3.2 COUPLED ATMOSPHERE-FIRE MODEL SIMULATIONS IN VARIOUS FUEL TYPES IN COMPLEX TERRAIN

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1. INTRODUCTION

Fire behavior is inextricably linked to the fuel type and loading and topography, among many other factors. These experiment show simulated fire behavior for a setup that reduces such a situation to its simplest elements. The experiment described here involves the propagation of a simple fireline over a small hill and on flat ground in two different fuel types in (steady) constant environmental conditions.

NCAR's wildfire simulation model is an important component of our studies to understand the dynamics of wildfires. This atmospheric prediction model, coupled to a wildfire model, has been developed to represent the complex interactions between the fire and local winds. In previous studies, (Clark et al. 1996a,b) it demonstrated the dynamic causes of the bowing of fire lines, the formation of vortices within the fireline, and sudden outbursts of small fingers of flame from the fireline.

Observations, laboratory experiments (Weiss and Biging, 1996), and computer models (Linn, 1997; Coen et al 1998) show that when fire spreads on sloped terrain, it generally spreads faster uphill, particularly on steeper slopes. This is due to a combination of dynamic effects, including the fire's convection increasing momentum and wind speeds near the ground, the dynamics of flow over hills that leads to accelerations and decelerations in wind velocities, even without a fire, and (although this effect is not captured in these simulations) the fuel effectively being brought closer to the fire, preheating and drying the fuel ahead of the fire (Rothermel, 1972).

Fuel characteristics contribute to fire behavior not only by the total amount of heat that is released (related to the mass burned) but the rate at which they carry the flaming front and the rate at which, once ignited, the fire consumes the fuel.

We first describe the current status of the wildfire simulation model, give an overall view of the features of the modeling results, and discuss implications for fire behavior raised by the simulation.

2. NUMERICAL MODEL

NCAR's coupled atmosphere-fire model is described in detail in Clark et al. (1996a,b). A three-dimensional, nonhydrostatic atmospheric prediction model (Clark, 1977, 1979; Clark and Hall, 1991; Clark and Hall, 1996) has been coupled with an empirical fire spread model such that sensible and latent heat fluxes from the fire feed back to the atmosphere to produce fire winds, while the atmospheric winds drive the fire propagation. This wildfire simulation model can thus represent the complex interactions between a fire and local winds.

The meteorological model is a three-dimensional non-hydrostatic numerical model based on the Navier-Stokes momentum, thermodynamic, and conservation of mass equations using the anelastic approximation. Vertically-stretched terrain-following coordinates allow us to simulate in detail the airflow over mountainous topography. It can ingest a changing mesoscale atmospheric environment. Its two-way interactive nested grids capture the outer forcing domain scale of the environmental mesoscale winds while allowing us to telescope down to the meter-sized fine dynamic scales of vortices in the fireline through horizontal and vertical grid refinement. Cloud physics are approximated using a warm rain parameterization. The ice physics of the model are turned off.

Since Clark et al. (1996a,b) the fire code has improved considerably. Local fire spread rates depend on the modeled wind components through an application of the BEHAVE fire spread rate formula (Rothermel, 1972). A BURNUP-type algorithm (Albini, 1994) characterizes how the fire consumes fuels of different sizes over time. Four tracers, assigned to each fuel cell, identify burning areas of fuel cells and define the fire front. A local contour advection scheme avoids any ghosting effects (Richards, 1994). The fire model has a simple formulation for canopy drying and ignition and a simple radiation treatment for distributing the sensible and latent heat in the atmosphere.

