

A landscape-scale wildland fire study using a coupled weather-wildland fire model and airborne remote sensing

Janice L Coen^{A C}, Philip J Riggan^B

^A National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO, 80301, USA,
janicec@ucar.edu

^B U.S. Forest Service, Pacific Southwest Research Station, Forest Fire Laboratory, 4955 Canyon Crest Drive, Riverside, California, 92507, USA, priggan@fs.fed.us

^C Corresponding author. E-mail: janicec@ucar.edu

Abstract

We examine the Esperanza fire, a Santa Ana-driven wildland fire that occurred in complex terrain in spatially heterogeneous chaparral fuels, using airborne remote sensing imagery from the FireMapper thermal-imaging radiometer and a coupled weather-wildland fire model. The radiometer data maps fire intensity and is used to evaluate the error in the extent of the simulated fire perimeter and to reveal dynamically active regions of the fire fronts, their intensity, and their depth. The simulations use a numerical weather prediction model tied to a fire behavior model to simulate fire growth, its impact on the atmosphere through heat release, and the feedback of these fire-induced winds on fire behavior. The model was initialized with a regional weather simulation and fuel mapping data enhanced by additional sources to examine the meteorological flow in the vicinity of the wildfire, the fire growth and interaction with the atmospheric flow, and compare with airborne measurements collected during the first days of the fire. Model results capture the rapid spread to the east-southeast, flank runs up canyons, bifurcations of the fire, and rough agreement in area, shape, and spread direction. The west-southwesterly spread of the fire and acceleration of winds near the surface result from complex, transient, three-dimensional atmospheric wave dynamics that transport higher momentum east-northeasterly winds down to the surface in combination with other topographic dynamic effects.

Additional keywords: fire behavior, fire mapping, coupled atmosphere-fire model

Introduction

This work examines our current ability to model landscape-scale wildland fires using a coupled weather-wildland fire model. Computer simulations with the Coupled Atmosphere-Wildland Fire-Environment (CAWFE) model tie numerical weather prediction models to fire behavior models to simulate the impact of a fire on the atmosphere and the subsequent feedback of these fire-induced winds on fire behavior - i.e. how all fires, to some degree, 'create their own weather'. Here we describe simulations of the October 2006 Esperanza wildfire, which was ignited near Cabazon, California, and spread during a moderate Santa Ana wind event through chaparral and coastal sage vegetation along the northern flank of the San Jacinto Mountain range. We present simulations and sample airborne infrared imagery with which detailed comparisons are being made.

Background

The Esperanza wildfire was ignited on October 26, 2006 at 0112 local time in a river wash outside Cabazon, California, during a Santa Ana event at the upwind edge of the San Jacinto mountain range. It spread rapidly uphill to the west-southwest under the influence of steep slopes, dry flammable brush, single-digit relative humidity, and gusty winds, burning approximately 9700 ha in 18 hrs (Esperanza Fire investigation Team 2007). Winds measured nearby in Banning Pass (a west-east oriented pass between the San Jacinto and San Bernardino mountain ranges) were easterly with average velocity of 6-10 mph and gusts of 20-25 mph. By containment on October 30, 2006, the fire had burned approximately 16300 ha (40,200 acres).

Model description

The CAWFE modeling system contains two parts: a numerical weather prediction model and a fire behavior model that simulates the growth of a wildfire in response to weather, fuel conditions, and terrain (Clark *et al.* 2004; Coen 2005). These are two-way coupled so that heat and water vapor fluxes from the fire alter the atmospheric state, notably producing fire winds, as the evolving atmospheric state and changes in humidity (including effects from the fire) simultaneously affect fire behavior, notably how fast and in what direction the fire propagates. This wildfire simulation model can thus represent the complex interactions between a fire and the atmosphere.

a. Atmospheric model

The meteorological model is a three-dimensional non-hydrostatic numerical model based on the Navier-Stokes equations of motion, a thermodynamic equation, conservation of mass equations using the anelastic approximation, and equations for conservation of several phases of water vapor, summarized previously in Clark (1979) and Clark and Hall (1991). Vertically stretched terrain-following coordinates allow the user to simulate in detail the airflow over complex terrain. The numerical weather prediction model is capable of modeling fine scale atmospheric flows (horizontal resolution of 10s-100s of m) in very steep terrain where the inclination may exceed 30°. Forecasted changes in the larger-scale atmospheric environment are used to initialize the outer of several nested domains and update lateral boundary conditions. Two-way interactive nested grids capture the outer forcing domain scale of the synoptic-scale environment while allowing the user to telescope down to tens of meters near the fireline through horizontal and vertical grid refinement. Weather processes such as the production of cloud droplets, rain, and ice are parameterized using standard cloud microphysical treatments (Clark *et al.* 1996).

b. Fire model

Because the modeling system is trying to represent fires at spatial and temporal scales too coarse to simulate combustion, the wildland fire component of the model treats these subgrid-scale processes with parameterizations and semi-empirical relationships.

