

High Resolution Wind Direction and Speed Information for Support of Fire Operations

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Abstract—Computational Fluid Dynamics (CFD) technology has been used to model wind speed and direction in mountainous terrain at a relatively high resolution compared to other readily available technologies. The process termed “gridded wind” is not a forecast, but rather represents a method for calculating the influence of terrain on general wind flows. Gridded wind simulations are typically produced at resolutions of 100 m using laptop computers. Resolution is limited only by elevation data resolution and computer memory. Initial comparisons between simulated winds and measured average wind speeds and directions for specific locations indicate excellent agreement. Results suggest that as the upper air wind speed increases the relative magnitude of uncertainty in the simulated winds decreases. The modeled winds generally seem to be most accurate for simulation scenarios associated with large scale strong pressure differences such as cold front passage, Foehn (Santa Ana), and onshore/offshore winds. This high resolution wind information has proven useful for identifying areas and/or conditions around a fire perimeter that may produce high fire intensity and spread rates and for identifying specific locations where fire spotting might occur. Currently the output from the process can be summarized in the form of a shaded relief map with wind vectors overlaid on the terrain image, GIS shape files, and custom wind direction and speed files that can be utilized by the FARSITE fire growth simulation program. The accuracy of FARSITE fire spread predictions is improved in the few cases where gridded winds have been used.

Introduction

Wind is one of the primary environmental variables influencing wildland fire spread and intensity (Rothermel 1972, Catchpole and others 1998). Nevertheless, methods to model local wind speed and direction are not readily available. In many cases, wind information available to fire incident personnel is limited to that available from weather forecasts and/or weather observations from a few specific locations, none of which may be actually near the fire. Mountainsides, valleys, ridges, and the fire itself, influence both the speed and direction of wind flows. A major source of uncertainty in fire behavior predictions is the lack of detailed wind speed and direction information for use in the fire behavior calculations. Wind and its spatial variability in mountainous terrain was a major factor in the fire behavior associated with recent fire incidents that resulted in firefighter entrapments and/or fatalities: South Canyon Fire 1994 (Butler and others 1998), Thirtymile fire (USDA Forest Service

2001), and Price Canyon Fire (Thomas and Vergari 2002). Fire behavior forecasts, fire growth projections and firefighter safety could greatly benefit from detailed local wind information.

Some efforts are underway to approach the problem from the atmospheric modeling standpoint. Ferguson (2001) is using atmospheric scale models to assess the dispersion of smoke from natural and prescribed fires. Zeller and others (2003) are exploring the application of meso-scale atmospheric flow models for the prediction of surface winds. And this year (2004) the National Weather Service provided public access to the National Digital Forecast Database (NDFD). The NDFD currently provides 2.5 km resolution, 8-day digital forecasts (and GIS support) for the conterminous US (NWS 2004). These approaches include many of the important physical processes but suffer from relatively coarse scale surface wind predictions (nominally 103 m scale) and large computational requirements and/or times. And, importantly, the meso-scale model approach is not easily configured

for “what if” applications wherein a single user can simulate various scenarios ahead of time to explore the relative effects of model inputs on surface wind flow and their impact on fire intensity and growth.

Lopes and others (2002) and Lopes (2003) describe a software system that calculates a surface wind field and includes topographical influences. The wind field simulator has been used to generate wind inputs to a fire growth simulator. Lopes and others (2002) implement two methods for producing wind fields: a diagnostic model called NUATMOS (Ross and others 1988) and a Navier-Stokes solver called CANYON (Lopes 2003). Typically, models like NUATMOS cannot accurately predict flow effects such as the recirculation on the lee side of ridges in mountainous terrain. More detailed submodels including conservation of momentum and turbulence are needed to account for the interactions between wind and surface structures such as ridges and canyons.

