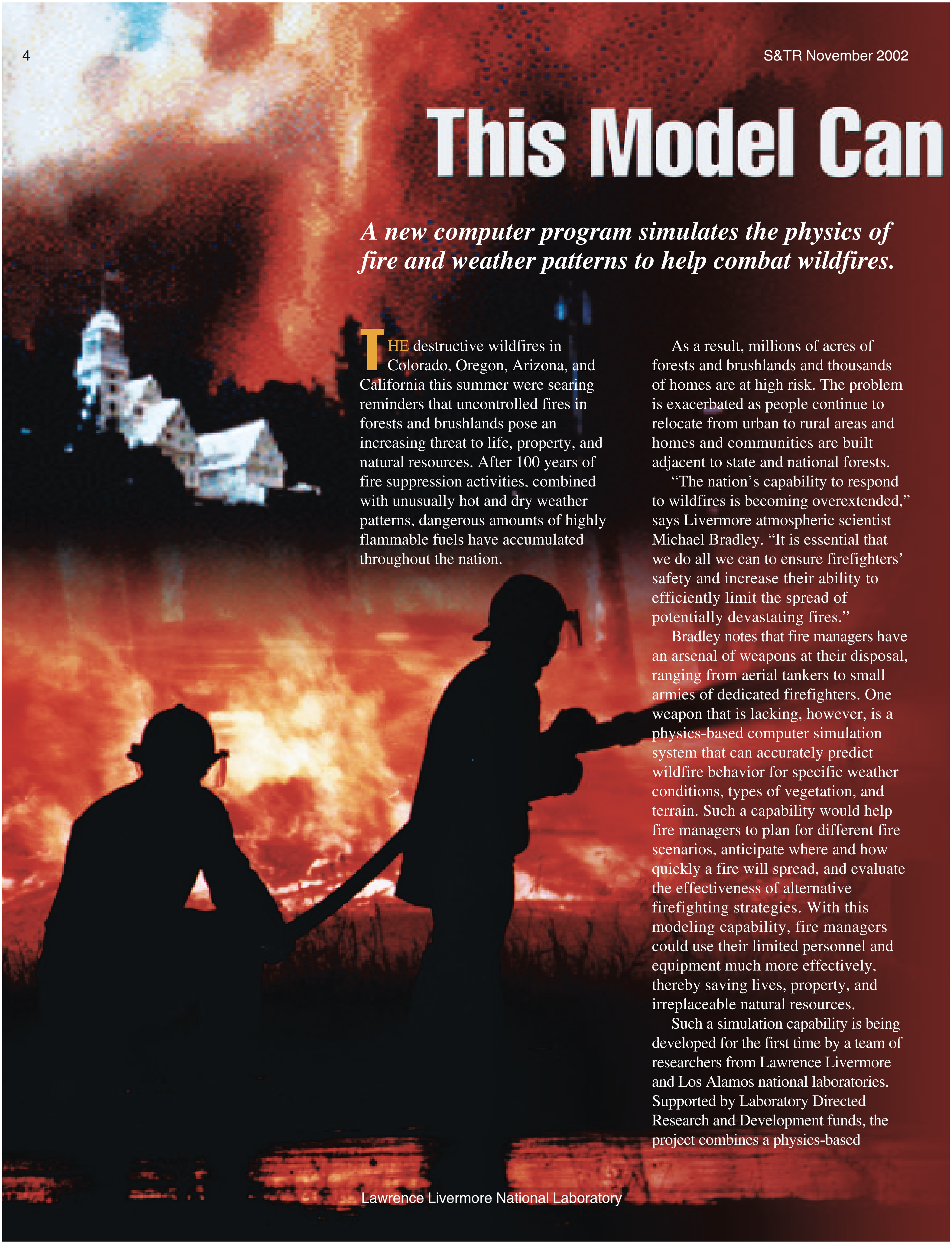


This Model Can

A new computer program simulates the physics of fire and weather patterns to help combat wildfires.

THE destructive wildfires in Colorado, Oregon, Arizona, and California this summer were searing reminders that uncontrolled fires in forests and brushlands pose an increasing threat to life, property, and natural resources. After 100 years of fire suppression activities, combined with unusually hot and dry weather patterns, dangerous amounts of highly flammable fuels have accumulated throughout the nation.

As a result, millions of acres of forests and brushlands and thousands of homes are at high risk. The problem is exacerbated as people continue to relocate from urban to rural areas and homes and communities are built adjacent to state and national forests.

