

Numerical simulations of grassland fire behavior from the LANL - FIRETEC and NIST - WFDS models

William Mell^a, Joseph J. Charney^b, Mary Ann Jenkins^c, Phil Cheney^d, Jim Gould^d

^aNational Institute of Standards and Technology (NIST), Gaithersburg, MD, USA; ^bUSDA Forest Service, North Central Research Station East Lansing, MI, USA; ^cYork University, Toronto, Canada; ^dCSIRO Forestry and Foresty Products, Kingston, ACT, Australia

1. Introduction

Two physics-based computational fire models (FIRETEC and WFDS), capable of predicting time dependent fire behavior and fire-atmosphere interactions in three-dimensions are applied to wind driven grassland fires over flat terrain. Because these are surface fires (i.e., relatively little vertical flame spread) in a single, homogeneous fuel they are a good choice for the first stage in model evaluation. By “physics-based model” we mean that all modes of heat transfer (conduction, convection, radiation) present in both the fire-fuel and the fire-atmosphere interactions are modeled (in some approximation). These models are in their initial stages of development and validation. It is unlikely, due to their computational requirements, that they will replace present day operational models and approaches (e.g., BEHAVE, Andrews [1986], FARSITE, Finney [1998], Forest Service Fire Behavior Predictor, Hirsch [1996], McArthur meters, Nobel [1980]) in the near future, at least in their present form. However, they do have the potential, in the near term, to provide reliable and detailed predictions of the behavior and effects of fire over a much wider range of conditions than operational models. Examples of near term research orientated applications include assessing the effect of fire on vegetation during prescribed burns, the response of a fire to a given fire break or thinning strategy, and furthering our understanding of the behavior and spread of fires through the intermix of structural and vegetative fuels that characterize the wildland-urban interface (WUI).

FIRETEC and WFDS have overlapping capabilities but significantly different modeling approaches. Their focus of application is also different: FIRETEC (developed at Los Alamos National Laboratory) is designed for vegetative wildland fires over landscape scales while WFDS (developed at the National Institute of Standards and Technology) is targeted for WUI and vegetative fires over a range of scales, from

laboratory (centimeters to meters) to landscape (tens to hundreds of meters). Both the complexity of the physical modeling approaches used in FIRETEC and WFDS and the numerous obstacles to repeatable field-scale fire experiments make evaluation of results from these two models difficult. The research presented in this talk is an initial step to a more extensive evaluation of these modeling approaches. Results from grassland experiments conducted in Australia (Cheney *et al.*, 1993; Cheney and Gould 1995; Cheney *et al.*, 1998) form the basis of the model evaluation. A goal of this effort is to advance our overall understanding of the modeling approximations used by each model. Originally, and ideally, our goal was to have the developers of both FIRETEC and WFDS participate in this study. Unfortunately, such a participation was not possible at this time. The authors of this paper include a developer of WFDS and a user of FIRETEC. As a result, our knowledge of FIRETEC is more limited than for WFDS. We hope collaboration with FIRETEC developers will be possible in the future so this study can continue in a more fruitful manner.

Fire models can be classified into three types (e.g., see Pastor *et al.* [2003]): empirical, semi-empirical, or physics based (here we use “physical” and “physics based” interchangeably). Empirical models involve no physical modeling since they are based on statistical correlations of a given experimental data set. Semi-empirical models are based on energy conservation but do not distinguish between the different modes of heat transfer (conductive, convective, radiative). Physics-based models (such as FIRETEC and WFDS) attempt to solve (in some approximation) the equations governing fluid dynamics, combustion, and heat transfer. A complete, physics-based, wildland fire simulation must include approximations for the fire/atmosphere and the fire/fuel interactions

2. Overview of the FIRETEC and WFDS

FIRETEC has been developed at Los Alamos National Laboratory (LANL) by Linn and colleagues (Linn 1997, Linn *et al.* 2002). FIRETEC provides fire spread predictions over landscape and requires significant computational resources (multiple processors). The governing equations are time averaged in a manner similar to Reynolds averaging. This results in additional closure equations which require a number of turbulence modeling assumptions. The numerical time stepping scheme explicitly handles the high frequency acoustic waves, Reisner [2000]. Chemical heat release from the combustion process occurs only in computational grid cells that contain the solid fuel, Linn *et al.* [2002]. For grid cell dimensions that are smaller than the flame length this is unrealistic and improvements are underway (Colman and Linn, 2003). Combustion is the result of a reaction rate that is a function of the density of both the solid fuel and the gas phase reactants, and an ad-hoc Gaussian-shaped probability density function (PDF) of the temperature. The use of this PDF is physically motivated but not yet validated. An assumed fraction of the heat produced by combustion is deposited in the solid fuel to help sustain pyrolysis. The solid fuel is assumed to be thermally thin. Thermal radiation transfer is computed using a diffusional transport approximation adapted from Stephens [1984]. There is not, in the results reported to date, a model for the solid phase that handles pyrolysis which is coupled, through resolved heat fluxes, to a separate model for the gas phase which handles combustion. Instead the pyrolysis of the solid phase and heat release from combustion in the gas phase are lumped together. This is the most significant difference (from a physical modeling point of view) between FIRETEC and other approaches, including the multiphase approaches discussed previously and the approach used in WFDS.

