J2.4 SIMULATION OF WILDFIRE INCIDENTS USING COUPLED ATMOSPHERE-FIRE MODELING

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1. INTRODUCTION

Numerical modeling of fires has progressed over the past decade. In addition to semi-empirically based fire spread models that have led to practical in-the-field tools, other tools built to understand the fundamental aspects of fire behavior, such as fuel inhomogeneities on fire behavior (Linn et al, 2002) and feedbacks between the fire and the atmospheric environment as the basis for the universal fire shape (Coen et al, 2001; Clark et al, 2004).

Thus, a range of models exist, including experience /intuition, BEHAVE, FARSITE, the NCAR coupled atmosphere-fire model (Clark et al, 1996a, 1996), Los Alamos FIRETEC, (Linn et al, 2002) and that of Dupuy et al. 1999) that vary in complexity but also increase correspondingly in computational cost, so much so that an full explicit treatment of combustion in wildland fuels in a realistic atmospheric setting does not exist and is beyond current supercomputers. While more complex model have great value in studying fire behavior and testing fire spread in a range of scenarios, from the application point of view, FARSITE and palm-based applications of BEHAVE have shown great utility because of their ability to provide estimates of fire behavior in real time. While the NCAR, Los Alamos, and Dupuy et al. models have the ability to incorporate the ability of the fire to affect its own local weather, and model many aspects of the explosive, unsteady nature of fires that cannot be incorporated in current tools, it remains a challenge to apply these more complex models in a real-time operational environment. However, this spectrum of models has reached a sufficient degree of realism that current efforts cannot solely focus on perfecting the models, but must address important questions: what specific pieces of information must models provide (instantaneous fire spread rates, or end-of-the-day fire perimeters), temporal and spatial resolution, time frame for decisions, what computational framework is needed (a national center-produced forecast on supercomputers, such as is done for weather prediction, vs. a portable laptop-based software), and how they will estimate uncertainty in their forecast. These “operational constraints” must be used to steer model development.

Here, we describe the components of a fire simulation, describe some preliminary example simulations and the implications for doing this type of simulation in an operational (better than real-time) simulation, and pose questions that can be used to guide future modeling work.

2. NUMERICAL MODEL

NCAR's coupled atmosphere-fire model is described in detail in Clark et al. (2004,1996a,b). A three-dimensional, nonhydrostatic atmospheric prediction model (Clark, 1977, 1979; Clark and Hall, 1991, 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.

2.1 Atmospheric model component

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

Fig. 1 . Photo of Big Elk Fire, 18 July 2002, showing the terrain, fuel distribution, and fire head as it crests Kenny Mountain. (Photo courtesy of Kelly Close.)

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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 two-species (cloud droplets and rain) warm rain parameterization and a three-category (ice crystal, pristine snow, and graupel/hail) ice-phase parameterization.

2.2 Fire model component

Local fire spread rates depend on the modeled wind components through an application of the BEHAVE fire spread rate formula (based upon the work of 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.

One wishes to choose a representative wind (the component normal to the fireline) that is driving the fire. However, 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 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 allow the model user to select a distance behind the fireline (along a line normal to the local fireline front) (we choose 2 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.

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:

$$1-F = \exp(-t/W) \qquad (2)$$

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.

Fig. 2. Photograph of the Hayman Fire on 9 June 2002, a day during which the fire made a 60,000 acre run for 16-19 miles.

3. NUMERICAL EXPERIMENT DESIGN

Here, we describe the input for simulations of periods during the Big Elk fire (17 – 22 July 2002, Pinewood Springs, CO, 2200 acres) (Fig. 1), and Hayman fire (8 June – 2 July 2002, ignited near Lake George, CO, estimated at over 137,000 acres) (Fig. 2), which we use as a demonstration of the process.

4. INITIALIZATION OF FIRE ENVIRONMENT

The three environmental factors that influence fire behavior are the primary inputs to the model.

4.1 Topography

Topography data at 3 seconds across North America is readily available. As is typical in the fires in the Front Range of Colorado, terrain is quite steep (in the case of the Big Elk fire it included sheer cliffs) and must often be filtered (smoothed) for simulating atmospheric flows.

4.2 Weather

The large-scale atmospheric environment is introduced into the model from either a single atmospheric upper air sounding or 3-dimensional gridded large-scale model data (either the analyses for post-incident study, or the forecast from a meso- or synoptic-scale numerical weather prediction model for predictions). Here, a locally run 36-hr daily MM5 forecast (http://rain.mmm.ucar.edu) is used to initialize the finer-scale NCAR atmosphere-fire model.