"The nation's capability to respond to wildfires is becoming overextended," says Livermore atmospheric scientist Michael Bradley. "It is essential that we do all we can to ensure firefighters' safety and increase their ability to efficiently limit the spread of potentially devastating fires."

Bradley notes that fire managers have an arsenal of weapons at their disposal, ranging from aerial tankers to small armies of dedicated firefighters. One weapon that is lacking, however, is a physics-based computer simulation system that can accurately predict wildfire behavior for specific weather conditions, types of vegetation, and terrain. Such a capability would help fire managers to plan for different fire scenarios, anticipate where and how quickly a fire will spread, and evaluate the effectiveness of alternative firefighting strategies. With this modeling capability, fire managers could use their limited personnel and equipment much more effectively, thereby saving lives, property, and irreplaceable natural resources.

Such a simulation capability is being developed for the first time by a team of researchers from Lawrence Livermore and Los Alamos national laboratories. Supported by Laboratory Directed Research and Development funds, the project combines a physics-based

Take the Heat

wildfire model developed at Los Alamos with the extensive emergency response capabilities of the National Atmospheric Release Advisory Center (NARAC) at Livermore, including its weather prediction and smoke transport codes and Livermore's supercomputers. The effort combines the special capabilities and resources of the two laboratories, says Bradley, who leads the Livermore effort that also includes atmospheric scientists Charles Molenkamp and Martin Leach and geographical information systems (GIS) experts Charles Hall, Lee Neher, and Lynn Wilder.

Predicting wildfire behavior is not a new concept. The models most widely used by firefighters, however, are relatively unsophisticated programs based on data obtained by laboratory experiments, for example, the burn rate of pine needles in wind tunnels. Such experimental results for a variety of vegetative fuels are used in look-up tables to estimate burn rates based on the total amount of fuel, wind speed, and the slope of simplified two-dimensional terrain. The model is then used to predict wildfire behavior, guide firefighting tactics, and assist in training and planning.

"Current models do not account for the many complex physical processes that characterize real wildfires and determine their behavior," says Bradley. The models also don't reflect how the terrain and vegetation change (sometimes dramatically within a few meters), how the weather changes, and, perhaps most importantly, how the fire and weather continuously interact.

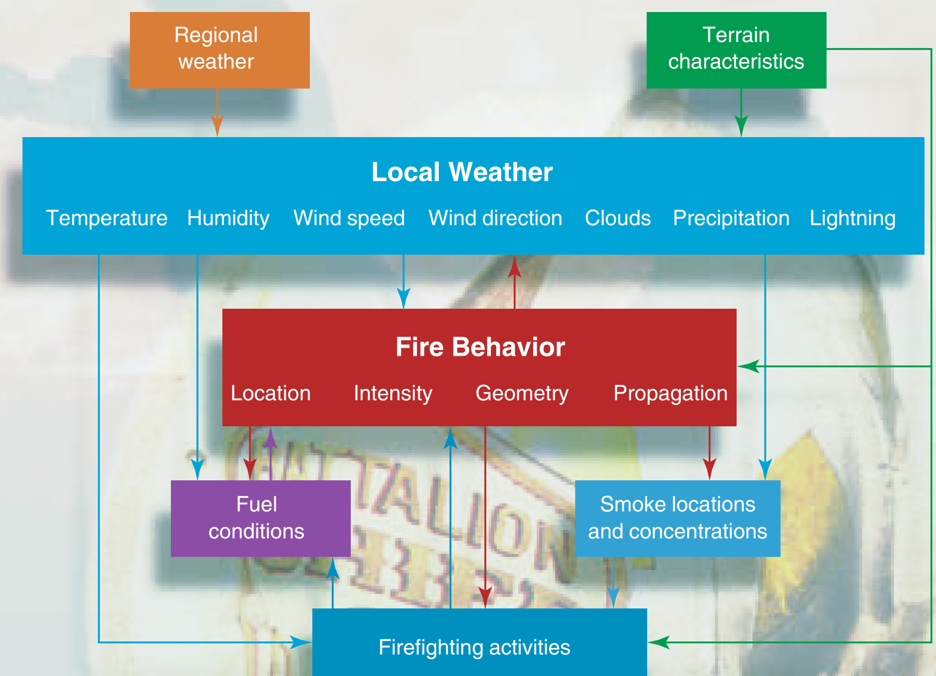
Winds, air temperature, humidity, and precipitation, for example, influence the flammability of fuel and largely determine the risk of fire ignition. In addition, wind speed and direction determine the rate of fire spread and the amount of transported embers from which new fires can be ignited. Weather conditions also determine the location and concentration of smoke plumes, which can interfere with ground and aerial firefighting operations and cause health hazards downwind.