WFDS is an extension of FDS (Fire Dynamics Simulator), a product of NIST (McGrattan, 2004; McGrattan and Forney, 2004). The development of FDS started in the 1980's and it was created to simulate structural fires in a computationally efficient

3. Overview of grassland fire experiments

The experimental results and data used here were reported in Cheney *et al.* [1993] and Cheney and Gould [1995]. The grassland fires were started by line fires, of varying lengths, along a fire break on the upwind edge of a grassland plot. One of two types of grass was present on a given plot: either *Eriachne burkittii* (kerosene grass) or *Themeda australis* (kangaroo grass). These two grasses differed in their structural and growth characteristics. In the models,

It can be run on single processor desktop computers or on multiple processors and on a range of operating systems. FDS is currently used worldwide by 100s of fire protection engineers for structural fires and can be downloaded free. Smokeview, a companion software package, was also developed at NIST to interactively visualize FDS results (Forney and McGrattan, 2004). A survey of validation studies of FDS given in McGrattan [2004]. The solution of the governing equations is based on basic Large Eddy Simulation concepts as first presented by Smagorinsky [1963]. The approach does not result in additional closure equations. Recently, modifications to FDS were begun to handle fire spread through vegetative fuels (Rehm *et al.*, 2003; Mell *et al.*, 2005a) with the goal of simulating fire spread in an intermix of vegetative and structural fuels (i.e., WUI fires). This modified version of FDS is called WFDS and is used here to simulate grassland fires. A low Mach number approximation to the governing equations is used (Rehm and Baum, 1978). This approximation, which has been applied successfully to a wide range of fire and combustion problems, and the use of a fast direct solver for the pressure, results in computational speeds that are 10 to 100 times faster than many other methods. The gas and vegetative phases are handled separately on different grids. The combustion model is based on the well established mixture fraction based approach that assumes the fuel and oxygen react instantaneously over time scales characteristic of the flow (Bilger, 1980). The solid fuel is assumed to be thermally thin. Radiative and convective heat transfer within the fuel bed is directly modeled in manner similar to Albin, [1985] and Morvan and Dupuy [2004]. The pyrolysis model of Morvan and Dupuy [2004] is used. Char oxidation is not included. Thermal radiation transfer in the gas phase is computed with a finite volume based solver, Raithby and Chui, [1990]. In the fuel bed a forward-reverse approximation (Ozisk, 1973; Mell and Lawson, 2001) is used for radiation transfer. Details on the model equations, numerical algorithm, and the approach used for igniting the solid fuel are given in Mell *et al.* [2005a].

however, physical differences in the fuel bed are accounted for only by the solid phase parameters listed in Table 1. The grassland plots measured 100 m x 100 m, 200 m x 200 m, or 200 m x 300 m and were surrounded by fuel breaks. At each corner of a plot the wind magnitude was measured every 5 s at a height of 2 m above the ground. Aerial photos and ground observations were used to obtain fire

perimeters, head fire widths, and quasi-steady head fire spread rates.

The following empirically based formula (Eq. 4 in Cheney *et al.*, 1998) relates the experimentally

$$(1) \quad R_o = (0.165 + 0.534*U_2)*\exp\{-0.859 - 2.036*U_2/W\}*\exp(-0.108*M).$$

Cheney *et al.* [1998] defined the effective head fire width as the width of the fire, measured at right angles to the direction of head spread (and thus at right angles to direction of the wind at the head fire), which influenced the shape and size of the head fire during the next period of spread measurement (Cheney and Gould [1995]). The effective width of the head fire can also be defined as that portion of the perimeter where the flames are leaning towards

observed head fire spread rate R_o (m/s), to the wind speed U_2 (m/s) at a 2 m height, the head fire width W (m), and the fuel moisture content M (%):

unburnt fuel. In WFDS the head fire width was defined to be the distance between the flank fires one fire depth upwind of the trailing edge of the head fire. For a sufficiently large head fire width the observed spread rate, R_o , obtained its potential quasi-steady value, R_{SS} . This spread rate is obtained from Eq. (1) for $W \rightarrow \infty$

$$(2) \quad R_{SS} = (0.165 + 0.534*U_2)* \exp(-0.108*M).$$

Simulated spread rates and head fire location were compared to their experimentally observed values through the use of these empirical relations.

4. Approach and Results

This is a first step at model evaluation. As such, the primary objective is to assess how well the models predict experimentally observed trends of macroscopic behavior. For reasons discussed in Sec. 5 we were unable to complete FIRETEC simulations of the AU grassland experiments by the due date of this conference paper. Thus, comparisons of only WFDS simulations and AU grassland fires appear here (see Secs. 4.1 – 4.3). In order to make some comparisons between FIRETEC and WFDS we ran simulations of fire spread in the tall grass fuel reported by Linn and Cunningham [2005] (see Sec. 4.4).

Table 1 lists the environmental parameters used in the simulations of fire in AU grasslands and tall grass. Parameters that were not measured in the AU experiments were determined from sources in the literature (Mell *et al.*, 2005a). Two AU experiments, each with a different grass, were considered. In Table 1, and in the following text, the two experiments are denoted F19 (natural *Themeda* grass) and C064 (cut, with cuttings removed, *Eriachne* grass).