One algorithm defines the burning region within each grid cell. At the surface, each atmospheric grid cell is further divided into two-dimensional fuel cells with fuel physical characteristics and fuel loads specified by the user, the defaults being those of the 13 standard fuel models (Anderson 1982). Four points within each cell (called tracers) make up a quadrilateral that contains the burning region of the cell. Together with neighboring cells, these

define the fire front, which is the interface between burning and unburned fuel. A local contour advection scheme assures consistency along the fireline.

Another algorithm relates fire properties such as rate of spread to local wind, terrain slope, and fuel characteristics through the Rothermel (1972) surface-fire algorithms. Fire spread rates are calculated locally along the fire front as a function of fuels, wind speed and direction from the atmospheric model (which includes the effects of the fire), and terrain slope.

A third algorithm implements a canopy fire model that calculates the energy used to heat and dry any canopy above a surface fire. The canopy is ignited if the residual heat flux, after heating and drying the canopy, exceeds a specified threshold value. Any canopy fire is assumed to remain collocated with the surface fire.

A fourth algorithm treats the post-frontal heat release rate (Albini, 1994) which characterizes how the fire consumes fuels of different sizes with time after ignition, distinguishing between rapidly consumed grasses and slowly burned logs.

A simple radiation treatment distributes the sensible and latent heat and smoke into the

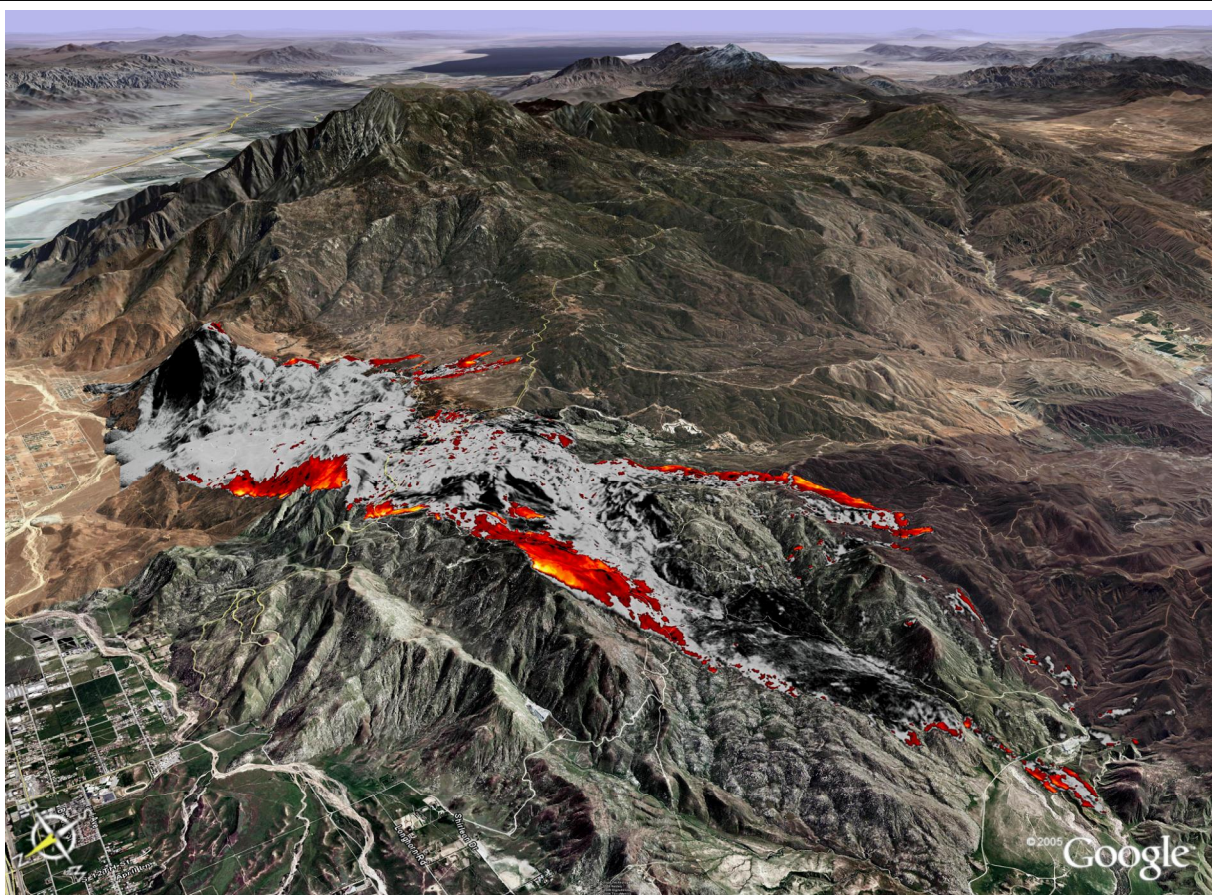


Fig. 1. Esperanza Fire, Riverside County, California, as viewed from the northwest at 11:15 local time, 26 October 2006, by the FireMapper thermal imaging radiometer. Color-coded surface temperatures, which reflect fire intensity, are shown as imaged in the thermal infrared and displayed in Google Earth. Here a moderate Santa Ana wind is driving the fire to the southwest through light fuels and chaparral.