In turn, the heat from wildfires causes rising air currents that strongly modify local weather patterns and create rapidly changing winds that may fan the fire. As a fire approaches, unburned vegetation preheats and dries and ignites more easily. All of these interacting physical processes are reflected by the Livermore–Los Alamos computer model.

Model Starts with FIRETEC

The basic fire-simulation code, called FIRETEC, has been developed over the past 7 years by a Los Alamos group headed by atmospheric scientist Rod Linn. The group experienced first-hand the destructive power of wildfires in 2000, when the Cerro Grande fire ripped through the Santa Fe national forest as well as parts of the town of Los Alamos and the Laboratory itself.

FIRETEC simulates the mechanisms of fire propagation in ways that far exceed the capabilities of wildfire models currently in use. FIRETEC predicts the spread of wildfires based on a fundamental treatment of physical processes such as combustion and turbulence and uses a terrain-following coordinate system based on digitized maps. It takes into account the two basic heating mechanisms of fire: the turbulent convective motion of heated air and the infrared radiation emitted by the fire. Using spatial resolutions of 1 to 10 meters, FIRETEC



Existing wildfire models, using data from isolated laboratory experiments, do not adequately represent the complicated, interactive processes of wildfires defined in this diagram.

also tracks the depletion of fuels and oxygen during combustion.

The code realistically represents the vegetation of an area, including the mixture of species, their densities, and their three-dimensional structure. Because the code includes a vertical fuel representation, it differentiates between grass, tree trunks, and tree crowns, thereby making simulations much more realistic. This degree of realism is needed because in some situations grass will burn without the fire spreading to tree crowns, whereas in other situations, the crowns ignite. In simple models, says Bradley, fuel is simply "flat," represented by a calculated number of tons of vegetation per acre, with no vertical structure.

To account for the interactions between fire and atmosphere, the Los Alamos group combined FIRETEC with the fine-resolution, high-gradient flow solver program known as HIGRAD, which was developed by Jon Reisner. HIGRAD delivers accurate atmospheric simulations at extremely high spatial (1 meter) and temporal (thousandths of a second) resolution.

HIGRAD, however, cannot represent the regional weather patterns within which wildfires burn. "HIGRAD simulates close-in air flow over small regions of a fire but does not take into account more remote weather processes such as cold fronts, high- and low-pressure systems, and precipitation that develop over much larger geographical areas," says Bradley.

Adding Regional Weather

To overcome this limitation, the team incorporated the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS), developed by the U.S. Naval Research Laboratory in Monterey, California, and later refined by NARAC scientists. COAMPS is run twice daily by NARAC to predict regional weather at scales ranging from about 1,000 kilometers down to a few kilometers. The Livermore wildfire team has run COAMPS using horizontal resolutions as fine as approximately 150 meters. COAMPS predicts winds, temperature, pressure, humidity, and precipitation for several days. The code is formulated in terrain-following coordinates, which are advantageous for atmospheric simulations over rugged terrain. "COAMPS provides the regional atmospheric environment within which HIGRAD–FIRETEC simulations run," explains Bradley.

He says that integrating HIGRAD–FIRETEC with NARAC's capabilities provides access to a wide range of resources that strengthen the wildfire simulation capability. These resources include a detailed global terrain database, global mapping system, global weather data acquisition system, and weather prediction systems. NARAC is supported by vast quantities of meteorological data that are collected daily—and sometimes hourly—from around the world.

NARAC also has the leading atmospheric smoke dispersion simulation model, called ARAC-3. Although the model was originally conceived to track radionuclide releases, the center can use it to respond to atmospheric releases of other materials, including toxic chemicals, biological agents, ash from volcanic eruptions, and, most relevantly for firefighting, smoke. Following Operation Desert Storm, NARAC provided twice-daily predictions of smoke dispersion from the burning oil wells in Kuwait. More recently, it predicted the dispersion of smoke from two massive tire-dump fires near Tracy and Wesley, California, from which smoke rose to almost 2,000 meters above ground level. (See *S&TR*, June 1999, pp. 4–11.)