Table 1: Gas and solid properties used in the simulations

	property	AU experiments		WFDS AU exp.	FIRETEC ^a tall grass	WFDS tall grass
		F19	C064			
gas phase	heat of combustion of volatiles, kJ kg ⁻¹	n/a	n/a	15600	8914	15600
	radiation fraction	n/a	n/a	0.35	n/a	0.35
	soot fraction	n/a	n/a	0.02	n/a	0.02
solid phase	surface area to-volume ratio, m ⁻¹	12240	9770	from exp	4000	4000
	char mass fraction	n/a	n/a	0.20	n/s	0.2
	grass height, m	0.51	0.21	from exp	0.7	0.7
	fuel element density, kg m ⁻³	n/a	n/a	512	n/a	512
	fuel loading, kg m ⁻²	0.313	0.283	from exp	0.7	0.7
	moisture, %	5.8	6.3	from exp	5.0	5.0

^a Linn and Cunningham [2005]

4.1 Head fire spread rate dependence on wind speed in AU grassland (WFDS only)

Four wind speeds, U_2 , were used in the simulations: $U_2 = 1, 3, 4, 5$ m/s. For each wind speed four different ignition line fires were used (a total of 16 cases) lengths: $L_{ig} = 8, 25, 50, 100$ m. Ignition lines with lengths of $L_{ig} = 8$ m and 25 m were 6.7 m; ignition lines $L_{ig} = 50$ m and 100 m had a depth of 3.3 m. The grassland fuel characteristics were those of experiment F19 in Table 1. The initial wind speed depends on height, z , above the ground according to a power law to approximate a boundary layer (Morvan and Dupuy, 2004):

$$(3) \quad u(x,y,z,t=0) = U_{2,1}*(z/2)^{1/7}.$$

Here $U_{2,1}$ is the value in WFDS of the initial wind speed at a height of 2 m. As the simulation proceeds, the wind speed at this height is modified by the fire (due to both entrainment and blockage effects) and by drag from the grass. When comparing head fire spread rates from a number of WFDS and from Eq. (1) a consistent value of U_2 must be used. In WFDS U_2 is the average value of the windward velocity, over the course of the simulation, in the first cell

above the vegetation at the center of the ignition line fire. The height of this velocity is within $z = 1.95$ m - 2.1 m for the simulation cases reported here.

Simulations with a number of grid resolutions and domain sizes were conducted to ensure that the results were not significantly influenced by grid resolution or boundary effects. All the simulations reported here used an overall computational domain area of 1500 m x 1500 m with a 200 m x 200 m grassland plot in the center. The height of the computational domain was 200 m. The horizontal grid for a central 300 m x 300 m area containing the grassland plot was $\Delta x = \Delta y = 1.66$ m; outside this central area $\Delta x = \Delta y = 3.33$ m. The vertical grid was stretched from $\Delta z = 1.4$ m to 5.5 m at a height of 200 m throughout the computational domain.

Figure 1 is a plot of head fire spread rate versus wind speed. The physical parameters of the fuel are listed in Table 1. Spread rates from WFDS (symbols), BEHAVE (Andrews, 1986) (solid line) and Eq. (2) (dashed line) are shown.

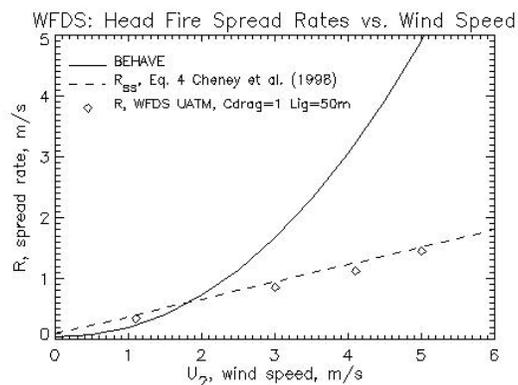


Figure 1: Spread rate versus wind speed from WFDS (symbols), BEHAVE (solid line) and Eq. (2) (dashed line).

As will be seen below, in Fig. 2, WFDS spread rates for $L_{ig} = 50$ m quickly reached a quasi-steady value. The linear dependence of the spread rate on the wind speed is well predicted by WFDS. The quantitative agreement of WFDS is also good, however it is important to note that the sensitivity of WFDS to realistic variations in environmental variables (wind speed, moisture content, etc.) has not yet been assessed. Another important issue is how the value of the wind speed, U_2 , is obtained. As discussed in the previous section, both Eq. (1) and Eq. (2) and WFDS

use a value of U_2 that is the average wind speed at a height of approximately 2 m. In BEHAVE the default height of the wind speed is at the mid-flame height. Experimentally observed flame heights, for $U_2 = 5$ m/s, were 2.7 m for this fuel. This suggests that the wind speed input into BEHAVE should be larger, leading to a prediction of even faster spread rates. BEHAVE's over prediction of the spread rate for fuels with a surface-to-volume ratio of 13100 m^{-1} , which is similar to the fuel used here, has been noted before, Gould [1988].