lowest atmospheric grid levels. The e-folding height over which the heat is distributed is specified by the user – typically 10 m for grass fires and 50 m for crown fires, based on analysis of fire observations (Clements *et al.* 2007; Coen *et al.* 2004).

The fire behavior is coupled to the atmospheric model: low level winds drive the spread of the surface fire, which releases sensible heat, latent heat, and smoke into the lower atmosphere, in turn feeding back to affect the winds directing the fire. Although this influence is most dramatic near the fire, model simulations show this influence can change the wind speed by several kilometers per hour even kilometers from the fire (Coen 2005).

Case study

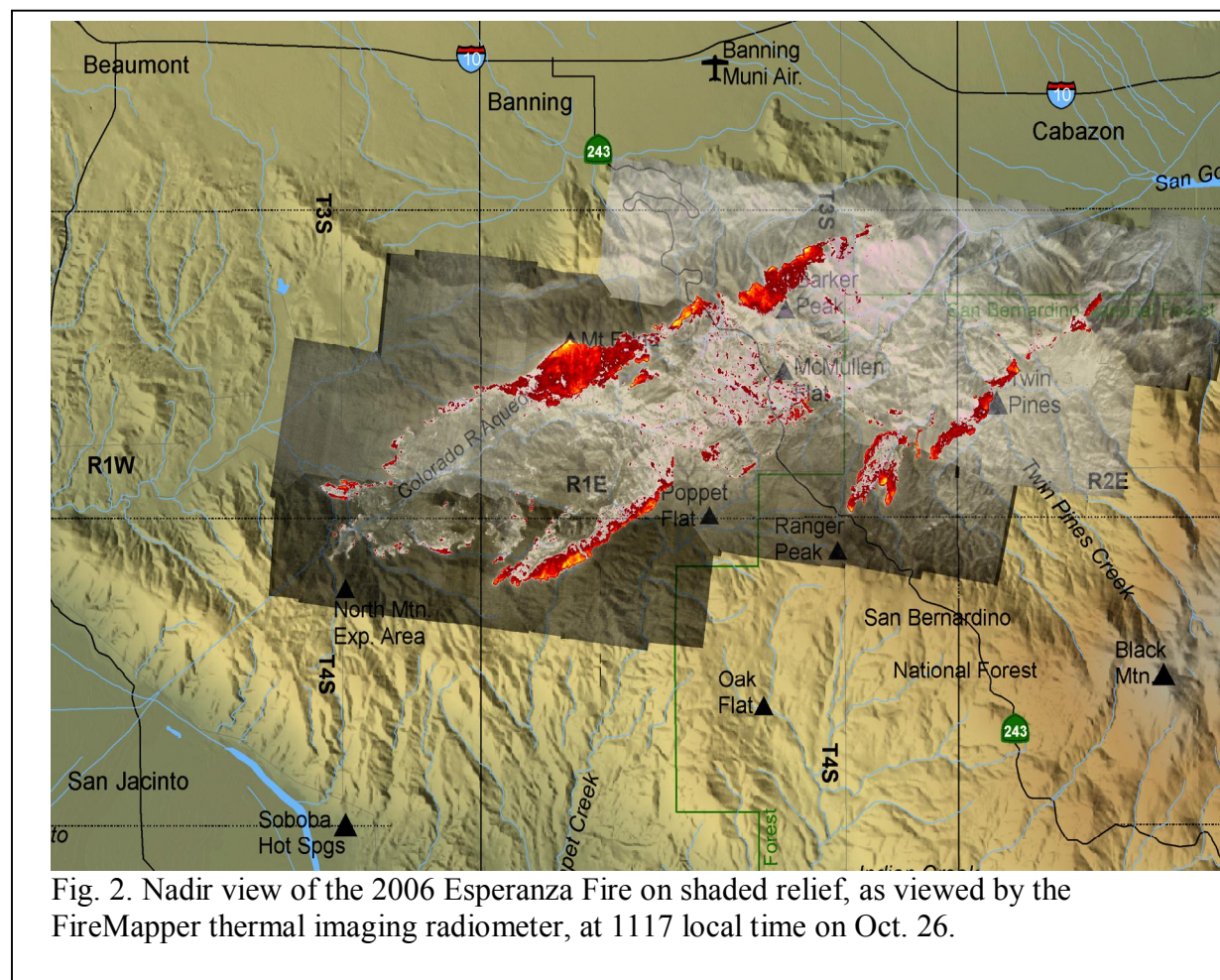
A 10-km horizontal resolution 48-hr MM5 mesoscale simulation of the region initialized at October 26 2006 0 Z (October 25 2006 1700 local time) was used to initialize the finer resolution CAWFE. This was done by interpolating the MM5 forecast state onto the CAWFE three-dimensional grid at the time the finer-scale CAWFE simulation starts and used at later times in the MM5 simulation to specify the boundary conditions of the CAWFE domain.

