8.1 APPLICATIONS OF COUPLED ATMOSPHERE—FIRE MODELING: PROTOTYPE DEMONSTRATION OF REALTIME MODELING OF FIRE BEHAVIOR

Janice L. Coen*
National Center for Atmospheric Research, Boulder, Colorado

1. INTRODUCTION

Recent developments in fire models have represented more complex of fire behavior. The cost, in general, has been to increase the computational requirements. For research studies that can be performed without time constraints, this is not a serious limitation. However, when operational constraints are included, such as the need to produce such forecasts faster than real time (i.e. be able to simulate a period of time in the life of a fire faster than time passes), or the need to do such calculations on a single processor machine (such as a laptop in the field), meet schedule constraints (e.g.: produce a 24 hr forecast before the 6 PM briefing), maintain robustness (99% reliability of forecast generation), or meet accuracy targets (the need to predict 24 hr fire growth within 10%), the challenge becomes a balance of how much accuracy can be achieved in producing the quantities of interest while meeting the specified operational constraints. This is a different paradigm than research simulations, where the singular goal is to increase understanding.

Current field tools such as BEHAVE and BEHAVE Plus have succeeded in producing timely estimates of instantaneous fire spread rates, flame length, and fire intensity at a point using readily estimated inputs of fuel model, terrain slope, and atmospheric wind speed. At the cost of requiring a PC and slower calculation, FARSITE represents two-dimensional fire spread and adds capabilities including a parameterized representation of crown fire ignition.

Many limitations attributed by various sources to these tools arise from the temporally and spatially varying weather near the fire, particularly transitions such as changes in wind speed and direction due to meteorological events such as cloud downdrafts, frontal passages, as well as erratic wind shifts caused by feedbacks of the fire itself upon the weather, which they do not incorporate. To date, methods that include some meteorological impacts in operational fire behavior modeling tools have included diagnostic flow adjustment procedures (e.g. Butler 2003) to diagnose wind speed near the surface from an upper level, and the use of numerical weather prediction (NWP) models (Zeller 2003) to produce mesoscale winds that can be used as input to fire behavior simulators such as FARSITE.

* *Corresponding author address:* Janice L. Coen, NCAR, P. O. Box 3000, Boulder, CO 80307-3000; email: janicec@ucar.edu; phone: (303) 497-8986

Still, fire forecasting remains a challenging problem. Part of this is due to challenges in weather prediction. The weather near a fire results from not only synoptic and mesoscale meteorological processes, which routinely run NWP models may capture, but may be dominated by very small scale processes (< 1 km in horizontal spatial resolution, with rapid changes) such as convective cloud gust fronts and motions due to solar heating of slopes (Coen 2005), processes that lie in the realm of very short range forecasting and “nowcasting” (0-6 hrs) (Wilson et al. 2004; Dixon and Wiener 1993). In addition to uncertainties arising from meteorological modeling, there are uncertainties in modeling fire behavior, even with known meteorological conditions. And, the feedbacks of fires upon the atmosphere have not yet been included in operational tools.

This work describes how a coupled atmosphere-fire model previously used as a research tool has been adapted for production of real-time forecasts of fire growth and its interactions with weather over a domain focusing on Colorado during summer 2004. This provides an opportunity to capture the fire-atmosphere feedbacks, time varying behavior, and some aspects of extreme fire behavior that previously could not be represented in operational tools. Section 2 describes the model and experiment design, Section 3 describes how the modeling system is applied, Section 4 describes some preliminary results, and Section 5 discusses future plans and issues remaining with this technique.

2. MODEL DESCRIPTION, INITIALIZATION, AND EXPERIMENT DESIGN

The Coupled Atmosphere-Wildland Fire-Environment model (CAWFE) is described in Coen (2005), with earlier versions in Clark et al. (2004) and Clark et al. (1996a,b). The modeling system is composed of a three-dimensional atmospheric prediction model that has been two-way coupled with an empirical fire spread model. The models are connected in that atmospheric conditions (and fuel conditions influenced by the atmosphere) affect the rate and direction of fire propagation, which releases sensible and latent heat (i.e. thermal and water vapor fluxes) to the atmosphere that in turn alter the winds and atmospheric structure around the fire. This wildfire simulation model can thus represent the complex interactions between a fire and the environment.