4.2 Head fire spread rate dependence on the head fire width in AU grassland (WFDS only)

Figure 2a below shows the fire spread rate versus the head fire width on the left from WFDS simulations with $U_2 = 1$ m/s and the four different lengths (Fig 2 (b-e) of the ignition line fire. The solid line is the spread rate from Eq. (1). The simulations reproduced the trend of an increasing head fire spread rate with an increasing width of the head fire. All L_{ig} cases reach a quasi-steady spread rate that is within 25% of the Eq. (2) value. The experimental fires, as described by Eq. (1), obtained a quasi-steady spread rate at narrower head fires than the simulated fires. Figure 2(b-e) are sequential snapshots of the burning region (shaded contours of the burning rate are shown) for each of the ignition line fire lengths used. Note that for the $L_{ig} = 50$ m and 100 m cases, Fig. 2(d,e) respectively, the flank fires reach the upper and lower fire breaks.

spread. For the cases with $L_{ig} = 25$ m, 50 m, and 100 m WFDS predictions of the head fire location agree well with Eq. (1). When $L_{ig} = 8$ m there is a period of time during which the head fire spread rate increases before reaching a quasi-steady value. The quasi-steady spread rate agrees with Eq. (1) at around $t = 110$ s (i.e., the solid line and a line through the circles become parallel). The head width (dashed line) at which the simulated head fire spreads in a quasi-steady manner is approximately $W \geq 65$ m (note Fig. 2a shows similar results for $U_2 = 1$ m/s). This is consistent with experimental observations that spread rates are relatively unaffected by L_{ig} when L_{ig} is sufficiently large. The head fire width is constant with time for $L_{ig} = 100$ m. Cheney and Gould [1995] noted at their highest wind interval between 4.7 and 7.1 m/s the head fire width of more than 125 m in open grassland is required to get spread rates within 10 percent of the quasi-steady rate of forward spread.

In Fig. 3 (left column) the location of the leading edge of the head fire versus time, from both WFDS (solid line) and from the Eq.(1) (circles) with $U_2 = 5$ m/s, is shown in the left column. Each row in Fig. 3 corresponds to a different L_{ig} . Also shown in the left column are the width (dashed line) and depth (dotted line) of the head fire. The head fire widths are used in Eq. (1) to plot the circle symbols. In each case an initial time period of relatively rapid spread is present, followed by a slower spread rate. This initial rapid spread may depend on the ignition procedure. This issue needs to be investigated. Equation (1) is implemented to determine the location of the head fire at the end of the initial time period of rapid

Figure 3 (right column) shows the fire perimeter at 60 s intervals. The relatively high wind speed results in head fire depths (10 m – 12 m) that are greater than the flank fire depths (5m – 7 m). This does not occur in the weak wind case ($U_2 = 1$ m/s in Fig. 2b-e). This behavior is consistent with field observations. Field measurements of the head fire depth for $L_{ig} = 175$ m and $U_2 = 4.9$ m/s range from 6.5 m to 10.5 m. Fire depths were interpreted from oblique photographs which were corrected and plotted onto a planar map of time isopleths of fire perimeter and fire depth.

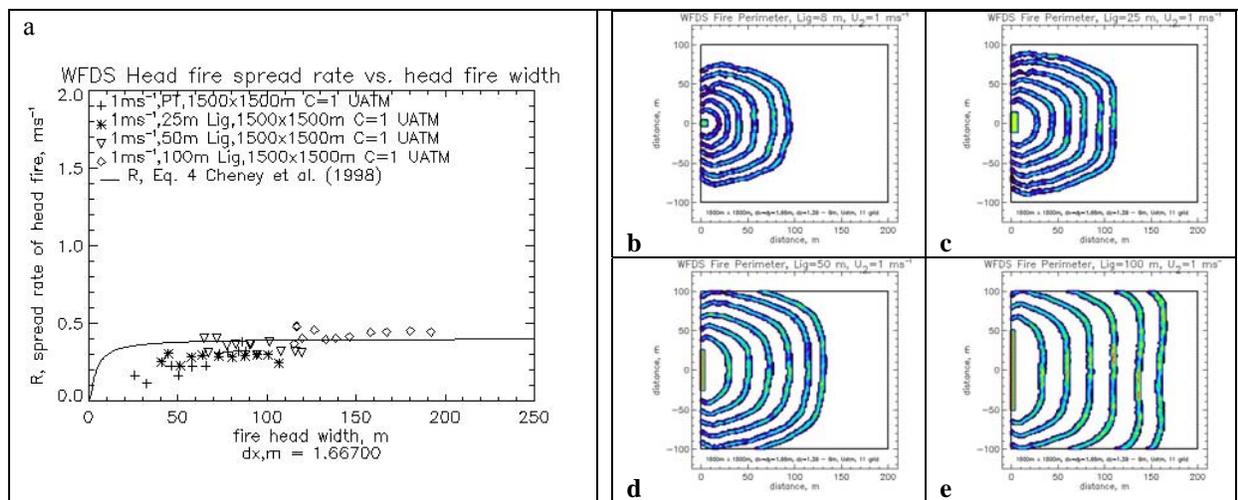


Figure 2: (a) Spread rate versus head fire width from WFDS for a wind speed of 1 m/s and four different ignition line fires is shown. The fire lines from which the spread data was determined shown on the right. The four ignition line lengths are (b) 8 m, (c) 25 m, (d) 50 m, (e) 100 m. The fire perimeters are plotted at times 0 s, 60 s, 120 s, 180 s, 240 s, 300 s, and 350 s. The fire spreads in a 200 m x 200 m grassland plot.

