}, 3 m s^{-1}, 6 m s^{-1}, 9 m s^{-1}, 12 m s^{-1}, and 15 m s^{-1} - were performed for each of the two-dimensional and three-dimensional periodic scenarios.

a) b)

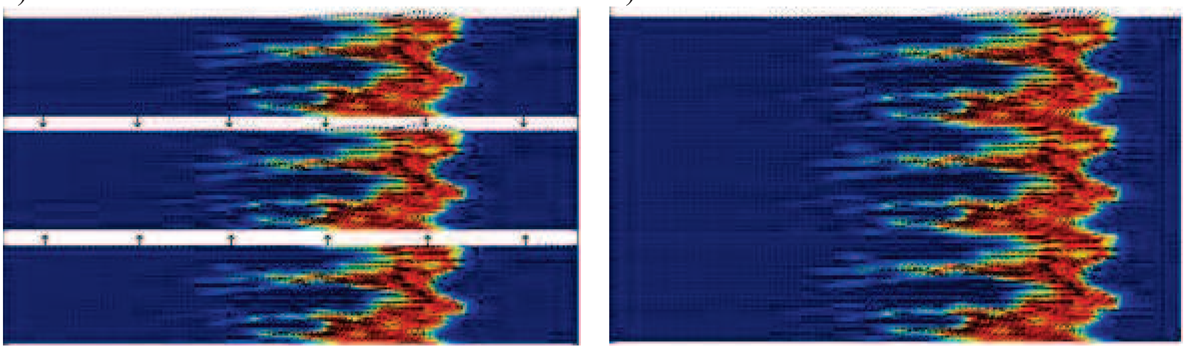

Figure 1. Top down view of 6 m s-1 wind 40 m wide fire simulation a) (in red dotted box) and the use of periodic boundary conditions to conceptually approximate an infinite-length fireline a) and b). In these images the colors indicate gas temperatures (Dark Blue is 300 K and red is greater than 1100K.) These images show the fingering behind the fireline and lobes in front of the fireline. This structure was ftypical for the infinite fireline simulations with 6 m s-1 and stronger winds.

Idealized FIRETEC simulations were also used to study the interactions between fireline shape and rate of spread (Canfield *et al*., 2014). Idealizations/simplifications similar to the infinite fireline approach described above were used except that these fires were finite in length and not periodic in the span-wise direction. These simulations, which were performed with ambient wind speeds of 3 m s^{-1} and 6 m s^{-1}, included finite-length ignition lines ranging from 20 to 400 m in length. In these simulations, the lateral boundary conditions were at least 100 m away from the ends of the ignition line. The winds at the boundaries were relaxed to the upstream flow velocity profile.

3. Results

All of the infinite-length simulations that were periodic in the stream-wise direction (Linn *et al*., 2012) showed some heterogeneity in the crossstream direction, even though the upstream winds, fuel, and ignition were uniform in this direction. This series of simulations suggest that the nature of atmosphere/fire coupling and the variability along the length of the fireline are influenced by wind speed. At low wind speed, variation along the length of the fireline exists but the fireline remains fairly straight and the spread rate is not significantly affected by the width of the domain (for domains greater than 10 m wide) for the duration of the simulations. For higher wind speeds, the upwind side of the simulated firelines are fingered and the downstream edge of the firelines exhibit lobes. The average spread rates vary by approximately 20% for the different domain widths (Table 1). This may indicate that the variety of sizes of atmosphere–fire structures influence spread rates and become affected by periodic domain constraints as the domain gets smaller. At higher ambient wind speeds, the structure of the wind and temperature fields also show evidence of streamwise vorticity.

Table 1. Rates of spread for periodic infinite-length fireline simulations of various widths and various wind speeds (measured 10 m above ground) (Linn et al., 2012).

