WRF-Fire: A Coupled Atmosphere-Fire Module for WRF

Edward G. Patton and Janice L. Coen
National Center for Atmospheric Research, Boulder, CO

1. INTRODUCTION

Several models ranging from simple linear algorithms to complex computational fluid dynamics codes have been developed to simulate the propagation and behavior associated with wildland fire. All attempt in some way to incorporate the effect of the three environmental factors affecting fire behavior. These factors are fuel, weather, and topography. Some semi-empirically based fire spread algorithms such as BEHAVE (Andrews 1986) and FARSITE (Finney 1998) have led to practical in-the-field tools that require simple point or two-dimensional surface values of meteorological fields such as wind as input. Other tools (Clark et al. 1996a, 1996b, 2004; Linn et al. 2002) have coupled atmospheric models to wildland fire behavior models to understand the feedbacks between a fire and the local weather, ranging from small-scale "firenadoes" to generation of supercell-like circulations affecting regional weather. Although this adds computational complexity, these models have become valuable research tools, as such models have provided insights into fundamental aspects of fire behavior. These models have shown that feedbacks between the fire and the atmospheric environment are the basis for the universal fire shape (Coen et al. 2001; Clark et al. 2004) and clarified the impacts of fuel inhomogeneities on fire behavior (Linn et al. 2002). They have also been applied to limited numbers of actual wildland fire incidents (Coen 2004).

While many challenging fire behavior research questions remain, many intriguing links between fire and other important issues remain to be explored, including fire impacts on air quality, water resources, and the carbon cycle. Yet, research-quality tools capable of exploring these complex interactions are not widely available to the research community. Also, although widely-used, established mesoscale models such as MM5 (Anthes and Warner 1978) have recently begun to be applied through regional centers to provide more directed meteorological information to fire operations (Riebau 2003). The centers do not make use of modeling advances such as the Weather Research and Forecasting Model (WRF) (Michalakes et al. 2000) nor do these models have a mechanism to incorporate the feedbacks from the fire to the atmosphere. Thus, for greater community participation and faster research and operational advances, a freely available research quality tool is greatly needed.

Here, we describe our progress in developing a coupled atmosphere-fire behavior module for WRF (WRF-Fire) based upon the NCAR coupled atmosphere-fire model in order to take advantage of this state-of-the-art weather modeling system and provide a supported community fire modeling tool to be used either as a research or operational system. We will describe our intent, methods and progress to date, along with planned links between WRF-Fire and other modules, such as WRF-Chem, as a tool for investigating the impacts of fire emissions on regional air quality.

2. NUMERICAL MODEL

NCAR's coupled atmosphere-fire model is described in detail in Clark et al. (1996a,b; 2004) and the most recent advances in Coen (2004). 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. In our development, WRF will replace that atmospheric model and interact with the fire component in the same way.

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 maintains the integrity of the overall fireline. 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.

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:

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

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 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.

3. IMPLEMENTATION OF FIRE MODULE IN WRF

The fire module will be implemented as an added physics option in WRF. The fire-atmosphere coupling will occur through passing winds from the lowest WRF level to the fire module. The fire module will use those winds to predict the fire spread and subsequent heat and water vapor emissions. Water vapor and heat emissions from the fire will be passed back to WRF and distributed vertically through an assumed extinction depth.

When using the fire module, WRF will need to be run in LES mode, i.e. no boundary layer model will be used. Rather, the turbulence will be resolved by the grid, and a subgrid-scale energy equation will be used to estimate unresolved fluxes of momentum, heat, water vapor, and other scalars of interest. Any of WRF's land-surface models (LSM) can be chosen to exchange these same quantities at the land surface; the heat and water vapor fluxes from the fire will be considered additive to those determined by the LSM.

4. INITIALIZATION OF FIRE ENVIRONMENT

The three environmental factors that influence fire behavior are the primary inputs to the model, and may require additional datasets over those already required for the atmospheric model.

4.1 Topography

Fine-scale topographic features, in addition to being a factor in local airflows, can play a role in fire behavior, as fires spread much faster upslope than on flat ground. Thus, although many aspects of fire spread and behavior can be captured at grid resolutions of 1-km and perhaps above (Coen, 2004), the user should consider that fine-scale simulations may be appropriate. 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 and must often be filtered (smoothed) for simulating atmospheric flows.