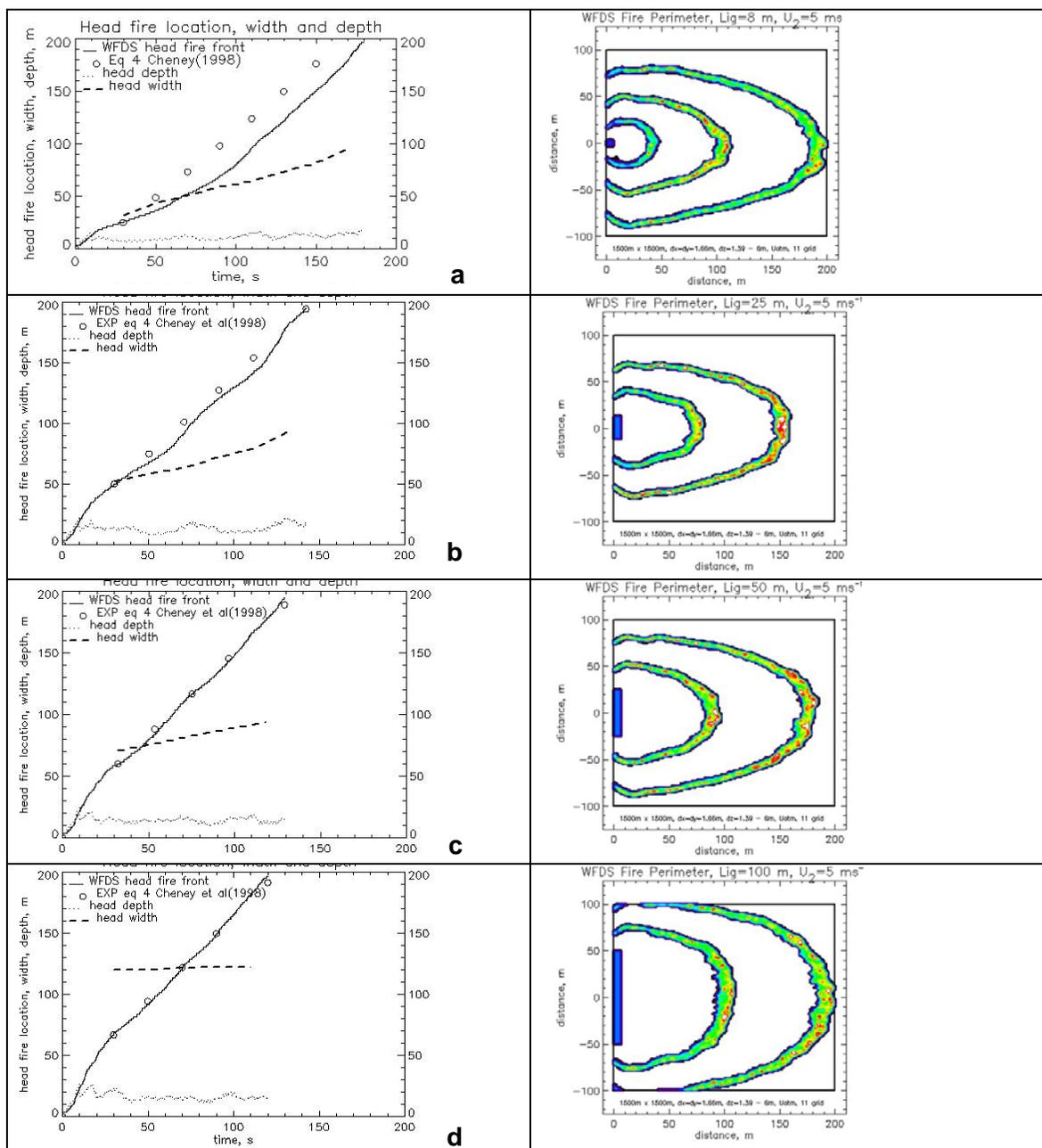


Figure 3: Left column shows the location of the leading edge of the head versus time from WFDS (solid line) and Eq. 4 of Cheney et al. [1998] (circles) for a wind speed of 5 m/s and the four ignition line fires are used 8 m (a), 25 m (b), 50 m (c), and 100 m (d) long (same as Fig. 2). The width (dashed line) and depth (dotted line) of the head fire are also plotted. The fire lines for each case are shown in the right column at 60 s intervals, starting at 0s.

4.3 Case studies – Fire perimeter in AU grassland (WFDS only)

The mechanism of fire spread can change along the fire perimeter depending on the wind speed. In zero ambient wind, entrainment by the fire creates a local wind into which the entire fire line spreads (backing fire). In the presence of an ambient wind the downwind portion of the fire perimeter spreads with the wind (heading fire), the upwind portion of the fire perimeter spreads into the wind (backing fire), and the sides or flanks of the fire perimeter spread under conditions that can alternate between heading and backing fires. Note that in the cases considered here there are no backing fires since ignition occurred along the fire break at the upwind border of the plot. Backing fires, in which the flame tends to tilt away from the unburned fuel, can consume the fuel from the base upward, resulting in more complete fuel consumption. Heading fires, in which the flame tilts toward the unburned fuel, can be associated with lower fuel consumption because the grass ignites at the top and burns downward, covering the unburned fuel beneath with a protective coating of ash. The spread mechanism in flank fire can involve, depend on the fire/wind interaction, both the burning downward mechanism of head fires and the burning upward mechanism of backing fires. Thus, predicting the evolution of the entire fire line is much greater challenge, due to variation along the fire line of the fire/wind interaction and spread mechanisms, than predicting the behavior of just the head fire.