CAWFE terrain used 1 or 1/3 arcsec terrain data (USGS 2010), smoothed with a pass of a 1-2-1 bidirectional filter to remove high frequency noise. The distribution of fuel models was taken from the LANDFIRE Fire Behavior Fuel Models data server (LANDFIRE 2010). The characteristics for the fuel types used, primarily grass (Fuel Model 1), shrubs (Fuel Model 4), and forest litter, were adjusted based on local on-site measurements (Weise *et al.* 2005). We simulated 17 hrs of weather and fire behavior beginning at October 25, 2006, at 2100 local time. CAWFE refined the resolution from 10.0 km horizontal resolution in the coarsest domain to 3.33 km, 1.11 km, 0.370 km, and 0.123 km in the finest resolution domain, with corresponding refinement in the vertical grid. We examined the meteorological flow in the vicinity of the Santa Ana-driven Esperanza wildfire, modeled the fire growth and interaction with the atmospheric flow, and compared with measurements collected during the first day of the fire.

Airborne fire remote sensing

The Pacific Southwest Research Station of the U. S. Forest Service develops and applies specialized remote-sensing systems to measure and understand wildfire behavior and impacts in the environment and provide fire intelligence needed to improve fire suppression operations, fire-fighter safety, and strategic fire management. One such system, the airborne FireMapper thermal-imaging radiometer, employs a BAE Systems microbolometer focal-plane array with two levels of onboard calibration to measure and map thermal radiation across a wide range of radiances in a broad-band channel encompassing wavelengths from 8 to 12.5 mm and narrow-band channels at 8.8 to 9.1 and 11.3 to 12.4 mm. The narrow-band channels each provide unsaturated data over large wildland fires. Images of wildland fires have been transmitted by satellite communications, geo-referenced to a map base, assembled into photo mosaics, and displayed via the Internet at <http://www.fireimaging.com> to provide fire fighting personnel with a current, detailed, and synoptic view of fire spread and activity. During the Esperanza Fire, the California Department of Forestry's incident command used FireMapper imagery in part to visualize and predict active fire spread so as to prioritize deployment of firefighting resources and to direct mop up during latter stages of the fire. The imagery also has provided unprecedented measurements of the behavior of a wildland fire under the influence of Santa Ana winds.

The upwelling radiation from wildland fires is comprised of emissions from a complex of high temperature flames, ash, residual flaming combustion, smoldering of larger biomass elements and unburned vegetation. Radiation from flames, which are of high temperature but low emissivity, is thought to be dominant in the remote sensing signal at short-wave infrared wavelengths. At long-wave infrared wavelengths, as measured by the FireMapper, radiation from fire fronts is likely dominated by emissions from lower temperature –yet very hot– ash of high emissivity (Riggan and Tissell 2009). Thus, FireMapper imagery depicts not only the location of fire fronts, but based on the temperature of the underlying ground surface, provides a measure of the fire's intensity. The duration of high temperatures behind the fire front reflects the sum of energy absorbed and emitted from the ground surface, so that the breadth of high temperature zones along a fire perimeter provides an indication of the amount of consumed fuel in the area. For more details on mapping of the fire and fuels with this instrument in this and other fires, see Riggan *et al.* (2010).