Livermore also offers substantial supercomputer resources. Computer models that accurately predict the behavior of wildfires require enormous processing power that currently can only be provided by massively parallel

The Claremont Resort narrowly escaped destruction during the 1991 wildfire in the hills of Oakland and Berkeley, California.

supercomputers (machines using many processors in tandem). Wildfire simulations performed at Livermore, for example, typically use 64, 64-bit processors belonging to Livermore's TeraCluster2000 680-billion-operations-per-second (gigaops) supercomputer.

Modeling Threats and Responses

Throughout the simulation program's development, the Livermore–Los Alamos team has conferred with federal, state, and local fire managers. Many valuable suggestions have been incorporated into the program's capabilities, and several applications have emerged.

Two applications—wildfire preparedness planning and long-term planning for communities and wildland management—are available now. With adequate funding, three additional applications—analyzing specific fire threats, predicting fire behavior for prescribed burns, and training firefighters—could be ready next summer. The ultimate goal, real-time firefighting support, is several years away and awaits the development of even more powerful computers for faster turnaround.

The wildfire preparedness planning application permits realistic simulations of past or hypothetical future fires for specific locations, with high-resolution modeling of terrain, types of vegetation, and weather conditions. "This is a powerful tool for community fire preparedness planning," says Bradley.

The long-term planning application permits evaluation of vegetation management options such as thinning trees or designing fuel breaks. Such planning is especially important at the urban–wildland interface in determining the fire threat to new homes, commercial development, and open areas.

Fire behavior predictions for prescribed burns would be available to fire managers a few hours before they ignite the fuel. This advance knowledge would enable managers to decrease the risk of prescribed burns going out of control (such as happened with New Mexico's Cerro Grande wildfire) and of violating air quality standards.

Fire threat analyses would produce physics-based predictions of potential fire behavior for specific locations with a few days' notice. This feature would be particularly useful to fire managers in assessing the relative risks of fire breaking out at various locations during periods of increased threat.

As a training tool, the program would be unsurpassed at showing how different factors affect the behavior of wildfires. After specifying the exact ignition point of a fire, students could vary the weather, vegetation, fuel conditions, and firefighting methods to understand their effects. "We envision this application serving a role similar to that of a flight simulation program," says Bradley. "Students could make mistakes without risking their lives."

The program's ultimate goal is real-time support for firefighters. In this application, the program would help fire managers to make critical operating decisions regarding the deployment of firefighters and equipment. The program could also predict the relative effectiveness of various firefighting procedures, such as fuel breaks, backfires, air tanker fire-retardant drops, and helicopter water drops.

Model Validation Essential

The team has been validating the program by simulating well-

(a) East Bay Regional Parks ranger Bill Nichols (left) and Livermore researchers Charles Molenkamp (center) and Michael Bradley used global positioning system tools to determine for the first time the ignition points of the 1991 fire in the Oakland–Berkeley hills. (b) The ignition point for the second fire (which began Sunday, October 20, 1991) in Tunnel Canyon is circled.

documented wildfires. An early simulation using HIGRAD–FIRETEC successfully re-created the Corral Canyon wildfire that occurred in Calabasas, near Malibu, California, on October 22, 1996. The fire had been smoldering in the riparian (vegetation along a gully) area at the bottom of a canyon. It suddenly rushed up one side of the canyon, catching firefighters off guard and injuring several. The simulation re-creates the rapid spread of the fire, from the bottom of the drainage area to the crest of the hill, within 28 minutes, about the time the actual fire took. By comparison, a simulation of the same fire with a traditional model predicts that it would take about 6 hours to burn the same area. The difference between the two simulations is the interplay among the terrain, fire, and winds that is represented by HIGRAD–FIRETEC.

"Firefighters sometimes think they have a lot of time when they really don't," says Bradley. The Corral Canyon simulation showed that strong sea breezes channeled by the terrain pushed the fire up the hill much faster than the firefighters thought possible. The model also shows that if the riparian vegetation were replaced with dry grass, the fire spreads up both sides of the canyon. "The simulation results are encouraging because they compare so well with field observations," Bradley says.