Neither FIRETEC nor WFDS can directly resolve the details in the grass fuel bed that differentiate a backing fire from a heading fire since the entire fuel bed is unresolved on the computational grid. For example, the height of the first grid cell in WFDS is 1.4 m while the height of the grass is 0.51 m. However, the fire/atmosphere interactions that occur over scales on the order of a few meters can be resolved. It is hoped that this level of resolution of the fire physics will be sufficient to capture the dynamics of the entire fire perimeter. It is important that a three-dimensional model predict the behavior of the entire fire perimeter. Otherwise, the overall heat release rate, fuel consumption, and smoke generation will be (to some degree) incorrectly predicted. These global fire characteristics are particularly important inputs to regional smoke transport models. In addition, the mechanisms behind extreme fire behavior (such as blow ups) are still poorly understood. A model that simulates the behavior of the entire fire perimeter, as opposed to only the head fire, is more likely to shed light on these issues.

In this section, model predictions of fire perimeters from two experimental cases are presented. In the first experiment, called F19, the ignition line fire is 175 m long. This line fire was created with drip torches carried by two field workers walking for 56 s (87.5 m) in opposite directions from the center point to the ends the line fire. The average wind speed, measured at the corners of the 200 m x 200 m plot and not including measurements influenced by the fire, equaled 4.9 m/s. In the second experiment considered, called C064, the ignition line is 50 m long. The average wind speed was 4.6 m/s. Fuel bed characteristics are given in Table 1 for both experiments. Figure 4 shows the leading edge of the fire perimeter from the experiments (symbols) and the entire fire bed from WFDS (shaded contours of the burning rate) at three different times.

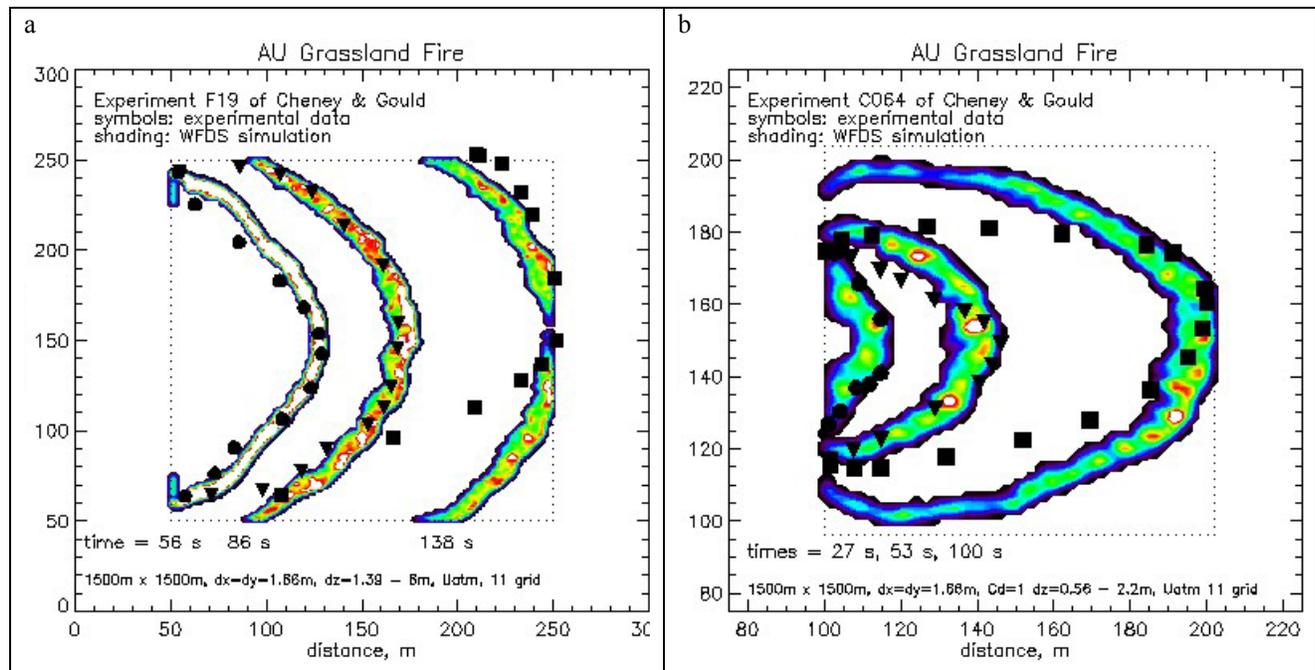


Figure 4: Fire perimeters from experiments (symbols) and WFDS simulations (shaded contours). (a) experiment F19 and (b) is experiment C064. See text for details and Table 1 for fuel/environmental parameters.

Experiment F19 is shown in Fig 4a. A wind shift occurs in the experiment after $t = 86$ s which breaks the symmetry of the fire perimeter, this does not occur in WFDS since a constant wind orientation is assumed at the inflow boundary. As expected from the previous results, the spread of the head fire is well predicted at all times. Before the wind shift, the predicted fire perimeter closely matches the measured fire perimeter. After $t = 86$ s it's not clear how well WFDS performs because the wind shift significantly changes the observed fire perimeter. Also, long flanking fires (as, for example, those shown in Fig. 3) do not develop for this case because the flank fires reach the fire breaks relatively quickly.