Wind Speed U_{10} (m s^{-1})	2D	10 m	20 m	40 m	80 m	160 m
1	.57	.25	.23	.22	.22	.22
3	1.10	1.33	1.35	1.25	1.18	1.14
6	1.24	2.15	2.27	2.14	1.91	1.92
9	.77	2.23	2.81	2.41	2.49	2.28
12	.76	2.67	3.14	2.96	2.94	3.01
15	1.63	3.17	3.31	3.56	3.47	3.44

In the periodic infinite-length simulations, rate of spread increases with wind speed as seen in previous investigations with this model (Linn and Cunningham, 2005) as well as other numerical works and observations. The magnitudes of the spread rates for the periodic simulations were in general larger than those seen in the Linn and Cunningham (2005) finite-length fireline simulations. This result suggests a reduction of rate of spread due to fire-scale three-dimensional features such as end effects and fireline curvature that were present in the Linn and Cunningham (2005) simulations.
In the finite-length fireline simulations (Canfield *et al*., 2014) the fires did not stay relatively straight as they did in the periodic simulations (Figure 2). Instead, they took on a shape that was parabolic-like. In these simulations, rate of spread increased with wind speed and length of ignition line (Table 2) as expected and shown by observations (Cheney *et al*., 1993) and previous numerical studies (Linn and Cunningham, 2005; Mell *et al*., 2007). Flanking fire behavior was also influenced by ignition line length. As a result, fireline shape was affected by ignition line length.

Table 2. Rates of spread for finite-length fireline simulations of various widths and 3 m s^{-1} and 6 m s^{-1} wind speeds (measured 10 m above ground) (Canfield et al., 2012).

Wind Speed U_{10} (m s^{-1})	20 m Ignition line	100 m Ignition line	200 m Ignition line	400 m Ignition line
3	.20	0.68	1.10	1.15
6	.27	1.19	1.45	1.75

3.1. Three-dimensional effects at fireline scales

A predominant feature of both the relatively straight periodic infinite-length and the curved finite-length firelines is the presence of stream-wise vorticies that originate well behind the fireline and extend into the fireline itself. Such structures have also been identified in laboratory experiments at the USDA Missoula Fire Lab and are believed to be very important to the spread of fires. These stream-wise vorticies form alternating pairs and occasionally combine into larger vorticies. The development and strengthening of these vorticies is linked to the buoyancy of the sustained burning, which itself is heterogeneous in the crosswind direction. These pairs contribute to the heterogeneous appearance of the heading-fire front by feeding upward momentum in the location where flaming towers are seen on the fireline. The helical nature of the vortices thrust hot gases through the fireline and down to the unburned fuel in the troughs between the towers (Figure 3).

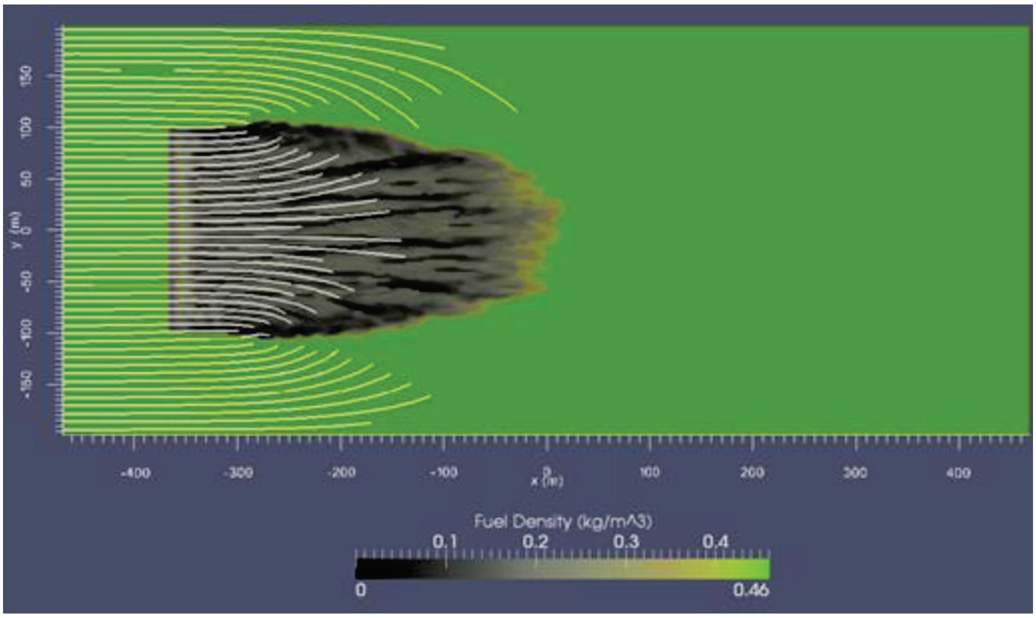

Figure 2. Top down view of 6 m s^{-1} wind 200 m-ignition fire. This image illustrates the parabolic shape of the progressing fire and the white streamlines illustrate the interaction between the upstream air flow and the competing indrafts of the flanking and heading firelines