With the advent of digital computing a tool has become available for the study of fluid dynamics. This technology termed computational fluid dynamics or CFD is widely used within the engineering disciplines (Launder and Spaulding 1974; Volker and others 2000; Barman 2001; Patankar 1980) to resolve flows in enclosures such as ducts, furnaces, or wind tunnels. However, it is only within the last few years that CFD has become available at a cost and in a form that allows a broad range of practitioners to approach complex fluid flow problems, for example modeling of the dispersion of toxic gases from hazardous waste spills, the selection of optimal sites for wind turbines, and wind loads on high rise buildings. As a result some previous studies have focused on the application of CFD technology for simulating wind flow over complex terrain (Raithby, Stubley and Taylor 1987, Alm and Nygaard 1995, Montavon 1998, Kim and others 2000). A few studies explored the interaction between wind and mountainous terrain within the context of wildland fire, but none have linked the wind simulations to wildland fire management efforts.

This study was initiated with three objectives: 1) explore the utility of CFD software for simulating surface wind flows in mountainous terrain, 2) identify how detailed surface wind information can assist wildland fire operations, and 3) develop a methodology by which the technology may be accessed by wildland fire incident management teams. This document outlines current work on objective #1 and efforts to quantify the accuracy of the high resolution wind-based fire growth simulations.

Discussion

The process of producing gridded wind information occurs in three steps and is detailed elsewhere (Forthofer

and others 2003). Basically it consists of importing elevation data in the form of digital elevation model (DEM) files into the CFD software and solving the Navier-Stokes equations to determine the flow speed and direction everywhere within the domain. The results from this set of calculations are then used to determine surface wind speed and direction at a resolution of nominally 100 m everywhere on the terrain of interest.

Wind modeling for a specific fire typically consists of simulating several different combinations of wind speed and direction. The simulations are selected to match a forecasted scenario or are based on historical weather patterns. The simulation accounts for the influence of elevation, terrain, and vegetation on the general wind flow. Output files are geo-referenced so that they can be incorporated into standard GIS information systems.

Transfer of results from the wind simulations to fire managers and field personnel can occur in three different forms: 1) Images consisting of wind vectors overlaid on a shaded relief surface image. The fire perimeter and marked prominent landmarks can be added to orient the viewer (fig. 1). These images display the spatial variation of the wind speed and direction and can be used to identify high and/or low wind speed areas along the fire perimeter caused by the channeling and sheltering effects of the topography. 2) ARCView or ARCMAP shape files of wind vectors. These vectors can be incorporated into a GIS database and custom maps/images developed. Some useful combinations are wind vectors over fuels maps, IR based fire perimeters, and 7.5 minute quad maps with contour lines, roads, and trails. The process can also produce input files for use by the FLAMMAP and FARSITE programs (Finney 1998). Naturally, the accuracy of fire growth projections are limited by the accuracy of the weather and wind forecasts used to develop the gridded winds. This implies that the uncertainty associated with both wind and fire growth projections will increase as the simulation progresses forward in time. Gridded wind simulations have been used to provide wind input to a small number of FARSITE fire growth simulations, in all of the simulations completed so far (less than 5) the accuracy of short term (< one day) fire spread projections, as compared to actual fire spread histories, has increased.

These simulations assume a neutrally stable atmosphere, meaning that they do not take into account density driven flows (diurnal winds and fire induced winds). Neglecting these flows introduces some error (especially at low wind speeds); however as the upper air wind speed increases the relative magnitude of this error decreases. Nor does this methodology account for momentum transfer due to thermal instability in the atmosphere.