2.1 Atmospheric model description

The meteorological model is a three-dimensional nonhydrostatic numerical model (Clark, 1977, 1979; Clark and Hall, 1991, 1996) based on the Navier-Stokes equations of motion, a thermodynamic equation, conservation of mass equations using the anelastic approximation, and conservation equations for water vapor and 5 hydrometeor particle types. Cloud microphysical processes 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. The vertical coordinate system employs terrain following coordinates and is vertically stretched, allowing the user to study flow in complex terrain. The model can be initialized with an atmospheric environment provided by theoretical background state, an atmospheric sounding, or large-scale gridded weather (either analyses or a forecast). Two-way interactive grid nesting allows the outermost domains to model regional weather at coarse resolution (10s of km horizontal grid spacing) while finer resolution inner domains telescope can be configured to next down to model fire dynamics within the fire line (at 10s of m) through both horizontal and vertical grid refinement.

2.2 Wildland fire model description

Atmospheric grid cells are further broken down horizontally into two-dimensional fuel cells at the surface, where fuel properties such as fuel type, fuel load, etc. may vary spatially from cell to cell. Fires are ignited either as a point or line, and growth according to fire spread rates that are calculated along the fire perimeter through an application of the Rothermel (1972) formula for rate of spread. (Other algorithms such as that of Noble et al. (1980) can be substituted easily.) 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. Heat fluxes from the surface fire may dry and ignite the canopy fuel above, igniting a crown fire. The sensible and latent heat fluxes are distributed in the lower levels of the atmosphere according to an exponential decay with a length scale set by the user, currently 50 m. Multiple fires can be modeled simultaneously, including the interactions between fires.

The user selects a distance behind the fire line (along a line normal to the local fire line front) (we choose 2 m in these calculations) and a height (we choose the fuel height) at which wind speeds for use in the spread rate calculation will be interpolated. These winds include and feedbacks from the fire.

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, with a characteristic time for each fuel type that best fit its mass loss with time.

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.

Fuel moisture response to atmospheric conditions is currently crude, and designed to capture diurnal variability impact on fire behavior. It is diagnosed from atmospheric conditions and mapped using a specified sinusoidal curve peaking at 0330 local time and reaching a minimum at 1530 local time.

2.3 Initialization of modeling system

The inputs to the model are fuel characteristics, topography, and large-scale weather forecasts for initializing and providing boundary conditions to this modeling system.

Fields that considered to remain static for the period of the program such as a map of fuel types, loads, and other physical characteristics, and terrain elevation are stored as a database from which needed data is sampled. Fuel characteristics are assigned to each fuel cell (10 x 10 exist in each atmospheric grid cell in these simulations). The fuel physical characteristics were specified using fuel properties associated with the 13 Anderson (1982) fuel models, using fuel information reported about the incident or fuel model maps of Colorado. The terrain is derived from 3-arcsecond North American topography data.

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 48-hr daily Pennsylvania State University / NCAR mesoscale model MM5 (Anthes and Warner 1978) forecast (http://rain.mmm.ucar.edu) is used to initialize the finer-scale NCAR atmosphere-fire model.

Fuel moistures for both live fuel moisture and initial dead fuel moisture are derived from available situation reports or fire intelligence.

2.4 Experiment design

This configuration uses 4 nested domains. The outermost domain has 15 km horizontal grid spacing (52 x 66; 46 vertical grid points), corresponding to resolution of the MM5 domain that is used to initialize it, while inner domains nest down at a 3:1 nesting ratio giving domains 2,3, and 4 horizontal grid spacing of 5 km (62 x 62; 34 vertical grid points), 1.67 km (68 x 68; 20 vertical grid points), and 0.55 km (74 x 74; 16 vertical grid points), respectively. The stretched vertical grid is also nested allowing finer resolution in inner domains. The surface experiences a heating due to solar heating depending on the date and orientation towards the sun.

The fire is ignited as either a point fire with specified radius or a line fire with specified length and width. Here, a point fire with radius of approximately 40 m is used. Currently, the model cannot yet start late in the life of a fire using known perimeters.