4.2 Weather

The weather impacting the fire comes from the winds modeled by WRF in the vicinity of the fire, as modified by feedbacks from the fire itself. In later development, the modeled weather will also be used to simulate changes in dead fuel moisture, which responds with time lags corresponding to the size of the fuel particles, primarily to humidity, precipitation, wind, and solar radiation. This forms a second feedback loop between the fire and the environment.

4.3 Fuel

Fuel is related to, but not the same as, the vegetation in the area of the fire, as not all vegetation is burned. While live vegetation may be dried and ignited by the fire (this is referred to as 'live fuel'), dead fuel (such as forest floor needles, cured grasses, and twigs and branches) plays a far more important role in fire behavior. Dead surface fuel types are typically classified into 13 Anderson (1982) fuels categories (or "models"). For example, typical fuels for Colorado include short grass (Type 1), grass with understory, (Type 2), tall grass (Type 3), and the timber litter categories (Types 8-10).

Fuel characteristics are assigned to each fuel cell (these can be much smaller than an atmospheric grid dynamics cell). Each fuel category includes values for fuel load (mass per unit area), depth, surface area to volume ratio, heat content, and fuel moisture are important physical parameters associated with each fuel type. The spatial variability of fuel categories can be specified, set as a function of altitude, or may be read from user-supplied databases.

Canopy fuel represents the living aerial vegetation that may participate in crown fires, in which a surface fire dries and ignites the living tree canopy. Fuel moistures for both live and dead fuel are sometimes given in incident reports. Ultimately, these properties and the evolution of fuel moisture should be derived using remote sensing techniques (e.g. Roberts et al. 1999) to quantitatively capture their spatial variability.

5. POTENTIAL AREAS OF FIRE RESEARCH

Fire has the potential to modify the regional meteorology many ways that have not been explored: (1) by initiating convective cells that propagate downstream (and trigger other convective cells), (2) by initiating cells that locally organize convection by 'selecting' the strongest convective cell, (3) modifying local circulations (unpredicted "rapidly shifting winds" directing the fire) which interact with the larger scale flow (scale interaction), (4) modifying land surface properties, (5) by increasing the number of cloud condensation nuclei thereby modifying the rain process in clouds, and (6) by introducing large amounts of 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 anvils. 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 2002 Hayman fire, many downwind effects and severe weather in Kansas were attributed to it. These effects of fires have yet to be explored.

6. LINKS WITH OTHER MODULES

Implementing a fire module coupled through two-way feedbacks with the WRF atmospheric model opens new opportunities for research. One example is a greatly enhanced capability to study the impact of fire emissions upon regional air quality. Currently, air quality modeling efforts struggle with the treatment of fire – since no fire is present in their atmospheric simulations, there is no explicit vertical transport of emissions nor is there any way to know how emissions vary with the evolution of fire behavior throughout a day. This results in assumptions of a vertical profile of released emissions based upon historical fires released in largely horizontal winds, that is, winds that do not contain the strong updraft produced by a fire. Moreover, fire intensity and emissions vary greatly between periods of smoldering and flaming combustion, resulting in differences in gaseous species as well as aerosol particle size, composition, and concentration. Although substantial progress has been made to characterize the wide range of chemical species detected in fire emissions, significant uncertainty exists in the amount released into the atmosphere due to wide ranges in fire intensity and fuel consumption in any given fire, as well as the transport height to which the buoyant updraft grows. Thus, the current ability to simulate quantitatively the impacts of fires on regional air quality is severely limited.

WRF-Chem (WRF Working Group, 2004) is an atmospheric chemistry package linked to WRF that simulates atmospheric chemistry and aerosols while running online (i.e. simultaneously simulating the interaction between chemistry, radiation, and dynamics, rather than through post-processing). WRF-Chem currently simulates dry deposition, biogenic emissions, the RADM2 chemical mechanism, photolysis, and aerosol parameterization. All species are transported by WRF grid-scale motions, with subgrid-scale transport by turbulence and convection.