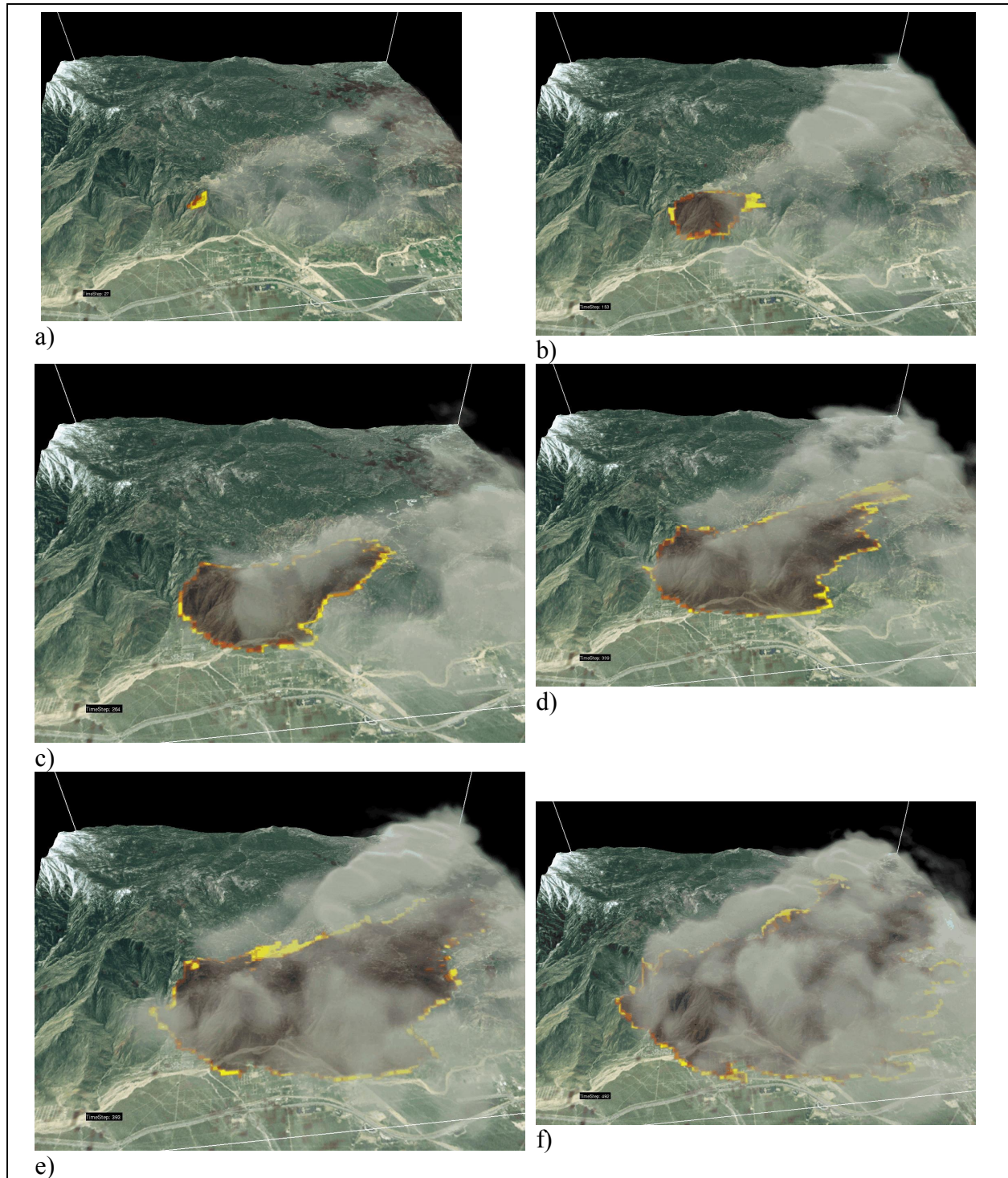


Fig.3. View toward south. Cabazon, CA, is in the foreground. Simulation on Oct. 26 at a) 0127, b) 0333, c) 0524, d) 0639, e) 0733, and f) 0923 local time. The misty field is smoke, colored by concentration. Higher concentrations are darker and more opaque. The colors identifying the burning areas correspond to radiant temperature color bar in Fig. 1. (brighter colors like yellow: higher surface fire sensible heat fluxes; darker browns: lower fluxes). Another field on the surface is the 'fuel load remaining'. Where the fire has passed, the surface is dark brown. Boxiness to the fireline shows the atmospheric grid sizes onto which the fire fluxes on the fire fuel cell scale (5x5 in each atmospheric cell) have been summed.

Results

At the time of the first observation at 1117, the primary run of the Esperanza Fire had traveled 16.5 km to the west-southwest (WSW) from the point of ignition. The primary run encountered vegetation there that was 6 to 10 years old and displayed little energy release as evidenced by low observed temperatures at the front of the fire line and lack of continuity across areas of elevated surface temperature. Substantial temperatures were evident primarily on north-facing aspects and higher productivity vegetation along the north flank of the fire and in vegetation older than 50 years in the southwest of the perimeter. A separate fire run developed in the southeast; it may have been isolated by fire fighting action and cleared ground in the vicinity of structures along Twin Pines Road. Other isolated runs with the wind were initiated along the southern flank of the fire such as immediately east of the main head of the fire in vegetation