Experiment C064 is shown in Fig. 4b (note the difference in scale from Fig. 4a). Extended flank fires do develop in this case. WFDS over predicts the spread rate of the flank fires. The reasons for this are the subject of ongoing model development efforts. The current version of WFDS does not faithfully model the upward spread mechanism that can be present in flank fires. Instead, the fire burns downward through the grassland fuel bed everywhere along the perimeter. Also, in the field the depths of flank fires are significantly smaller than head fire depths for this experiment. The horizontal grid resolutions used here (1.66 m) adequately resolve the head fire depth but this may not be the case for the flank fires.

4.4 Simulation of tall grass (FIRETEC and WFDS)

Linn and Cunningham [2005] simulated fire spread in a fuel similar to NFFL standard model 3. The parameters of this grass fuel are listed in Table 1. Two different lengths of an ignition fire line were used, $L_{ig} = 16$ m, 100 m and four different ambient wind speeds, constant with height, $U = 1, 3, 6, 12$ ms^{-1} . Six WFDS simulations were made: $U = 1, 3, 12$ for each of the two L_{ig} values. The results are listed in Table 2. The most significant difference in the two models was that backing fires (spreading upwind) and flank fires are more likely to occur in

WFDS. For both models backing fires, when present, were more robust for the longer ignition lines. Field observations of backing fire behavior suggest that they are less likely to survive at higher wind speeds. This trend is less well reproduced by FIRETEC which Linn and Cunningham [2005] recognize and the issue is under investigation. When a backing fire is not present in WFDS, as in case $L_{ig} = 16$ m, $U = 12$ ms^{-1} after $t = 50$ s, a similar head fire shape, which is necked inward toward the centerline, is predicted by both WFDS and FIRETEC. Head fire

spread rates could not be compared because backing fires in WFDS influence the wind at the head fire locations.

Table 2: Summary of results from FIRETEC and WFDS simulations of fire spread in tall grass.

U	Lig	backing fire		flank fire	
		FIRETEC	WFDS	FIRETEC	WFDS
1	16	no	yes/no*	no	yes*
1	100	no	yes	no	yes
3	16	no	yes	yes	yes
3	100	no	yes	yes	yes
12	16	yes	yes/no**	yes	yes
12	100	yes	yes	yes	yes

* fire spread erratically and eventually extinguished due to the weak ambient wind

** backing fire survived for approximately 50 s before it was extinguished due to convective cooling.

5. Model implementation issues

In the sections above WFDS model predictions of fire spread were compared to experimental findings. In order for a model to be useful to researchers outside the developer's institution there are a number of additional capabilities and features it should have. These include:

1. a full description of the governing equations and the methods used to solve them,
2. a full description of all assumptions and physical properties used,
3. a clear description of key model inputs and their role in the governing equations,
4. the computational requirements of the model (e.g., number of computers and the amount of computer time) should not be too demanding. A useful tool should not preclude conducting easily repeatable exploratory simulations,
5. a straightforward way to analyze the results (i.e., post-processing). This is essential in facilitating error-checking and exploratory simulations.

WFDS is an extension (to fires in vegetation) of the structural fire simulation tool FDS used by hundreds of engineers world wide. Since FDS is designed for use by practicing fire protection engineers it has all of the above listed characteristics. Feedback from users

around the world has helped to make FDS a robust simulation tool. FIRETEC, however, was not developed for, and is not used by, a large user community. The lack of documentation (users manual, technical manual) has made it difficult to determine what FIRETEC input values would be compatible with the experimentally measured variables. In addition, FIRETEC requires significantly more computational resources to run. Exploratory simulations on relatively small domains (120 m x 120 m x 200 m; 60 x 60 x 34 grid points) required 3 days and 16 processors for 100 s of simulated time. The same simulation with WFDS ran on a laptop in less than 1 hour, over a factor of 100 faster. For these reasons, despite a number of weeks of effort, we were unable to produce FIRETEC simulations of the Australian experiments. It is unclear at this point how much of FIRETEC's computational inefficiency is due to its numerical approach (e.g., the need to account for high speed acoustic waves) or in its modeling approach. Subsequent comparisons of FIRETEC and WFDS should include the developers of FIRETEC so that the advantages and disadvantages of the physical models used by both approaches can be investigated.

References:

- Albini, F.A. (1985) "Wildland fire spread by radiation -- a model including fuel cooling by natural convection," *Combust. Sci. and Tech.*, **45**: 101-113.
- Andrews, P.L. (1986) "BEHAVE: Fire behavior prediction and modeling system -- BURN subsystem part 1," *USDA For. Serv. Gen. Tech. Rep. INT-194*. See also <http://www.fire.org>
- Bilger, R.W. (1970), "Turbulent Reacting Flows," Ch. 4 in *Turbulent Flows with Nonpremixed Reactants*, Springer-Verlag.
- Cheney, N.P., Gould, J.S., and Catchpole, W.R. (1993) "The influence of fuel, weather and fire shape variables on fire spread in grasslands", *Int. J. Wildland Fire*, **3**: 31-44.