With the addition of emissions factors of chemical species relevant to fire, the combined application of WRF-Chem and WRF-Fire will allow the user to calculate the rate of emission of chemical species and aerosols according to the behavior of the fire, simulate the vertical transport and mixing of these species in the buoyant fire updraft, and their transport and chemical evolution without making many of the current assumptions needed today.

7. REFERENCES

Albini, F. A., 1994: PROGRAM BURNUP: A simulation model of the burning of large woody natural fuels. Final Rept. On Research Grant INT-92754-GR by U.S.F.S. to Montana State Univ., Mechanical Engineering Dept.

Anderson, HE, 1982: Aids to Determining Fuel Models for Estimating Fire Behavior. *USDA Forest Service, Intermountain Forest and Range Experiment Station, INT*-122, 22 p.

Andrews, P.L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system-BURN subsystem, part 1, Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 130p.

Anthes, R. A., and T. T. Warner, 1978: Development of hydrodynamic models suitable for air pollution and other mesometeorological studies. *Mon. Wea. Rev*., 106, 1045-1078.

Clark, T. L., 1977: A small-scale numerical model using a terrain following coordinate transformation. J. Comput. Phys., 24, 186-215.

Clark, T. L., 1979: Numerical simulations with a three-dimensional cloud model: lateral boundary condition experiments and multi-cellular severe storm simulations. J. Atmos. Sci., 36, 2191-2215.

Clark, T. L. and W. D. Hall, 1991: Multi-domain simulations of the time dependent Navier Stokes equation: Benchmark Error analyses of nesting procedures. J. Comp. Phys., 92, 456-481.

Clark, T. L. and W. D. Hall, 1996: On the design of smooth, conservative vertical grids for interactive grid nesting with stretching. J.. Appl. Meteor., 35:1040-1046.

Clark, T. L., J. L. Coen, and D. Latham, 2004: Description of a coupled atmosphere-fire model. Intl. J. Wildland Fire. 13:49-63.

Clark, T. L., M. A. Jenkins, J. Coen and David Packham, 1996a: A Coupled Atmospheric-Fire Model: Convective Feedback on Fire Line Dynamics. J. Appl. Meteor. 35, 875-901.

Clark, T. L., M. A. Jenkins, J. Coen and David Packham, 1996b: A Coupled Atmospheric-Fire Model: Convective Froude number and Dynamic Fingering. Intl. Journal of Wildland Fire. 6:177-190.

Coen, J. L., 2004: Simulation of a wildland fir eincident using coupled atmosphere-fire modeling. Intl. J. Wildland Fire. Submitted.

Coen, J. L., T. L. Clark, and D. Latham, 2001: Coupled atmosphere-fire model simulations in various fuel types in complex terrain. Preprints 4th Symposium on Fire and Forest Meteorology, Nov. 13-15, Reno, Amer. Meteor. Soc.

Finney, M.A., (1998): FARSITE: Fire Area Simulator - Model Development and Evaluation, *USDA Forest Service Rocky Mountain Research Station*, RMRS-RP-4, 47 p.

Linn, R., J. Reisner, J. J. Colman, and J. Winterkamp, 2002: Studying wildfire behavior using FIRETEC. Intl. J. Wildland Fire. 11:233-246.

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, W. Skamarock, 2000: Development of a next-generation regional weather research and forecast model. Proceedings 9th ECMWF Workshop on the use of Parallel Processors in Meteorology. Reading, U.K., November 13-16. Argonne National Laboratory Preprint ANL/MCS-P868-0101.

Riebau, A. R., 2003: Fire consortia for advanced modeling of meteorology and smoke – FCAMMS: A national paradigm for wildland fire and smoke management. Preprints, 5th Symp. Fire & Forest Meteorology/2nd Intl. Fire Ecology and Fire Management Congress, Orlando, FL, American Meteorological Society, CD-ROM, J12.1.

Roberts, D.A., P.E. Dennison, M. Morais, M.E. Gardner, J. Regelbrugge, and S.L. Ustin, 1999: Mapping Wildfire Fuels using Imaging Spectrometry along the Wildland Urban Interface. *Proc. of the Joint Fire Science Conference and Workshop*, June 17-19, 1999, Boise, Idaho, Vol. 1, 212-223.

Rothermel, R. C., 1972: A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper INT-115. 40 pp.

WRF Working Group, 2004. http://www.wrf-model.org/WG11