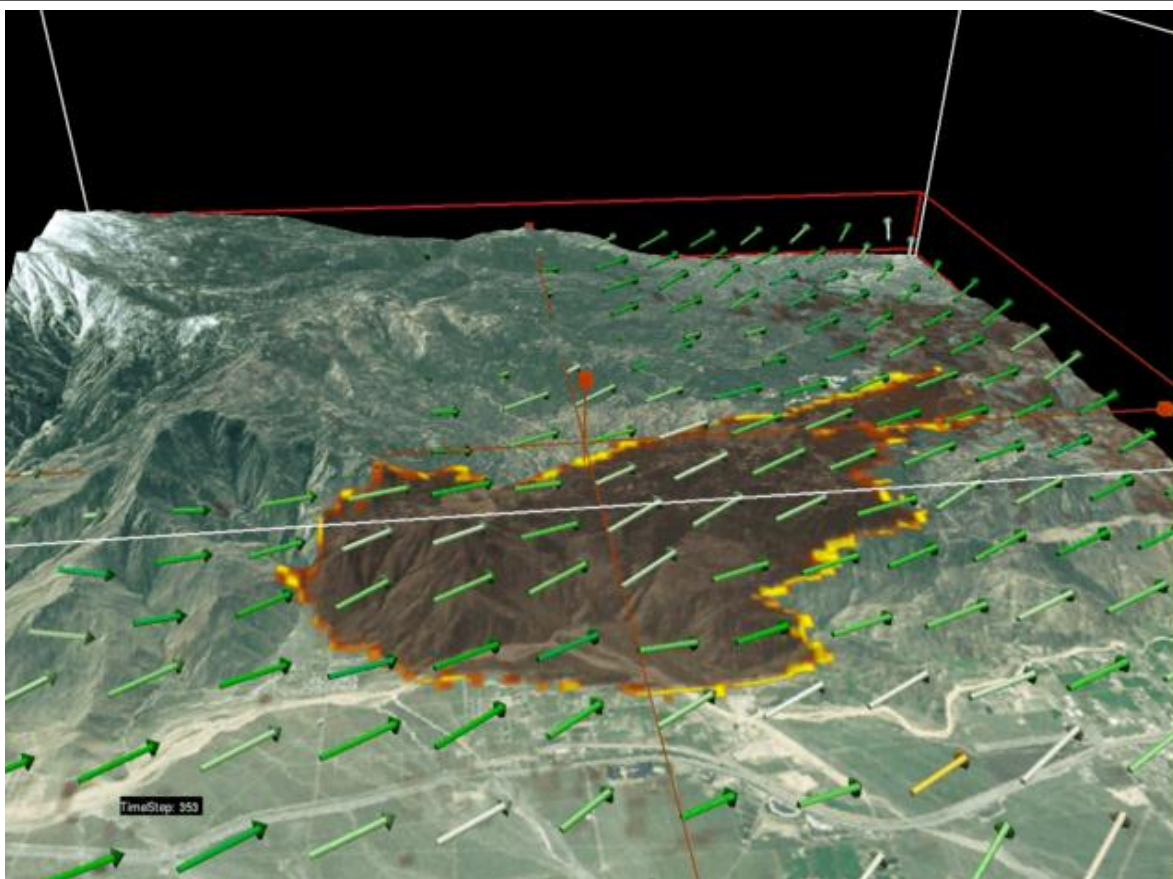


Fig. 4. The simulation at 0652 local time. The fire heat fluxes and fuel remain the same as Fig. 3. The vectors show the winds at a constant elevation 1500 m above sea level. The length and direction of the vectors show the strength and direction of the horizontal winds. The colors superimposed on the arrows represent the vertical velocity: white is 0, warm colors (yellow to orange to red) reveal updrafts, cold colors (green increasing to blue increasing to violet) represent downdrafts. Over the fire area, the arrows are greenish, which is interpreted as a slight downdraft at this elevation. Some areas are mostly white, which means there is no up or down component there. A few vectors near lower right and sometimes over Cabazon Peak (center left) show upward motion.

older than 50 years. Little long-range fire spread by development of spot fires was evident at the head of the fire. Only one spot fire, disconnected from the fire front, was observed and that was located only 90 meters ahead of the front. This imagery is shown in Figs. 1 and 2.

The simulated airflow during the incident was complex. As expected in a typical Santa Ana event, winds turn counterclockwise with height, such that surface winds in the pass were easterlies and at the elevation of the fire were northeasterly. Compounding that, there were