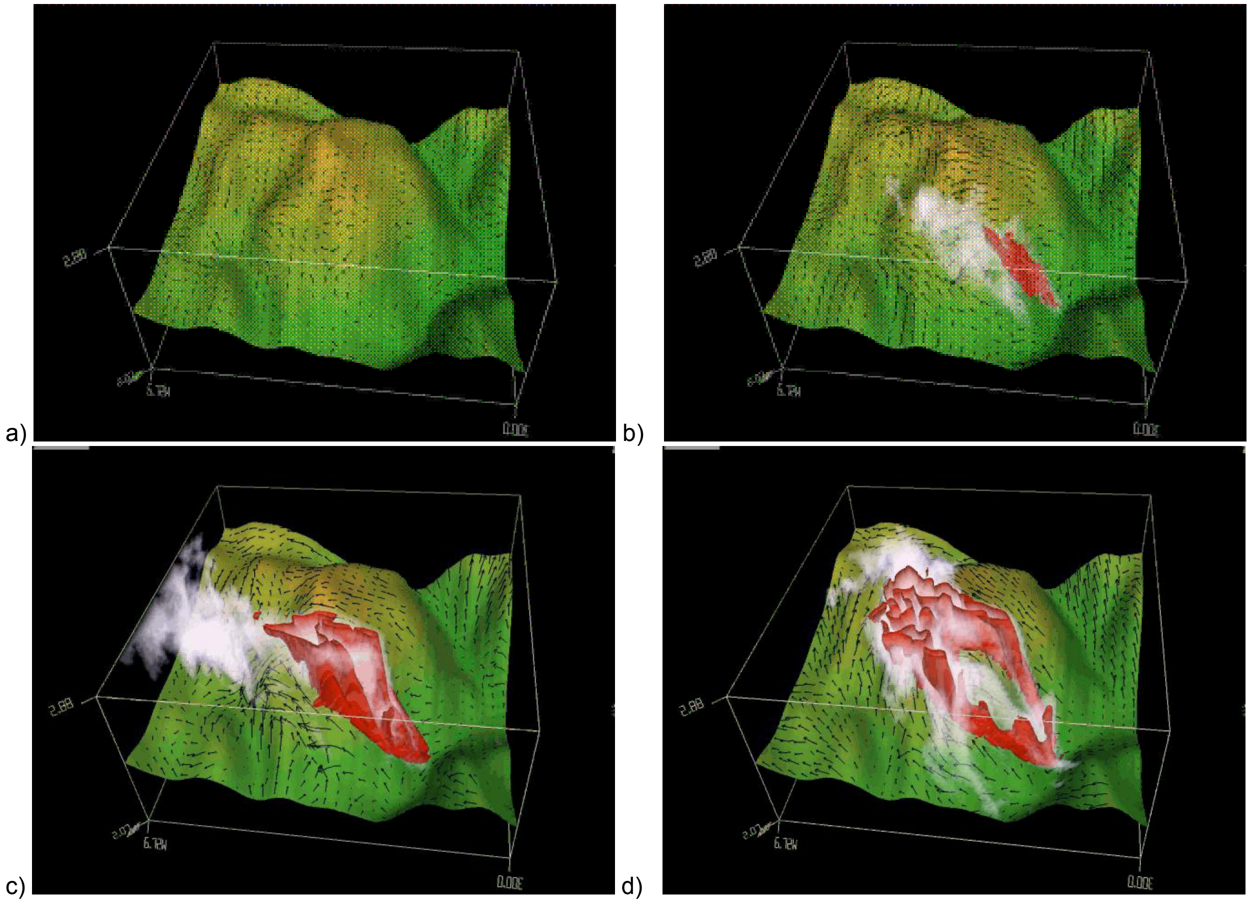

Fig. 3. Four time periods in the first four hours of the Big Elk Fire. The fire began in the valley, then rapidly climbed the steep slope driven by small-scale upvalley winds. The domain is 6.78 km on the horizontal side, and 0.8 km tall. The red isosurface is10 deg. Buoyancy, the misty white field shows smoke, and the vectors are the winds near the surface.

4.3 Fuel

Fuel characteristics are assigned to each fuel cell (these can be much smaller than an atmospheric grid dynamics cell). The fuel characteristics can be mapped according to the 13 Anderson (1982) fuels for fire behavior, specified according to altitude (this works well in the Big Elk fire) or slope aspect, or may be modified according to better information on fuel load, etc. In these experiments, both located in Colorado, the typical fuel types are short grass (1), grass with understory, (2), tall grass (3), and the timber litter categories 8-10. Canopy loads are estimated. Fuel moistures for both live and dead fuel are given in incident reports. Ultimately, these properties will be derived using remote sensing techniques (e.g. Roberts et al., 1999) to quantitatively capture their spatial variability.