In the two-dimensional simulations there were no cross-stream variations. These scenarios are more representative of a fire burning between two very-close plates of glass with wind blowing between them than they are of a two-dimensional slice through an infinitely long fireline. With ambient wind speeds of 1 m s^{-1}, the general structure of the plume appeared similar to those seen in the 1 m s^{-1} three-dimensional periodic simulation, but the spread rate was more than twice as fast as in the three-dimensional simulations. For wind speeds above 3 m s^{-1}, a significant effect of the two-dimensional restrictions was to preclude stream-wise and vertically oriented vortex structures. These structures occurred and proved to be important in the three-dimensional calculations, but are prevented in two-dimensional calculations because they require heterogeneity in the cross-stream direction. The elimination of the three-dimensional vorticity under two-dimensional constraints diminishes the ability of the wind to mix through the heated plume and entrain hot gases down into the fuels ahead of the fire. This causes a much slower spread rate in the two-dimensional simulations compared to the periodic three-dimensional simulations for ambient winds of 6 m s^{-1} and higher.

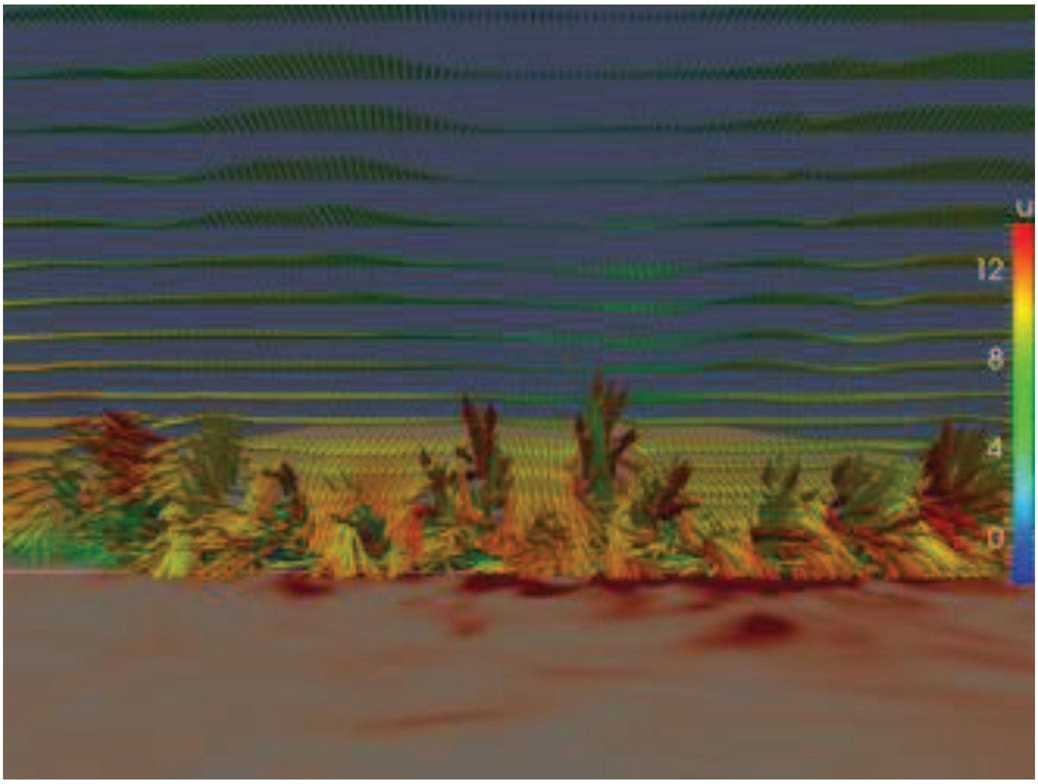

Figure 3 – Head on FIRETEC simulation of finite-length fireline (looking from in front of the fire as it approaches). This image illustrates the significance of the heterogeneity along the fireline in the cross-stream direction (left and right in the image). The fuel surface is colored by convective heating of the fuel where red is heating and blue is cooling. The vectors are in a y-z plane extending vertically above the white line and the vectors are colored by stream-wise velocity and scaled by total velocity