3. FORECAST GENERATION

Many different usage scenarios are possible, ranging from (1) detailed tactical modeling of fire behavior over a small area for a period of hours to warn of wind shifts and weather/fire/fuel/topography combinations that lead to blowups, (2) daily modeling of fire progression over a few day period to foresee fire progression, identify changes in anticipated future resource requirements, identify potential suppression opportunities provided by weather changes, to (3) landscape fire modeling over a period of weeks that might identify which ignitions of many have the potential (due to combined weather, topography, and fuel conditions) to become megafires. These all pose different scientific and forecasting challenges. Here, we explore the application of a model as in scenario (2), as a daily forecast tool.

The model has been adapted for production of real-time forecasts of fire growth and its interactions with weather over a domain focusing on Colorado during the summer of 2004 for this test. The model was run on-call when fires occurred in the region and initialization data about fire location could be obtained. Many scenarios for using the model as a forecasting tool could be constructed. The usage scenario shown here is the following: upon learning a fire has ignited within the region of interest, ignition time and location data, and fuel moisture data is collected from all available sources (incident web sites, GACC websites, news media, etc). Fuel and topography data is sampled from a database covering a much wider region. The most recent large-scale MM5 (or other larger-scale gridded model) forecast is retrieved and interpolated onto the CAWFE model 3-dimensional grid to initialize it and provide boundary conditions at later times. A fixed model configuration is set ahead of time and, when a fire occurs, the modeling system is centered upon the location of each fire. The atmospheric model is started at a time several hours before the fire ignition to allow for model spin up. From this coarse scale CAWFE modeling domain (15 km in horizontal grid spacing), a sequence of three finer atmospheric domains (5 km, 1.67 km, and 0.56 km) are sequentially set in motion. When the model reaches the ignition time, a small fire is ignited in the model at the time and location of the reported fire. The growth of the fire, its feedback upon the meteorology, the smoke produced by the fire, and atmospheric dynamics are then modeled for the remainder of the 48-hr MM5 forecast. Analysis plots are routinely produced during the run and from saved model data. These could be posted at a web site.

The information that must be gathered to generate a forecast is (1) the time and location (latitude and longitude) of the ignition point and (2) fuel moisture in dead and live fuels. The simulations were done with a single processor, as might be done in a field environment.

4. RESULTS

The summer of 2004 was a below average season in terms of fires in Colorado, nevertheless, several wildfire ignitions and a prescribed fire provided opportunity for testing this new system. During long periods when no fires occurred in Colorado, the configuration was applied to fires in northern California, which had several active fires at the time.

One case example is the Well fire, which was an ignition of a previous lightning strike a week earlier but flared up on 29 August 2004 at 12:50 local time in western Colorado, 9 miles southeast of Red Mesa (approximate coordinates –(37.88^{o}N, 108.27^{o}W). A GeoMAC (http://www.geomac.gov) display of the fire location after 2 days is shown in Figure 1. Atmospheric conditions were very dry with relative humidities ranging daily from approximately 10% to 20%. Winds were reported as 4.5-6.7 m s^{-1} (10-15 mph). It reportedly burned through heavy beetle-killed pinon and juniper fuels, growing from 20.2 ha (50 acres) at 1700 local time to an estimate of over 405 ha (1000 acres) at 1900 local time. The Well fire grew to 452 ha (1117 acres) over the next 2 days, after which two days of cooler cloudy weather allowed it to be contained. Simulated extent of the fire at various times is shown in Figures 2-5. Other output (not shown here) can show the winds in the environment of the fire, the height and transport of the smoke plume, and fire intensity.

The time required for simulation depends on number of points used (a function of the size of the domain and the grid vertical and horizontal resolution), the time step (related to the grid resolution as well as the dynamics that are occurring), and the speed of the computer. Timing statistics from a 4-year old Compaq Alpha workstation indicate that considering a midday ignition, a simulation that begins with the weather that morning, includes the fire ignition at the observed time, will complete a forecast of the fires' growth that calendar day by late afternoon, and forecast the next day's growth that evening. This can be further optimized through better choices of vertical coordinates, optimizing the code for speed, refining the domain, and other ways. Once started, the model performed reliably in this configuration. More detailed performance statistics using current machines will be presented.