5. EXPERIMENT DESIGN

These idealized experiments examine a fire simulated using 6 nested domains. The outermost domain has 10 km horizontal grid spacing, corresponding to the MM5 domain that is used to initialize it (28 x 38; 50 vertical grid points) , while inner domains nest down at a 3:1 nesting ratio giving domain 4 a horizontal grid spacing of 370 m (50 x 50; 52 vertical grid points), and domain 6 a grid spacing of 41 m (128 x 128; 40 vertical grid points). The stretched vertical grid is also nested allowing finer resolution in inner domains,

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

Solar heating plays an important role in local circulations in this area, with sensible heat fluxes on clear days of 400 W/m^2. Here, the surface experiences a heating due to solar radiation depending on its orientation relative to the sun, thus east facing slopes warm in the rising sun, etc

In addition to simulations in the early periods of the Big Elk and the Hayman fires, a number of sensitivity tests were performed while simulating the Big Elk Fire that

- varied the finest atmospheric grid resolution. This is done by running one simulation with 4 domains (finest grid spacing: 370 m) and

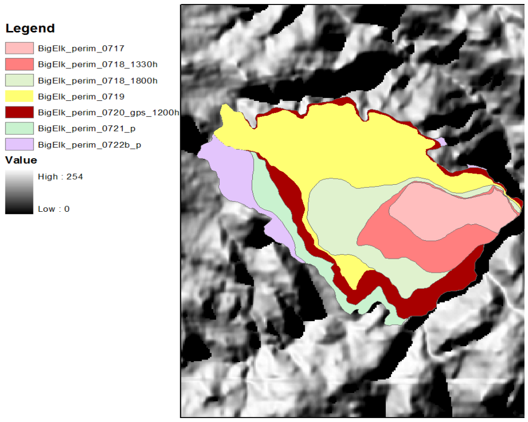

Figure 4. Fire perimeter of the Big Elk Fire from data collected by the Type II incident management team. (Figure courtesy of Kelly

another with 6 (finest grid spacing 41 m). This is important for determining the resolution needed for simulating wildfires. Coarser resolutions require fewer grid points and can be run much faster.

- Turn off the feedback of heat and water vapor from the fire back into the atmospheric model. This feedback is what allows fires to "create their won weather". Turning off this feedback tests whether it is necessary to include this atmosphere-fire coupling that creates locally strong winds. Off, the fire spreads as if it is just driven by winds - this is what fire spread calculations made using mesoscale model winds would produce if they could be run at these fine scales.
- Run the atmospheric model without any fire. In comparison with the simulation with fire, this allows us to see the distance over which the fire affects the local circulation. If this is wide or substantial, it suggests that the fire is an important impact on the meteorology in the area, and that numerical weather prediction forecasts (which do not include the fire) may err a great deal by not including this effect.

6. RESULTS

Several frames from the simulation of the first 4 hours of the Big Elk Fire using 6 domains are shown in Fig. 3. The actual fire progression is shown in Fig. 4. The general progression of events, captured in the simulation, was the rapid spread to the northwest of the fire (ignited in the valley) upslope. It is interesting to note that the fire is driven by the small-scale, solar-heating-driven winds (weak 3 m/s upslope) and the convective heating produced by the fire, not the ambient winds in that area, which nearby surface stations and soundings identify as generally westerly. Mesoscale models would not capture this valley flow, as the valley itself is narrower than one grid length, and the mesoscale flow in this area was generally westerly.

Past simulations (often at 10-20 m resolution) have shown a great deal of intense, very small-scale bursts, vortices, and runs associated with the fireline. This made the prospect of real-time simulations at this resolution daunting. However, simulations testing the resolution of the atmospheric grid spacing show that, surprisingly, the 4 domain simulation captured the overall spread of the fire nearly as well as the 6 domain simulation, which is significant because this configuration runs over 6 times faster than real time on a single processor of current PCs. Thus, a realistic coupling between the fire and environment does not necessary make this an intractable forecasting problem from the performance perspective.

We found that turning off the coupling between the fire and atmosphere did degrade the accuracy fire progression. This is because, as pointed out in past work (Coen et al, 2001; Clark et al 2004), the feedback from the fire itself into the atmosphere creates the "universal fire shape", including head, flank, and backing regions of the fire. Fig. 5 shows this effect.