3.2. Three-dimensional effects at fire scales

In the finite-length fireline simulations, the curvature of the fireline and ability for winds to move around the fire lead to different fire behaviour than seen in the infinite-length fire scenarios. These differences are exacerbated by a couple of three-dimensional fire-scale interactions between the fire and the atmosphere. The head and flanking sections of the fire influence each other through their fire-induced indrafts. Indrafts from the flanking portions of the fireline compete with each other for the supply of upstream wind. For example, flanking portions of the fire draw from the airflow upstream, leaving a reduced amount of stream-wise wind to push the head fire forward and thus slowing down the forward spread rate. For wider fires, the separation between the flanking fires is large enough that competition between flanking fires is a non-issue. In scenarios where the flanking portions of the fire are relatively short compared to the length of the head fire, the wind can more effectively reach the headfire and transport hot gases to the unburned fuel in front of the fire. Similarly, as the competition between flanking fire and headfire sections of the fireline decreases, the wind arriving at the inside of the flanking fire sections can increase, enabling more effective heat transfer to the unburned fuel on the flanks as well. The competition between the indrafts of flanking and head fire and the net impacts on spread rate should be investigated experimentally in the future, as it has the potential to tie observable fireline geometry characteristics to corrections for rate of spread calculations.

The idealized finite-length grass fire simulations also suggest that there might be an overall negative pressure gradient from upwind of the fireline to downwind of the fireline. This pressure gradient may affect the penetration of wind through the fireline and the convective heating of unburned fuel. The magnitude of the effective pressure gradient across the fireline is influenced by the upstream in-draft competition between flanking and headfires. These firelines did not extend across the entire domain and air was free to move around them, unlike in the periodic infinite-length simulations described above where air cannot move around the firelines. The wind flow around the fires in the finite-fire simulations alters the upstream to downstream pressure gradient and therefore can contribute to the differences in spread rate between the infinite firelines and the finite length firelines. This effect contributes to the difference between the finite-length firelines and infinite-length fires where the firelines become much deeper (in the streamwise direction) firelines and have larger rates of spread. In the periodic infinite-fireline scenarios, the larger pressure gradient across the firelines and inability of the winds to move around the fireline increase the flow through the fireline and the heat transfer to the unburned fuel in front of the fire.

4. Conclusions

This work suggests ways that the three-dimensionality of coupled fire/atmosphere behavior at a variety of scales affect fireline dynamics. The three-dimensional phenomena outlined here (described in detail in Canfield *et al*., 2014 and Linn *et al*., 2012) provide the basis for hypotheses that need to be tested in laboratory and field experiments. The three-dimensionality of the fire/atmosphere interaction also has significant implications for measurement strategies in such experiments. The analysis of any point measurements should include both knowledge of the position of the measurement with respect to the shape of the fireline as well as the context of the measurement with respect to the towers and troughs of the fireline itself.

These simulations suggest that caution be taken when attempting to use a two-dimensional assumption for wildland fire spread modelling. This is especially important when attempting to interpret results in the context of a process-based model such as that of Linn (1997), where the two-dimensional nature of the calculations are believed to have significant impacts on the simulated fire behavior. Care should be taken to account for the combined impacts of the variations in the flow field and plume structure in the third dimension. It is possible that the effects of local three-dimensionality could be represented in a manner similar to how turbulence kinetic energy is modelled without actually resolving the velocity fluctuations; however, this is not a trivial task and has not been accomplished to date. Such advances will likely come from a combination of modelling, laboratory experiments and field observations.

5. References

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