5. DISCUSSION

This work demonstrates for the first time the application of a model that incorporates both weather and fire behavior, including the feedbacks between the two, in a forecast mode. Although much work remains validating and improving the skill of such a forecast, this demonstrates that it is possible to apply a more sophisticated tool in a real time manner on commonly available computing equipment. Depending on the skill of the model, this could allow for prediction of many troublesome aspects of fire behavior that pose safety problems, including rapid increases in spread rates and burning intensity, transition to a crown fire, fingers of flame observed to burst upslope ahead of a crown fire (Coen et al 2004), sudden wind shifts arising from changing meteorological conditions and/or interactions with fire-induced winds, fire whirls, and smoke production as well as its transport.

Several issues remain with this process. One is how the forecast may be verified. Traditional meteorological forecasting verification statistics may be used to assess the gridded meteorological fields in comparison to meteorological data, however assessing the fire growth prediction is more difficult. Data that would routinely be available would be fire perimeter data at a few times daily, as instantaneous fire spread rates, which vary substantially along a fire line, are not routinely mapped across a fire. For comparison with perimeter data, it is better treated as an object. Only Fujioka (2002) has addressed methods to verify fire perimeter forecasts. Object-based verification techniques (Brown et al. 2004) are being investigated for application to this problem and comparison with recorded fire perimeters from incident data. In some cases, where detailed scientific data are available (e.g. Riggan et al. 2004), it is desirable to make comparisons with other fields than fire extent, such as fire line intensity and geometry, depth of the fire line, sensible heat and carbon fluxes, and plume temperature and updraft velocity.

Second is the availability of data for initialization. Static inputs such as the fuel data must be available for the region being modeled. Other studies (Wiedinmyer, Coen, and Wilhelmi, in preparation) have shown that fire behavior and dynamic processes such as the plume rise are particularly sensitive to the fuel properties and the resolution of such data, due to the feedback of the fire's heat release upon atmospheric winds and thermodynamics. Thus, even more so than in methods where one-way input of atmospheric winds into fire models is used, here it is particularly important to represent the spatially heterogeneous nature of fuel properties (including the spatial variability of fuel loads of the same fuel model) accurately. In addition, for real time modeling, rapid access to fire ignition time and location is necessary for forecast generation - preferably at a centralized internet site that allows automated retrieval, so that automated forecast generation can occur, as is done for meteorological forecasts. Currently, numerous web sites are searched and phone calls made before the specific coordinates and fire environment information is found.

Third, it is likely that this deterministic approach to fire forecasting meteorological techniques such as ensemble forecasting and data assimilation will

Future work will include developing and applying object-based verification techniques for simulated fires, improving representation of fuel moisture response to forecast atmospheric conditions, developing techniques to assimilate both fire and weather data into the model, rigorous comparison of case studies where comprehensive datasets on both inputs exist.

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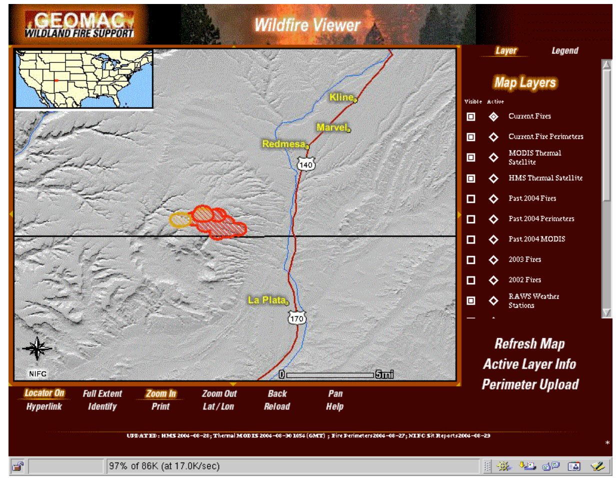

Figure 1. GeoMAC display of MODIS-derived Well fire location at 0654 local time on 30 August 2004. Figure courtesy of the Geospatial Multi-Agency Coordination Group.