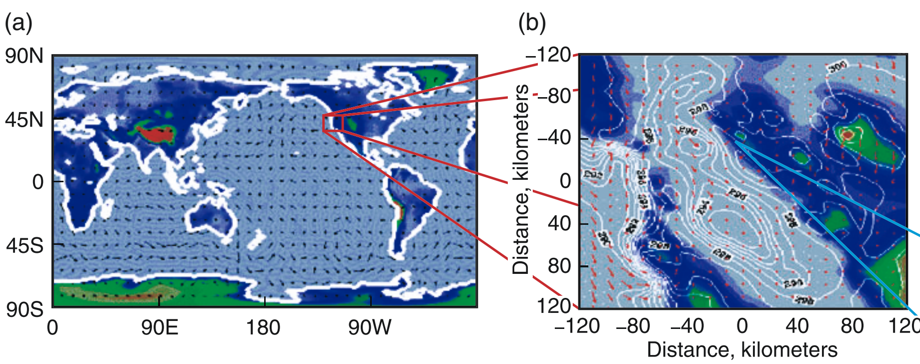
To provide a more exhaustive validation of the program's capabilities, Bradley and his group, together with Livermore GIS experts, have been reconstructing the early stages of the catastrophic 1991 fire in the hills of Oakland and Berkeley, California, and are looking at current fire dangers to neighborhoods that escaped the conflagration. Bradley is sharing the results with East Bay fire agencies, the city governments of Oakland, Berkeley, and El Cerrito, the East Bay Regional Park District, the East Bay Municipal Utilities District, the University of California at Berkeley, Lawrence Berkeley National Laboratory, and the California Department of Forestry and Fire Protection.

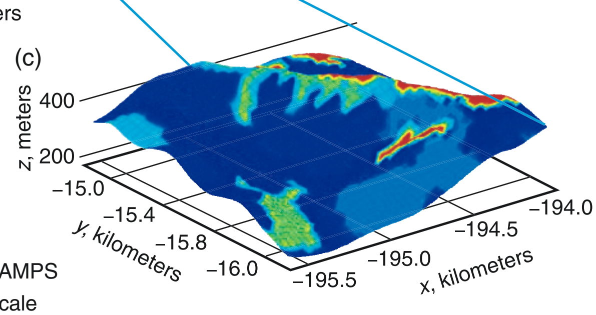
The Oakland–Berkeley hills fire claimed 25 lives and destroyed more than 3,000 dwellings. The simulations re-create its start at about 11 a.m. on Sunday, October 20, 1991, in Tunnel Canyon. (One day earlier, a small grass fire occurred about 100 meters from the ignition point of Sunday's fire. Embers from Saturday's fire, at first thought to have been extinguished, almost certainly started the Sunday conflagration.)

Working with the East Bay Regional Park District, the Livermore group produced the first global positioning satellite coordinates for the ignition points of the Saturday and Sunday fires. Next, the team built a virtual atmosphere for October 20, 1991, by using historical weather data provided by the European Center for Medium Range Weather Forecasting. The data, which had a resolution of about 120 kilometers, were fed into COAMPS to simulate the humidity, temperature, wind direction, and wind speed over the area of the incipient wildfire.

Re-creating Front Yard Weather

The COAMPS data were used by HIGRAD to simulate fine-scale weather at 10-meter resolution. "At this resolution, we're actually simulating the weather that occurred in the front and back yards of individual homes in the Oakland–Berkeley hills," notes Bradley. Volumes of detail on the terrain and





The wildfire modeling capability zooms down to extremely fine resolution. For the Oakland–Berkeley hills fire that began October 20, 1991, the team constructed (a) a virtual atmosphere by using historical weather data provided by the European Center for Medium Range Weather Forecasting. The data, which had a resolution of about 120 kilometers, were fed into the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) to simulate (b) the humidity, temperature, wind direction, and wind speed over the San Francisco Bay Area. The COAMPS data were used by the high-gradient flow solver (HIGRD) program to simulate (c) fine-scale weather at 10-meter resolution over the Oakland–Berkeley hills.

vegetation were fed into FIRETEC along with the dimensions of a football-shaped scar on the hillside, which resulted from the Saturday fire.