The impact of fire on the meteorology away from the immediate area of the fire is a more difficult question to address. During intense fires such as the Hayman fire, many downwind effects and severe weather (even in the next state) were attributed to it. Fire has the potential to modify the regional meteorology many ways:

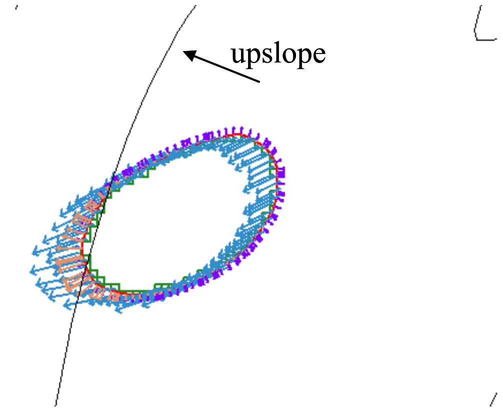

Fig. 5. A snapshot of fire spread during the simulation shown in Fig. 4. The red line shows the fire perimeter, the blue vectors show the wind (affected by the fire) near the fire, and the orange vectors show the calculated fire spread. Note that this fire-affected wind pattern creates the rapidly spreading head, the flanks where the wind blows along the fireline (not driving it into fresh fuel), and the creeping backing region, where the wind blows against the fireline.

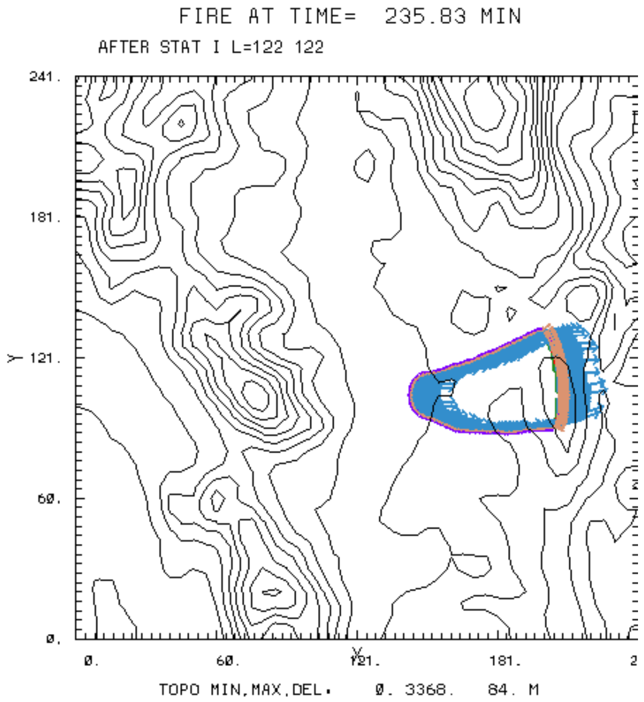

Fig. 6. Simulation of the Hayman fire during the early period of 9 June 2002 using the NCAR coupled atmosphere-fire model, initialized and boundary conditions updated with the daily MM5 forecast. Red line shows the fire perimeter, blue vectors show the strong atmospheric winds, and orange vectors show the rapid fire spread ENE. Topography contours are shown every 84 m.

- by initiating convective cells that propagate downstream (and trigger other convective cells),
- by initiating cells that locally organize convection by 'selecting' the strongest convective cell,
- modifying local circulations (unpredicted "rapidly shifting winds" directing the fire) which interact with the larger scale flow (scale interaction),
- modifying land surface properties, increasing the number of cloud condensation nuclei thereby modifying the rain process in clouds,
- introducing water vapor into the atmosphere (approx. 56% of dry fuel mass is converted to water vapor), and
- reducing solar insolation reaching the ground due to dense, long-loved anvil.

Another issue forecasts must deal with is the uncertainty in any deterministic simulation. Thus, single mesoscale model forecasts ultimately prove unsatisfactory. There is some uncertainty inherent in the initial conditions, and this results in error and uncertainty in the forecast. For example, a single simulation of the mesoscale environment using MM5 is used to initialize the NCAR coupled atmosphere-fire model. Our preliminary simulation of the Hayman fire forecast for 9 June 2002 showed the outcome of model uncertainty in fire propagation. An error of 10-20 degrees in wind direction leads consequently to an error in fire spread direction. Although one can improve models, ultimately a prediction must accept the range of uncertainty that is present in forecasts. Thus, ultimately, it will be important to use techniques employed in numerical weather prediction to include estimates of uncertainty (or probability of occurrence) along with the forecast – one example is ensemble forecasting, where a suite of models is run simultaneously with slightly different conditions. The peak of the probability density function (PDF) representing the spread of the model forecasts is the most likely outcome, and the standard deviation, or spread in the forecasts can be used as a proxy for the uncertainty (or probability) of that outcome. In other words, small spread in the model predictions leads to greater confidence in the outcome. In other cases, wide disagreement between the ensemble forecasts leads to "no forecast", i.e. no consensus.

In summary, these simulations pose questions meant to guide further model development towards useful tools that may give advance knowledge of wildland fire behavior and spread.

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