Two methods have been utilized to quantify the accuracy of CFD based wind simulations. The first is to

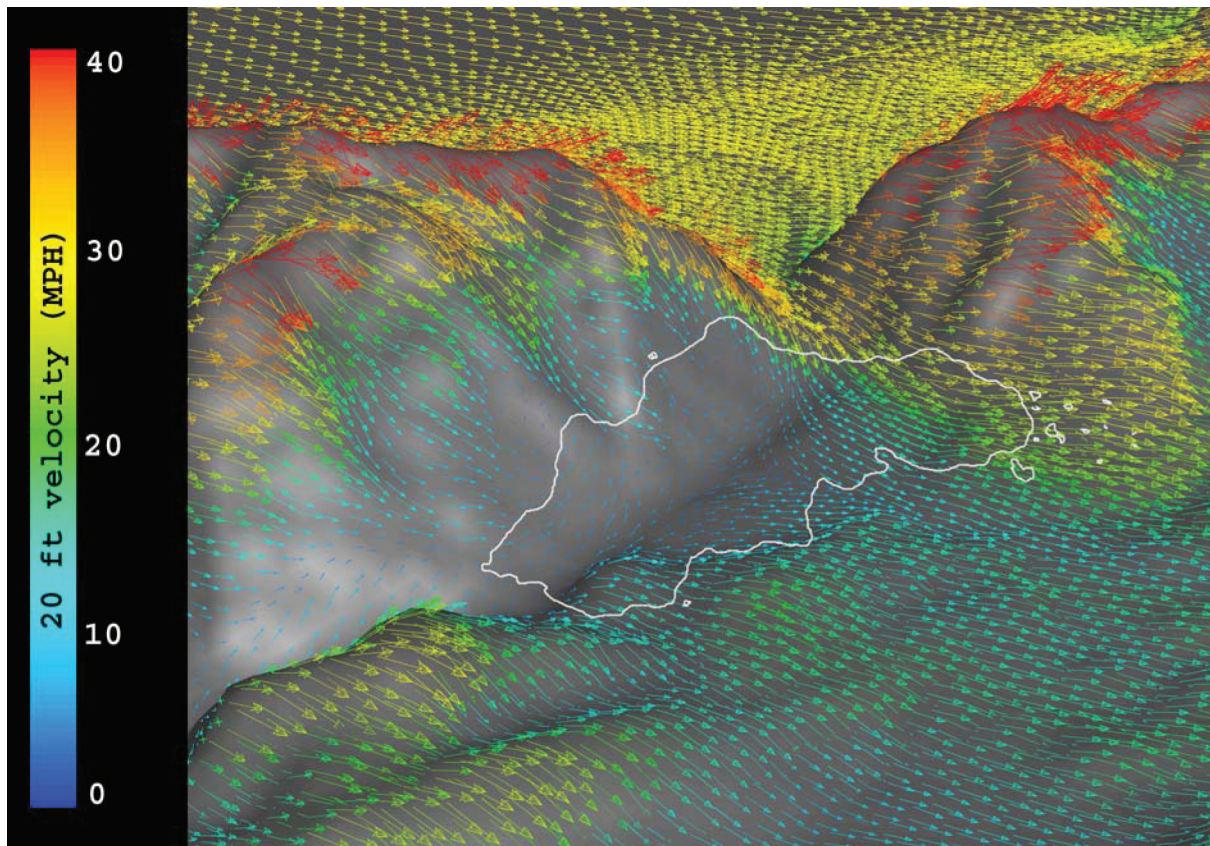


Figure 1. Example of gridded wind simulation for the Hungry Horse fire that burned in Northwestern Montana during the summer of 2003. The white line represents the fire perimeter.

compare modeled wind speed and direction against direct measurements. The second is to compare fire growth simulations with and without gridded wind against actual fire growth.

A set of measurements were collected specifically for the purpose of characterizing surface wind simulations (Taylor and Teunissen 1987). The site was a 116 m high hill located on the west coast of the island of South Uist in the Outer Hebrides of Scotland. Vegetation was relatively uniform and consisted primarily of heather and grass. Winds were measured using over 50 10 m tall towers instrumented with cup anemometers. The towers were deployed along three lines (fig. 2). Ten minute mean wind speed and direction measured 10 m above ground level were recorded during the 3 hour experiment. The overall mean direction and speed were 210 degrees and 8.9 m/s respectively. Using an input flow speed and direction of 10 m/s from 210 degrees a CFD-based simulation was completed (fig. 3). The simulated wind speeds along line A were compared against measured wind speeds (fig. 4). Generally the modeled wind speeds were within 9 percent of those measured except for the location approximately 198 m downwind from the intersection of the A and B lines where the simulated wind speed was 32 percent greater than the measured value. This location is