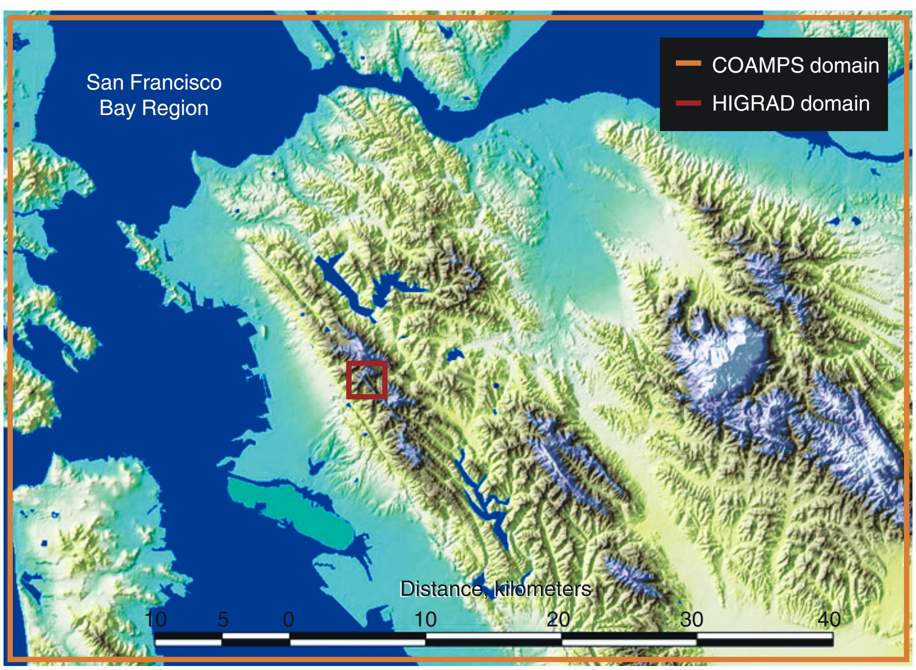
The fire was "lit" in the FIRETEC program by raising the temperature by 100°C at the exact ignition location determined earlier by the Livermore team. The simulation shows wind-whipped flames quickly spreading outward from the ignition point throughout Tunnel Canyon, which contained bone-dry trees, bushes, and grasses. Other aspects of the simulation show the direction and speed of winds (as affected by the fire) and the percentage of vegetation burned.

Bradley says that a common reaction to watching the simulations is that the fire spreads unrealistically fast, but fire officials who have seen the simulation say it is an accurate representation of what happened. "Conditions were nearly perfect for a devastating fire," Bradley says.

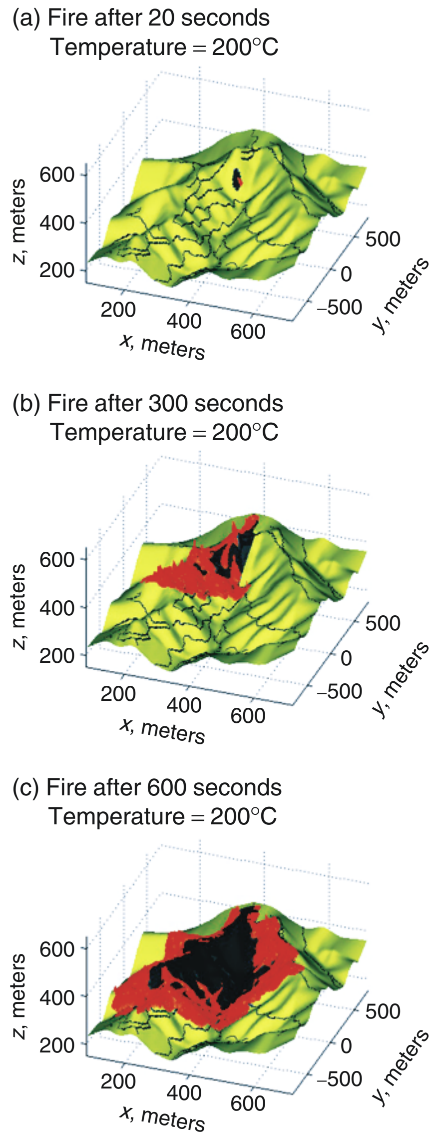
As with the Calabasas fire simulation, the Oakland hills model shows that the exact ignition location is important. If Sunday's ignition point is moved only 100 meters away, to the other side of the canyon, the fire follows a different course.

The team has also developed a fire consequence analysis capability by meshing model results with data maps created with computerized GIS tools. (See *S&TR*, September 2002, pp. 10–16.) GIS analyses make the program more useful to fire chiefs and other emergency planners by superimposing layers of digitized visual information over the simulation. The GIS map layers include roads, schools, fire stations, electrical transmission lines, and even the location of fire hydrants. A GIS layer of land parcel maps, for example, allows users to select specific homes and determine their vulnerability to wildfires.