There are conceptual problems with how to apply a spread rate formula such as BEHAVE in a coupled atmospheric model, for which it was not designed. In principle, one wishes to choose a representative wind (the component normal to the fireline) that is driving the fire. Such spread rate formulas, developed in laboratory wind tunnels containing burning fuel, require input of the local horizontal wind (the "mean wind" or "midflame" wind speed) that (for practical reasons) could be measured in the field as one of several key inputs; usually 0.2 times the free stream wind speed, or 0.2 times the 10 m wind is used. In the numerical model, atmospheric winds are located at fixed points on a three-dimensional grid, and must be interpolated to the point where the spread rate is required. However, more fundamentally, it is not practical to identify a background wind, since the fire dramatically alters the winds in its environment. And, since we are trying to capture the interaction of the fire with the winds, a wind closer to the fire should be more representative of the winds driving the fire. It is possible to refine the grid to a point and interpolate to identify the wind speed normal to the

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	Tall grass	Chaparral
Dry fuel load	0.674 kg m^{-2}	3.584 kg m^{-2} (16 ton/acre)
Moisture content	7.0 %	20.0 %
Fuel depth	0.762 m	2.0 m
Surface area to volume ratio (SAVR)	4921 m^{-1} (1500 ft^{-1})	(not used)
Oven dry fuel density	32 lb ft^{-3}	(not used)
Fuel particle effective mineral content (SE)	0.010	(not used)
Fuel particle total mineral content (ST)	0.0555	(not used)
Weighting parameter for mass consumption	7.	180.

Table 1. Fuel characteristics used in these experiments.

fireline very close to the line itself, however, since the fireline is a point of convergence of winds from ahead of and behind the fire, the horizontal wind is effectively zero. Thus, we have chosen to proceed by allowing the model user to select a distance behind the fireline (along a line normal to the local fireline front) (we choose 5 m in these calculations) at a specifiable height (we choose the fuel height) at which wind speeds for use in the spread rate calculation will be taken.

Two types of fuel were used in these experiments, tall grass and chaparral. Some fuel characteristics distinguishing each are contained in Table 1. The characteristics for some chaparral fuel parameters are not used because the following formula was used to calculate the fire spread rate:

$$S_f = 1{,}294 * U^{1.41} \quad (1)$$

which is capped at a maximum spread rate of 6 m/s. When the component of wind normal to the fireline is 0, the backing rate of spread (S_{fo}) for chaparral is specified as 0.033 m/s. (In other fuel types, S_{fo} is calculated using BEHAVE as the spread rate for no wind on flat ground.

Using the parameterized spread rate, the rate at which fuel is consumed once ignited is described using a mass loss parameterization, where the mass remaining as a function of time was assumed to decrease exponentially, an approximation to the general curve produced by the BURNUP algorithm, according to the formula:

$$1\text{-}F = \exp(-t/W) \quad (2)$$

where F is the fraction of fuel that has been burned, t is time since ignition, and W is a weighting factor determining how fast the fuel mass is consumed. W is currently selected to best fit the analogous BURNUP mass loss curve. The mass loss curves for the two fuel types used here are shown in Figure 1.

The propagation of the fire line through a fuel cell means that points within the cell will have been burning different lengths of time. To determine the fractional mass loss over a time step, we estimate the time history of the area burned in the fuel cell and integrate to calculate the currently remaining fuel mass.

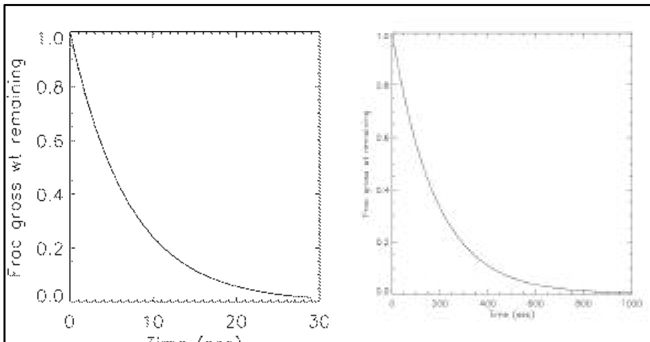

Figure 1. Mass loss curve for (a) tall grass (W=7), and (b) chaparral (W=180.).