approximately midslope on the leeward side of the hill and is likely related to differences between the steady state calculations produced by the CFD-based model and the transient nature of turbulent eddies forming on the leeward side of the hill (Castro and others 2003). This result suggests that the CFD-based methodology may not capture the transient nature of the flow. Simulated wind direction was also compared against measured values (fig. 5). As shown the agreement is not as good as that of the speed comparison but is still less than 13 degrees for all locations. The largest difference between the simulated wind direction and measured values were greatest near the base of the hill for both the upwind and leeward sides.

While the Askervein hill is topographically relatively simple, the comparison between simulated and measured winds suggests that the CFD-based methodology for simulating surface wind flow over mountainous terrain can provide relatively accurate information. A second evaluation of the relative impact of gridded wind on fire behavior modeling was explored by comparing the results of two FARSITE simulations of fires spreading over the Askervein hill. For the fire growth simulation a point ignition was applied near the southwest end of the AA line. The first simulation assumed a uniform (constant)

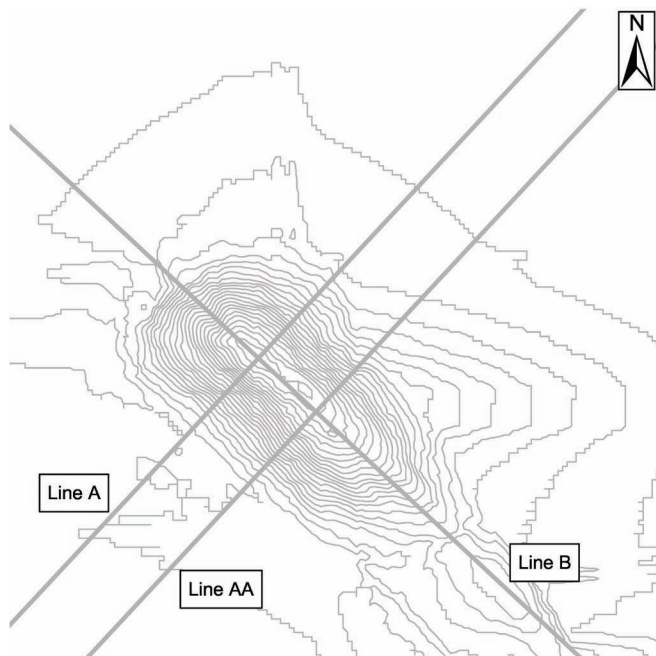


Figure 2. Topographical image of Askervein hill. Anemometer towers were deployed along lines A, AA and B. Contour interval is 5 m.

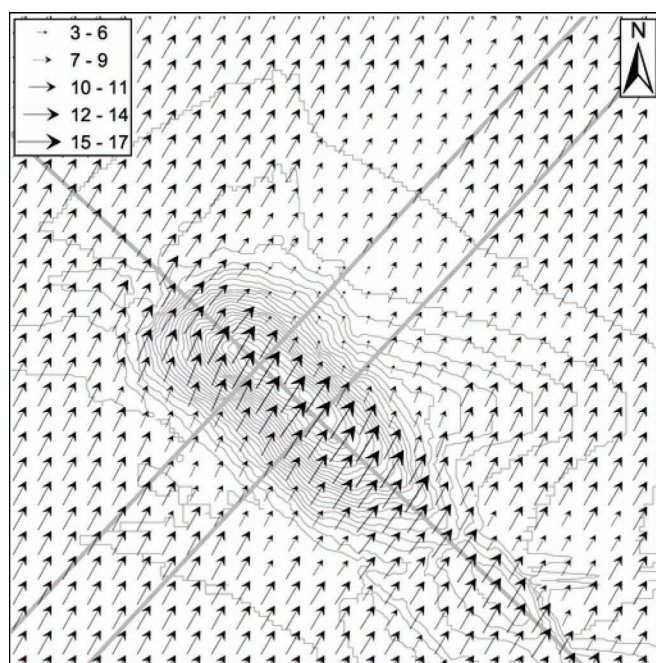


Figure 3. Gridded wind simulation results for general input flow of 10 m/s from an angle of 210 degrees.