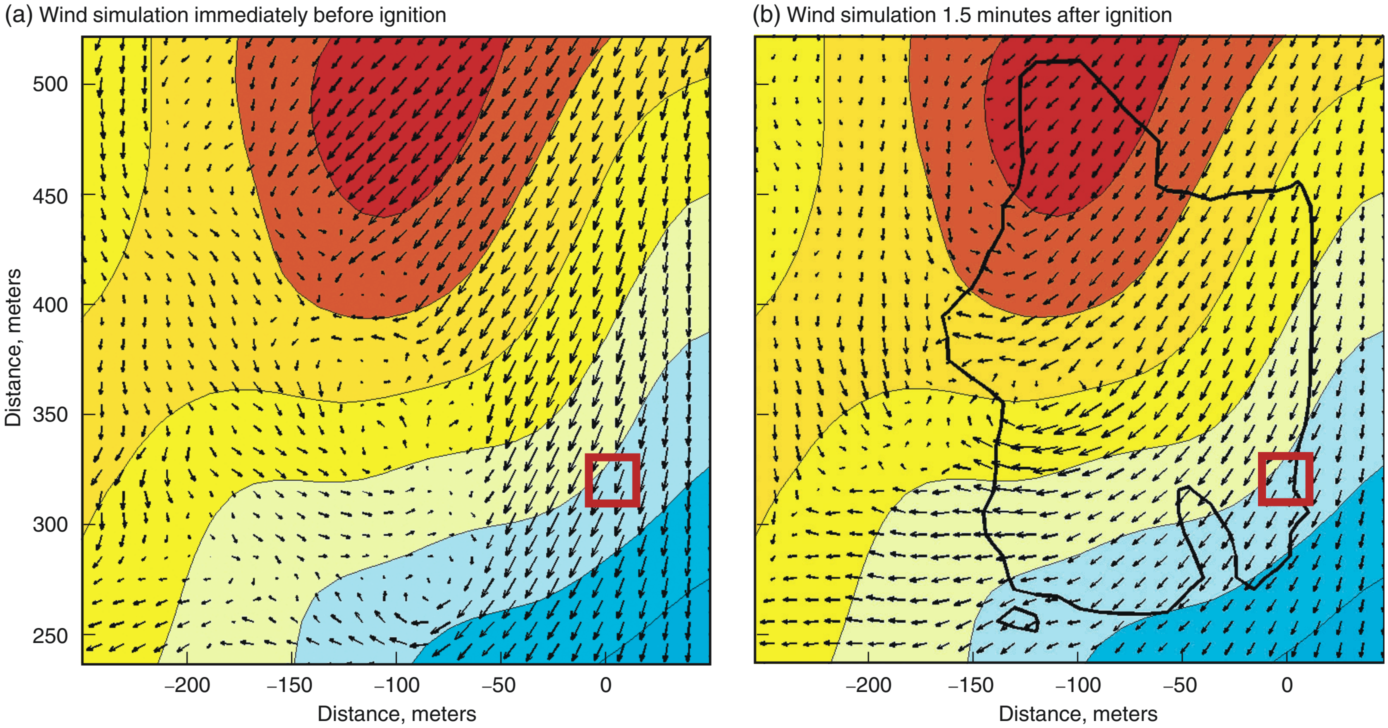
By combining the wildfire models with GIS tools, says Bradley, fire chiefs



A topographical map of part of the greater San Francisco Bay Area. The Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) weather prediction code modeled the larger area, while the high-gradient flow solver code (HIGRAD) is restricted to a 1.6-square-kilometer area directly over the Oakland–Berkeley hills fire.



A sequence of three frames taken from the computer simulation of the Oakland–Berkeley hills fire, which started in Tunnel Canyon. (a) A football-shaped dark area corresponding to Saturday's extinguished fire can be seen. Sunday's fire broke out just 30 meters away. (b) Three-hundred seconds (5 minutes) later, the fire is spreading quickly up the canyon. (c) Six-hundred seconds (10 minutes) after ignition, the fire has spread to neighboring canyons.



(a) A simulation of the wind with 10-meter resolution immediately before ignition of the Oakland–Berkeley hills fire. The arrows' directions indicate wind direction, while the arrows' lengths indicate wind speed. The red box is the fire's ignition site. (b) One and one-half minutes after ignition, winds are significantly altered by the fast-moving fire (perimeter is outlined).

and analysts can plan the best routes for firefighters to take as well as the safest evacuation routes for residents at risk. Planners can also readily determine the effects of thinning stands of trees or building fire breaks.

The Livermore group is particularly interested in areas in the Oakland and Berkeley hills that didn't burn in 1991 and that contain a substantial amount of vegetation, homes, and research facilities. The group hopes to evaluate the effectiveness of fuel breaks and other vegetation management techniques for areas that escaped the 1991 fire. It also hopes to simulate wildfires in Claremont Canyon and in Strawberry Canyon, the site of Lawrence Berkeley National Laboratory, the Lawrence Hall of Science, and a portion of the University of California at Berkeley campus. These simulations will not only help the group to further understand and improve the model, but they will also provide valuable information for local agencies.