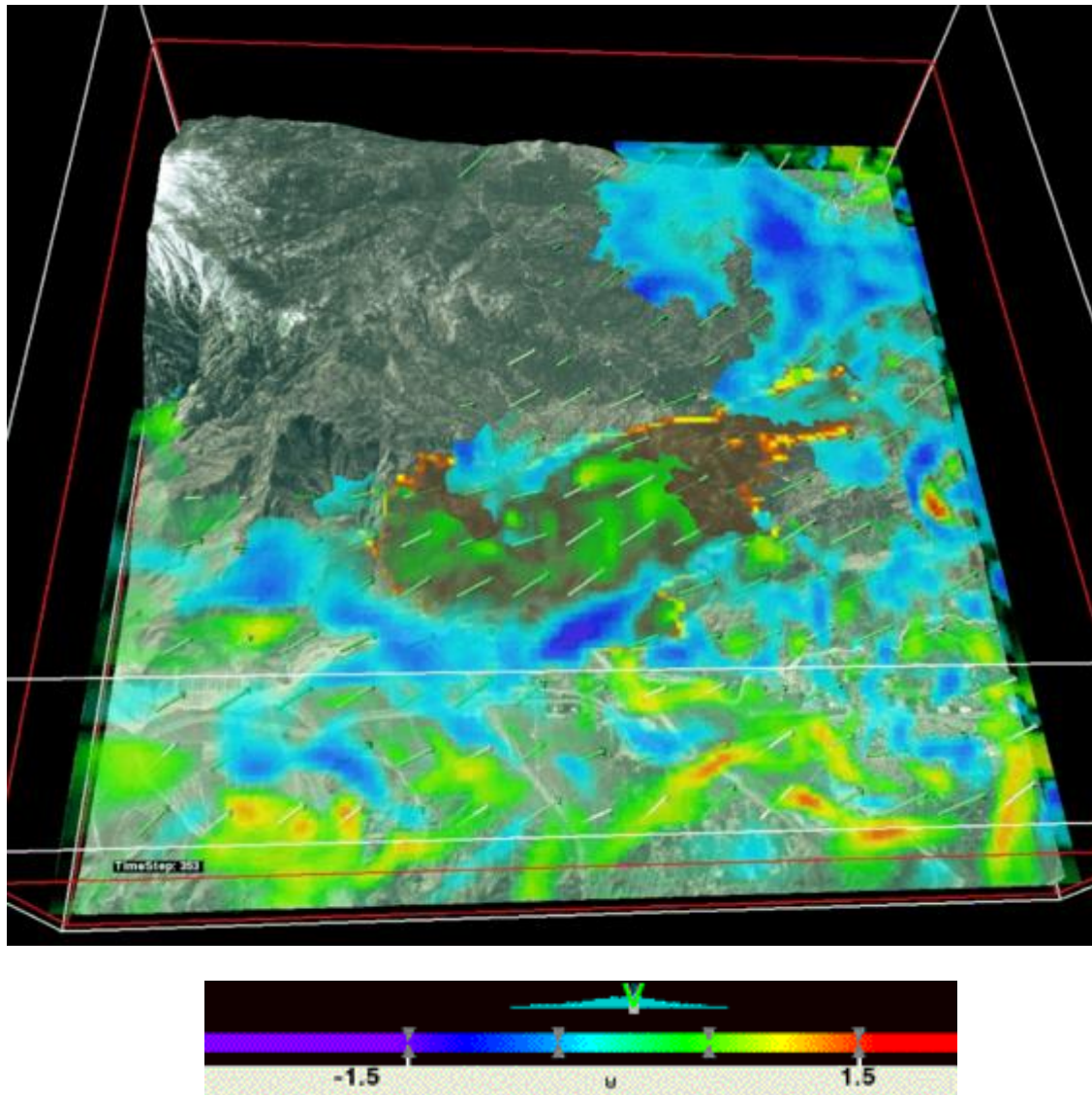


Fig. 5. In this image at 0653 local time, a contour of the vertical velocity field (see legend, values in m s^{-1}) at 1500 m is superimposed and shows the transience in the terrain-induced gravity waves from upstream San Bernardino mountain range encountering the San Jacintos, complicated by smaller-scale terrain features, shear-generated motions, and convection generated by the fire.

complicated three-dimensional terrain induced flow effects, including gravity waves bringing higher-momentum east-northeasterly airflow from upper levels down to the fire. Moreover, these effects varied in time and space, as the locations of the updrafts and downdrafts moved and evolved as the Santa Ana event moved and altered the wind direction with respect to the terrain ridges and local topographic features.

The simulated fire behavior captured the rapid spread to the WSW and had rough agreement in area, breadth, shape, and direction of spread at periods for which fire location data were available, although it overestimated the rate of spread over the first 10 hours by arriving 2 hours early. The simulated fire spread out onto the low elevations of Banning Pass because firefighting efforts to hold line there were not simulated. Simulations capture flank runs up canyons, bifurcations of the fire into two heads, and feathering into fingers in sparse fuels at the leading edge of the fire which can surround features and rejoin. The simulated fire progression and smoke is shown in Fig. 3. Secondly, results show that the acceleration of winds near the surface can be understood as resulting from complex three-dimensional atmospheric wave dynamics (Figs. 4 and 5) set up by the Santa Ana events flowing over upstream mountain ranges that are a common component of many of the largest fires in this fire-prone region. As in the airborne remote sensing observations, the most intense burning areas simulated were along the flank of the fire, where we see flank ‘runs’ that were supported by satellite and aircraft imagery.