3. EXPERIMENT

These idealized experiments examine a fireline propagating up the relatively sharp slope of a small Gaussian hill (height 200 m, half-width 300 m). The hill extends north-south over the entire modeling domain. We initialized a 409 m fireline to the west of this hill.

The ambient flow had constant 3 m/s wind from the west (left). The atmospheric temperature structure was stable such that the potential temperature lapse rate was 10 deg per km.

The simulations use 3 nested domains. The domains, from outer to inner, are 8.4 x 8.4 km, (with 120 m grid spacing), 3.36 x 3.36 km, with (40 m grid spacing), and 2.8 x 2.8 km (20 m). There is 2:1 vertical grid refinement between each domain.

The heat from both fuels is deposited into the atmospheric over a 50 m extinction depth

Four experiments are compared (Table 2).

4. RESULTS

Figure 2 shows the fire perimeter for experiment GRHL at 8 times. What appear to be odd variations in

	Grass	**Chaparral**
Flat ground	GRFT	CHFT
Hill	GRHL	CHHL

Table 2. List of experiments.

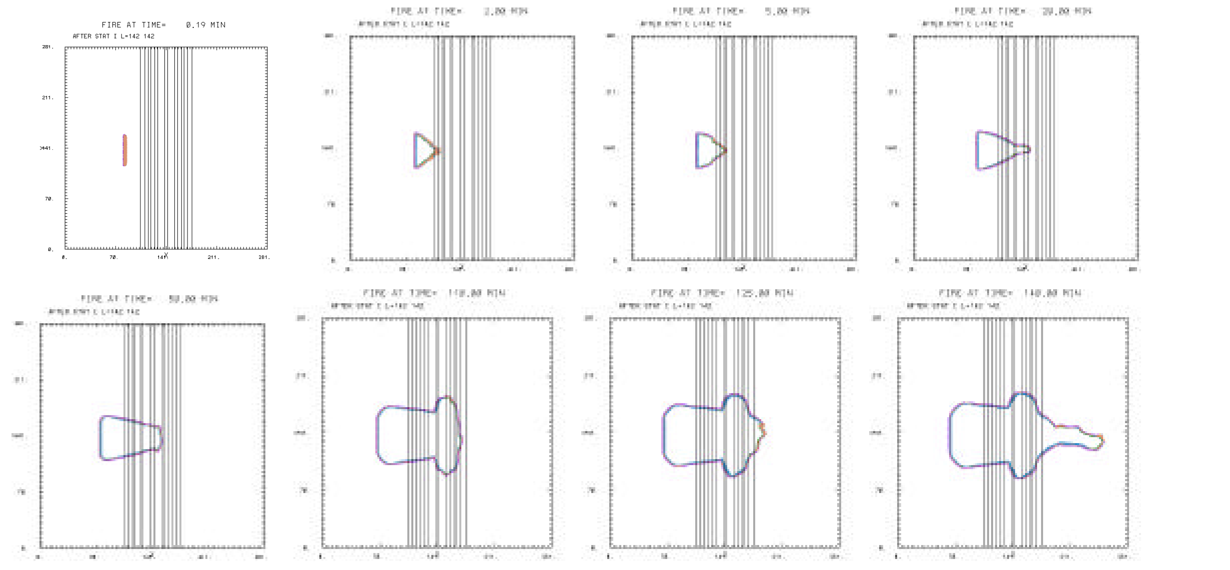

Figure 2. Fireline as fire crosses north-south oriented hill (topography contours every 50 m) at 8 times.

the shape are responses to the fire's effects on its local winds. Although all simulations will be presented in more detail at the meeting, several items of interest arose:

- Well-known regions of the fires are apparent and behave as known. The head of the fire propagates quickly generally in the direction of the environmental wind. The flanks of the fire propagate at an intermediate speed growing until the winds created by the fire blow parallel to the line. The slowest spreading part is the back, which creeps against the wind.
- Depending on the rate of heat release in the interior of the fire and whether external winds displace the location of surface convergence under the convective updraft over the fire or ahead of it, the fires experience a range of behavior from "plume" to "wind-driven".