- Cheney, N.P., Gould, J.S. (1995) "Fire growth in grassland fuels", *J. Wildland Fire*, **5**: 237-347.
- Cheney, N. P., Gould, J.S. and Catchpole, W. R. (1998) "Prediction of fire spread in grasslands", *Int. J. Wildland Fire* **8**:1-13..
- Colman, J.J. and Linn, R.R. (2003) "Non-local chemistry implementation in HIGRAD/FIRETEC," *2nd Intl. Wildland Fire Ecology and Fire Manage. Congress and 5th Symp. on Fire on Forest Meteorology*, 16-20 November, Orlando, FL, American Meteorological Society.
- Fons, W.L., (1946), "Analysis of fire spread in light forest fuels", *J. Agricultural Res.*, **72**:93-121.
- Forney, G. P. and McGrattan, K.B. (2004) "[User's Guide for Smokeview Version 4: A Tool for Visualizing Fire Dynamics Simulation Data](http://fire.nist.gov/bfrlpubs/Dynamics%20Simulation%20Data)," *NIST Special Publication 1017*, <http://fire.nist.gov/bfrlpubs/>
- Finney, M.A. (1998), "FARSITE: Fire Area Simulator-Model, Development and Evaluation," *USDA Forest Service, Rocky Mountain Research Station Paper, RMRS-RP-4*.
- Hirsch, K.G. (1996), "Canadian forest fire behavior prediction (FBP) system: user's guide", Canadian Forest Service, Special Report 7, Northwest Region, Northern Forestry Centre.
- Larini, M., Giroud, F., Porterie, B., and Loraud, J.-C. (1998) "A multiphase formulation for fire propagation in heterogeneous combustible media," *Int. J. Heat Mass Transfer*, **41**:881-897.
- Linn, R.R., (1997) "A transport model for prediction of wildfire behavior", Ph. D. thesis, New Mexico State University, also published as Los Alamos Report, LA-13334-T
- Linn, R., Reisner, J., Colman, J.J., Winterkamp, J., 2002 "Studying wildfire behavior using" FIRETEC, *Int. J. Wildland Fire*, **11**: 233-246.
- Linn, R., Cunningham, P. (2005) "Numerical simulations of grass fires using a coupled atmosphere-fire model: Basic fire behavior and dependence on wind speed," *J. Geophysical Research*, to appear.
- McGrattan, K.B. (2004) Fire Dynamics Simulator (Version 4), "Technical Reference Guide", *NISTIR Special Publication 1018*, McGrattan, K., editor, <http://fire.nist.gov/bfrlpubs/>
- McGrattan, K.G. and Forney, G. (2004) Fire Dynamics Simulator (Version 4), "Users Guide", *NISTIR Special Publication 1019*, <http://fire.nist.gov/bfrlpubs/>
- Mell, W., Jenkins, M.A., (2005a), "A physics based approach to modeling grassland fires", to be submitted to *Int. J. Wildland Fire*.
- Mell, W.E. and Lawson, J.R. (2000) "A Heat Transfer Model for Firefighters' Protective Clothing," *Fire Technology*, **36**:39-68.
- Mell, W., Rehm, R., Maranghides, A., Manzello, S., Jenkins, M.A., (2005b) "Wildland-Urban Interface and Wildland Fires", *webpage*, <http://www2.bfrl.nist.gov/userpages/wmell/public.html>
- Morvan, D. and Dupuy, J.L. (2004) "Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation," *Comb. Flame*, **138**: 199-210.
- Nobel, I.R., Bary, G.A.V. and Gill, A.M (1980), "McArthur's fire-danger meters expressed as equations," *Australian J. of Ecology*, **5**: 210-203.
- Ozisk, M.N. (1973) "Radiative Heat Transfer and Interactions with Conduction and Convection," John Wiley & Sons, 1st Edition.
- Pastor, E., Zarate, L., Planas, E., Arnaldos, J. (2003) "Mathematical models and calculations systems for the study of wildland fire behavior," *Prog. Energy. Combust. Sci.*, **29**: 139-153.
- Rehm, R.G. and Baum, H.R. (1978) "The Equations of Motion for Thermally Driven, Buoyant Flows," *Journal of Research of the NBS*, **83**:297-308.
- Rehm, R., Evans, D., Mell, W., Hostikka, S., McGrattan, K., Forney, G., Bouldin, C., Baker, E., (2003) "Neighborhood-Scale Fire Spread", *5th Symposium on Fire and Forest Meteorology*, November 16-20, American Meteorological Society, paper J6.7.
- Raithby, G.D. and Chui, E.H. (1990) "A Finite-Volume Method for Predicting Radiant Heat Transfer in Enclosures with Participating Media," *J. Heat Transfer*, **112**: 415-423.
- Reisner, J., Wynne, S., Margolin, L., and Linn, R. (2000) "Coupled Atmosphere-Fire Modeling Employing the Method of Averages," *Monthly Weather Review*, **128**: 3683-3691.
- Rothermel, R.C. (1972), "A mathematical model for predicting fire spread in wildland fuels," *Research Paper INT-115*, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA
- Smagorinsky, J. (1963) "General Circulation Experiments with the Primitive Equations I. The Basic Experiment," *Monthly Weather Review*, **91**: 99-164.
- Stephens, G.L. (1984) "The parameterization of radiation for numerical weather prediction and climate models," *Monthly Weather Review*, **112**: 827-867.