Discussion

It is significant that the simulations captured WSW spread of the fire because all available surface stations (the standard mechanism for predicting fire growth), located at lower elevations in Banning Pass, measured easterlies due to the west-east orientation of the pass and backing of winds with height in standard Santa Ana flow. We note this is not a matter of terrain extending up into elevations where winds were stronger, but a result of atmospheric gravity waves bringing the higher-momentum ENEly air down to the surface. It is encouraging to capture many elements of the phenomenology of fire spread in a landscape scale fire where the weather, terrain, and fuels are so complicated. We think the rate of spread at the head and flanks could be overestimated due to a number of factors, including errors in the large-scale forecast, errors due to assumptions in the vertical interpolation of winds from the current lowest CAWFE model level (67 m) to the height of the fuel, errors in representing the fuel available for burning, conceptual errors in using a rate of spread calculation designed for a heading fire at all points along the fire front, and the conceptually difficult assessment of which wind elevation and location relative to the fire to use for calculation of fire rate of spread. Even with these very high-resolution simulations, it is still undetermined what effect even finer unresolved terrain features, such as small drainages, which are common in this area, had on the airflow directing the fire.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants No. 0324910, 0421498, and 0835598. The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We thank collaborators Charles Jones for the MM5 simulation used to initialize these simulations and Francis Fujioka, David Weise, and Shyh-Chin Chen (USDA Forest Service Riverside Fire Laboratory) for their insights and

comments. Trade names, commercial products, and enterprises are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

References

- Albini FA (1994) PROGRAM BURNUP, 'A simulation model of the burning of large woody natural fuels.' Final Report on Research Grant INT-92754-GR by USDA FS to Montana State University, Mechanical Engineering Dept.
- Anderson HE (1982) 'Aids to determining fuel models for estimating fire behavior.' USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-122. (Ogden, UT)
- Clark TL, Coen J, Latham D (2004) Description of a coupled atmosphere-fire model. *International Journal of Wildland Fire* **13**, 49–64.
- Clark TL (1979) Numerical simulations with a three-dimensional cloud model: lateral boundary condition experiments and multi-cellular severe storm simulations. *Journal of Atmospheric Sciences* **36**, 2191-2215.
- Clark TL, Hall WD (1991) Multi-domain simulations of the time dependent Navier Stokes equations: Benchmark error analyses of nesting procedures. *Journal of Computational Physics* **92**, 456-481.
- Clark TL, Hall WD, Coen JL (1996) Source code documentation for the Clark-Hall Cloud-scale model: Code version G3CH01. The National Center for Atmospheric Research (NCAR) Technical Note. NCAR/TN-426+STR. 174 pp.
- Clements CB, Zhong S, Goodrick S, Li J, Potter BE, Bian X, Heilman WE, Charney JJ, Perna R, Jang M, Lee D, Patel M, Street S, Aumann G (2007) Observing The Dynamics Of Wildland Grass Fires: FireFlux: A Field Validation Experiment. *Bulletin of the American Meteorological Society* **88**, 1369-1382.
- Coen JL, Mahalingam S, Daily JW (2004) Infrared imagery of crown-fire dynamics during FROSTFIRE. *Journal of Applied Meteorology* **43**, 1241-1259.
- Coen JL (2005) Simulation of the Big Elk Fire using coupled atmosphere-fire modeling. *International Journal of Wildland Fire* **14**, 49–59.
- Esperanza Investigation Team (2006) Esperanza Fire Accident Investigation Factual Report, Riverside County, California. [Online]. Available at http://www.fire.ca.gov/fire_protection/downloads/esperanza_00_complete_final_draft_05_01_2007.pdf. (Verified 12 December 2010)
- Riggan PJ, Wolden LG, Cissel RG, Coen J (2010) Remote sensing fire and fuels in southern California. In 'Proceedings of 3rd Fire Behavior and Fuels Conference,' October 25-29, 2010, Spokane, Washington. (Ed DD Wade). CD ROM. International Association of Wildland Fire.(Birmingham, AL)14 pp.
- Riggan PJ, Tissell RG (2009) Airborne remote sensing of wildland fires. Chapter 6. In: 'Wildland Fires and Air Pollution, Developments in Environmental Science, Volume 8.' (Eds A Bytnerowicz, M Arbaugh, A Riebau, and C Andersen) pp. 139-168. (Elsevier: Amsterdam).
- Rothermel RC (1972) 'A mathematical model for predicting fire spread in wildland fuels.' USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115. (Ogden, UT)