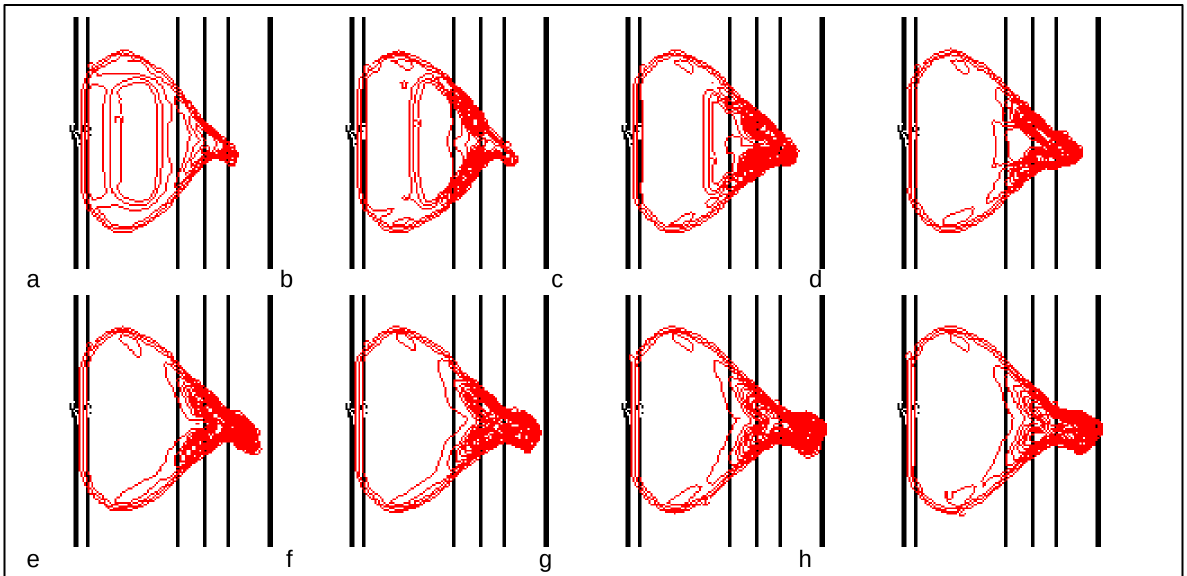

Figure 3. Buoyancy (contours every 2 degrees) at 9 times (61 - 69 minutes at 1 minute intervals) in experiment CHHL. The fire area is approximately 0.6 km north to south and east to west at this point. The solid lines are topography contours at 50 m intervals; the thickest line at the right of each image is the hill crest.

- Fire behavior is very sensitive to local changes in the low-level winds that the fire itself produced. For example, the winds along a steadily propagating flank are parallel to the fireline at low levels, not contributing to outward spread. A perturbation of outward growth near the back end of a flank (whatever its source) creates a locally stronger convective updraft that causes some surface winds to be directed outwards across the fire, causing a local enhanced burning feature, directing the winds nearby to be directed outward, propagating this feature forward to the head of the fire (as a vortex moving along the edge) where it bursts forward (Figure 3). This may be a mechanism of forward bursts observed in crown fires on slopes (Radke et al, 2000).
- The hill (even a symmetric north-south ridge) acts to funnel the convective updraft toward the center of the fire's head, where the convergence creates strong surface winds at the updraft base that spread the fire faster, increasing the fuel that is burned there, increasing the updraft strength, etc., leading to a narrow, rapidly spreading fire head.

As pointed out by Albini (1992) "It is a remarkable fact that the general shape is the same for a savanna fire, a shrub fire, or a timber crown fire". Although not all the complexity of a fire has been represented in the model, we can see the fundamental shape characteristics arise in even simple experiments and are a direct consequence of fire/atmosphere interactions.

6. Acknowledgements

This work was supported in part by funds provided by the Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture.

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