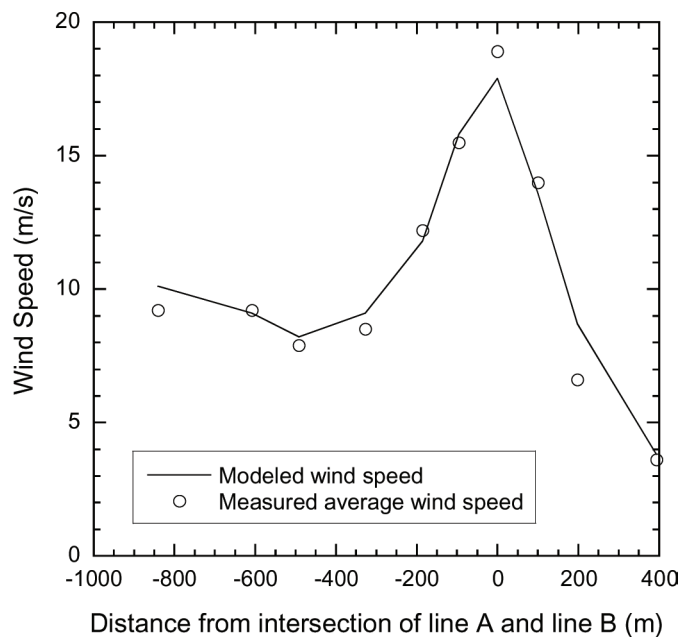


Figure 4. A comparison of measured and predicted wind speeds along line A.

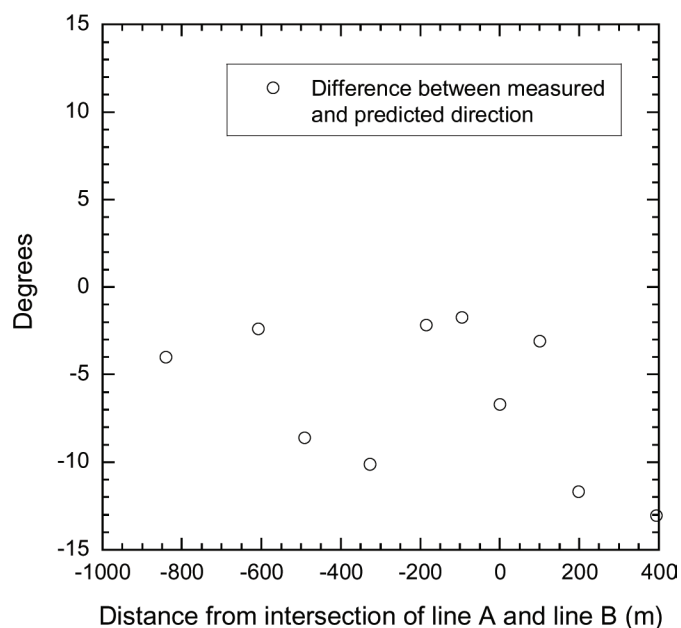


Figure 5. A comparison of the variation from the overall 210 degree flow direction for the measured and predicted winds along line A.

wind field in both speed and direction (fig. 6). Because the winds are everywhere uniform the simulation does not account for the influence of terrain on the wind field, except through a slight impact on the midflame wind (Rothermel 1972, Finney 1998), and the effect of slope on fire spread rate. A second simulation was completed using the gridded wind and keeping all other factors equal to those of the uniform wind simulation. The fire growth over time is indicated by the succeeding fire perimeters (fig. 7). A comparison of the relative differences between the two images suggests that wind speed and direction dramatically affect fire spread even in simple terrain like that of the Askervein hill. While no actual fire burned, these comparisons illustrate the impact that terrain influenced wind can have on fire growth simulations even over relatively short (< one day) periods.