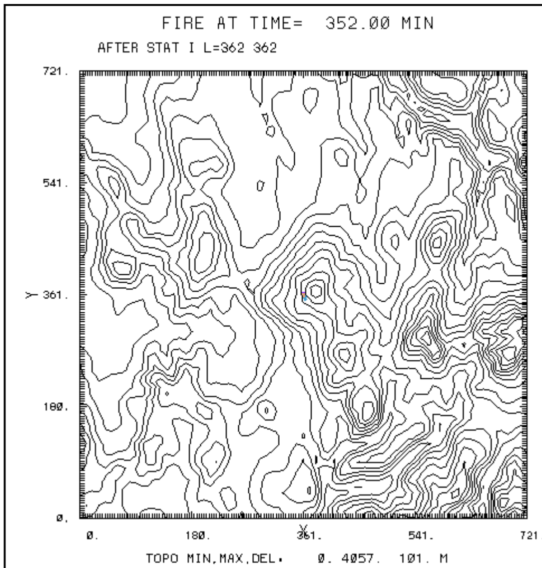

Figure 2. Location of Well Fire at flare up, 12:50 local time on 29 August 2004.

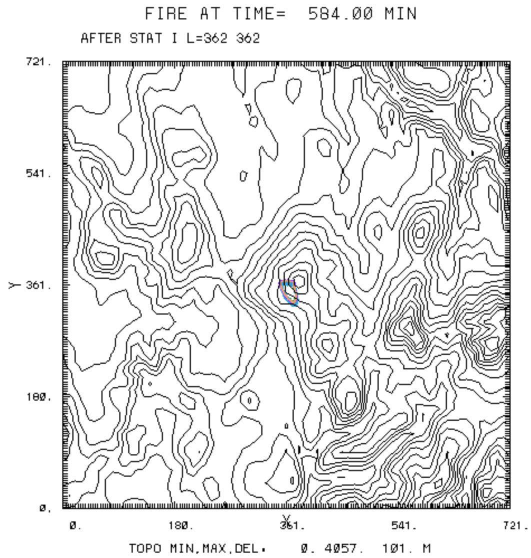

Figure 3. Simulated location of Well Fire at 4:45 pm local time on 29 August 2004.

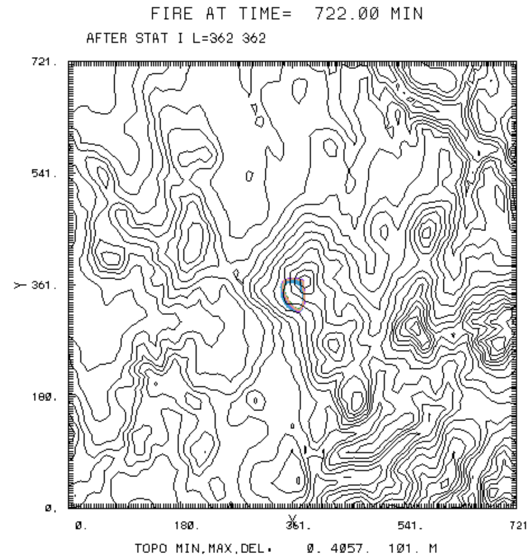

Figure 4. Simulated location of Well Fire at 7:02 pm local time on 29 August 2004.

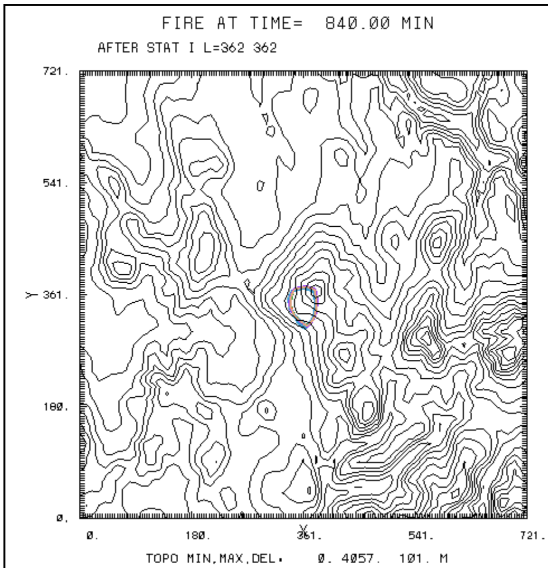

Figure 5. Simulated location of Well Fire at 9:00 pm local time on 29 August 2004.