As noted previously, a second method for evaluating the accuracy and impact of this technology is to compare fire growth simulations against those demonstrated by actual fires. Simulations were performed for the Price Canyon fire that burned in Southern Utah on June 30, 2002 (Thomas and Vergari 2002) using the FARSITE fire area simulator. The first assumed a constant wind speed and direction for the time period of interest based on measurements obtained from remote weather stations in the vicinity. The increase in fire size over time is displayed by the fire perimeters (fig. 8). As in most naturally burning fires, the only method for comparing the accuracy of fire spread and growth simulations is by comparing predicted fire perimeter at some point in time to that recorded from either infrared images, observations from over flights, or witness accounts. In this case the fire growth predictions for the conditions on June 30 are compared to the final fire perimeter published by the incident review team (Thomas and Vergari 2002). As shown in the image there is significant under prediction of the fire growth on the north edge of the fire and over prediction of fire growth on the southern edge of the fire. A second set of simulations were completed using gridded wind data for the same period keeping all other factors the same (fig. 9). Agreement between the actual and predicted final fire perimeters is much better. The discrepancy between predicted and actual perimeters on the right (west) edge of the fire area is due to a burnout operation that was conducted by the firefighters, and was not simulated in the FARSITE runs. While these initial test cases are not conclusive they suggest that surface wind modeling based on commercial CFD software captures variations in wind speed and direction at the 100 m scale and that wind information at this scale increases the accuracy of short term (< one day) fire growth simulations.

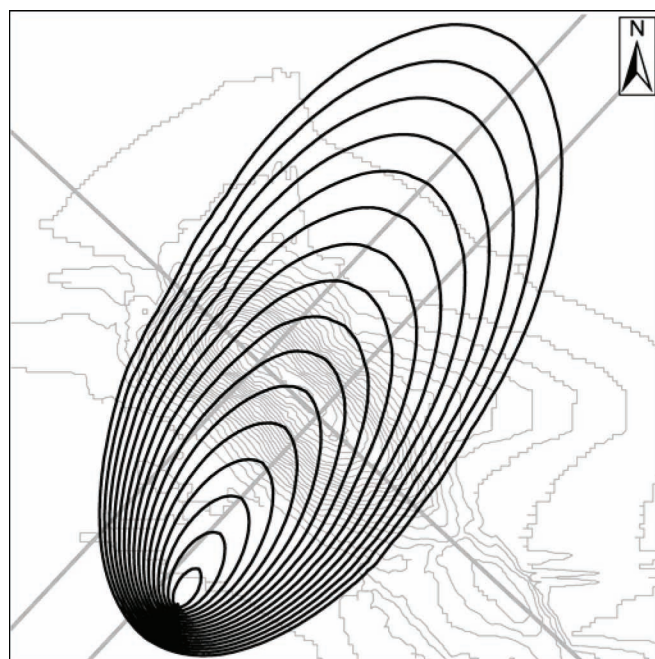


Figure 6. FARSITE fire area growth simulation assuming uniform wind speed and direction.

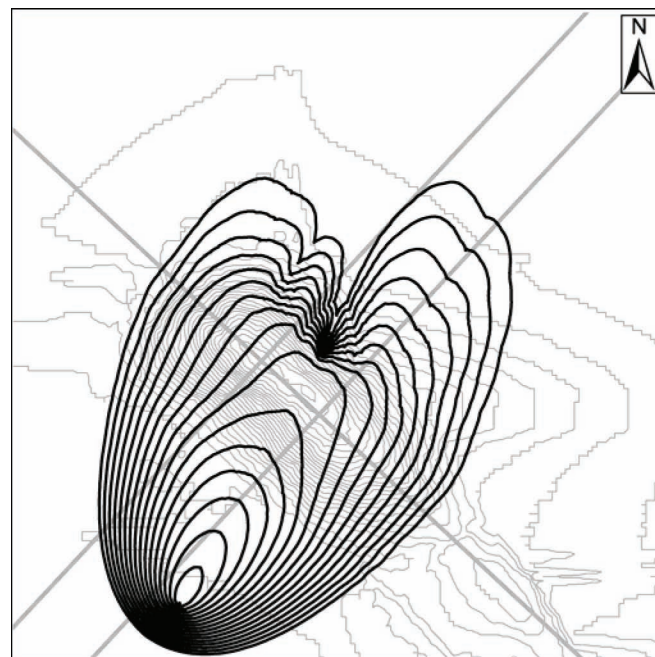


Figure 7. FARSITE fire area growth simulation using gridded wind simulation.

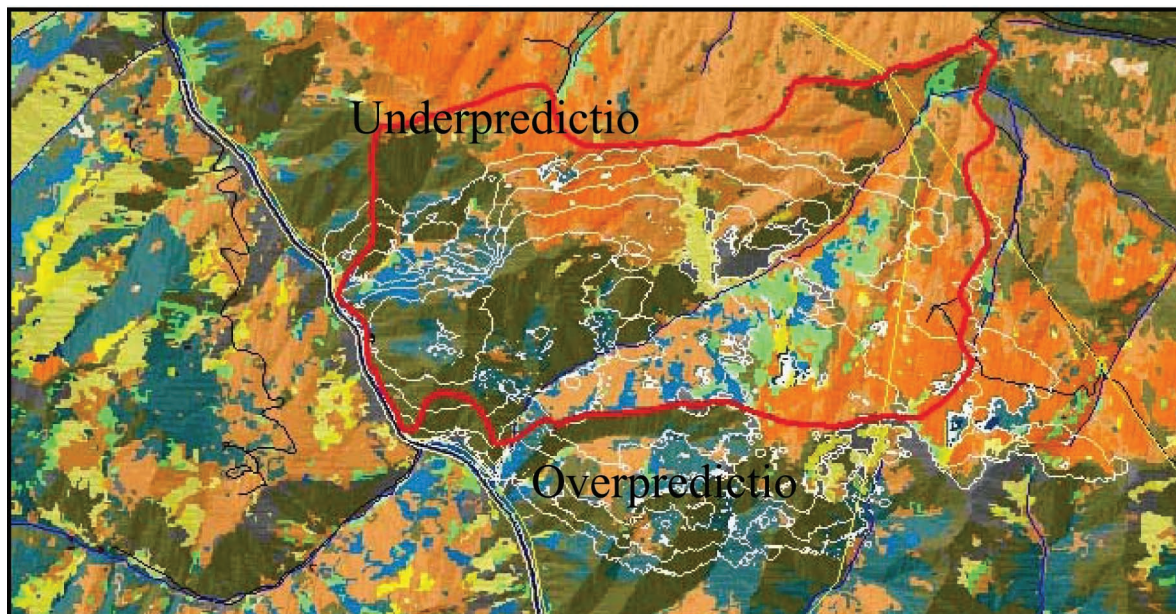


Figure 8. FARSITE simulation of the Price Canyon Fire assuming uniform wind speed and direction from the left to right (west winds). White lines represent successive fire perimeters produce from the FARSITE simulation, heavy red line represents actual final fire perimeter. Fire started on the extreme left edge of the perimeter along the railroad on the canyon floor.

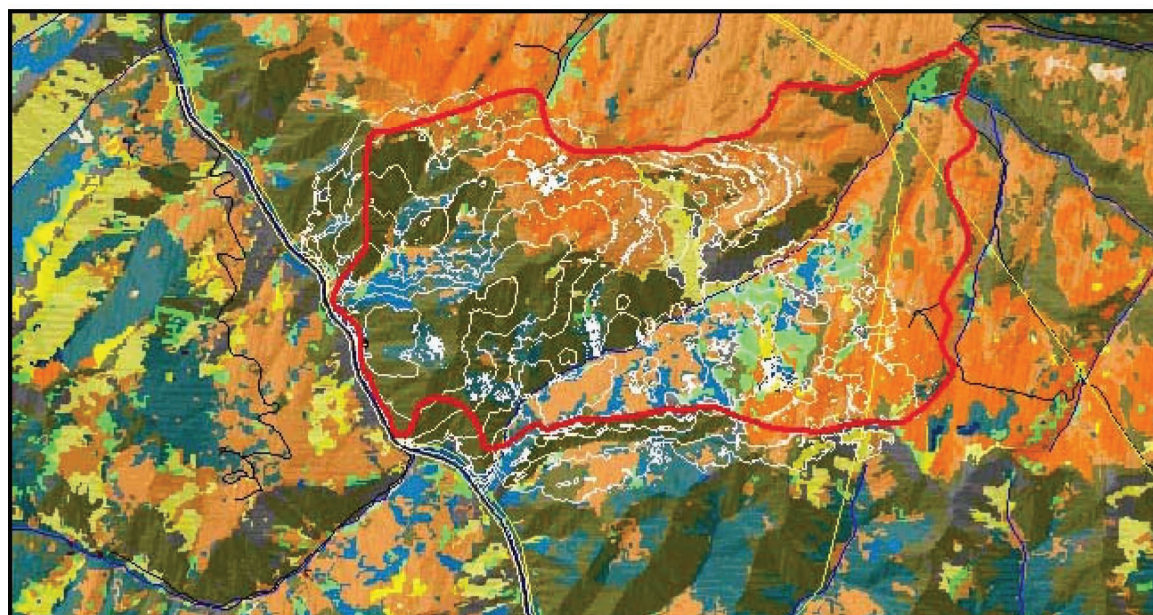


Figure 9. FARSITE simulation of the Price Canyon Fire using gridded wind data from CFD-based simulation. General wind flow input to CFD was from the left to right (west winds). White lines represent successive fire perimeters produce from the FARSITE simulation, heavy red line represents actual final fire perimeter. Fire started on the extreme left edge of the perimeter along the railroad on the canyon floor.

Conclusions

The CFD-based methodology for simulating the influence of terrain on surface wind flow represents a new technology, at least from a fire management perspective. Research efforts over the past two years have demonstrated that this technology, termed gridded wind, can provide highly detailed wind speed and direction information in time frames suitable for use by fire incident management teams (Price Canyon Fire-Thomas and Vergari 2002; Hayman Fire- Graham 2002). Although computationally intensive, the process has been refined so that a typical solution (10 to 100 m resolution wind speed and direction) on a grid measuring 40 by 40 kilometers can be completed in a matter of two to three hours using a laptop computer.

The accuracy of the wind simulations has been evaluated by comparing gridded winds against measured wind averages at discrete points. The results indicate general agreement and that the simulated gridded wind speeds and directions are most accurate for pressure gradients such as cold fronts, Foehn (Santa Ana), onshore/offshore winds and are less accurate for the low speed density driven flows such as those associated with diurnal heating and cooling of the earth's surface.

Gridded winds are simulations not forecasts. They are simulations of what the wind flow would be under different general (synoptic) wind scenarios. Gridded wind information has been used to identify areas and/or conditions that may produce high fire intensity and spread rates and for identifying locations where fire spotting might occur. Comparison of fire growth simulations using the FARSITE fire growth simulator with and without gridded wind information have demonstrated that the accuracy of short range (< one day) fire growth predictions is significantly higher using gridded wind than without it.

Acknowledgments

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