Bradley notes that the Oakland and Berkeley hills areas are telling examples of the dangers posed by the urban–wildland interface, where homes are nestled within thick vegetation.

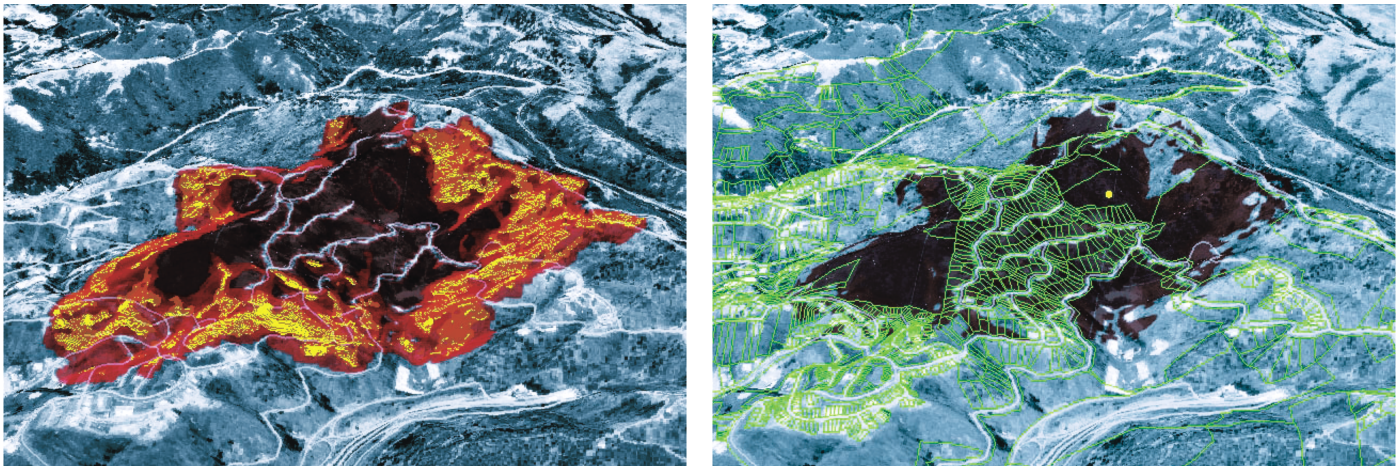
Chance to Make History

Because prescribed burns are planned far in advance, they provide the best opportunity for validating the program's accuracy. The burn location and ignition time are known before the burn occurs; the amount, type, and moisture content of vegetation are calculated before ignition; the weather conditions are known; and the behavior of the fire can be documented.

Bradley has successfully simulated smoke dispersion from several prescribed burns that were conducted at Site 300, Livermore's remote research facility. The simulations used the ARAC-3 dispersion model and compared well with observations of the smoke plume. He is hoping to use the full predictive power of the Livermore–Los Alamos model to provide reliable estimates of the fire behavior and smoke dispersion at least 24 hours before the prescribed burns are ignited at Site 300 in 2003.

"By next summer, it is possible we will be able to run the system fast enough to predict the first 30 minutes or so of the fire's behavior during a

(a) (b)



These images combine the result of (a) a computer simulation of an early stage of the Oakland–Berkeley hills fire with (b) a geographical information systems map of land parcels in the Oakland–Berkeley hills. Any home on the land parcel map can be selected to determine its address and its risk from a fire.

prescribed burn. If we are successful, it will be a truly historic event for fire science.” The team also has received several offers from fire management agencies to participate in their prescribed burn programs.

Enthusiastic Reception

The concept of an advanced wildfire simulation capability has been received positively by potential users. As the program’s development has progressed, an increasing number of agencies have expressed interest in the project, including the Los Angeles County Fire Department, the nation’s largest. In October, the University of California sponsored a wildfire physics workshop that explored how other scientists and fire managers can use the Livermore–Los Alamos program as the basis for advanced wildfire behavior studies. “We want to build a community of scientists and firefighters,” says Bradley. A second workshop is planned for early next year.

The team is looking at the current program as a central core to which additional modules can be added to strengthen its overall capabilities. For example, the increasing threat of wildfire at the wildland–urban interface makes it appropriate to include structures such as homes and businesses in the simulation system. The team is in contact with researchers at the National Institute of Standards and Technology who are developing a code that simulates burning structures. Developing such a code is a substantial task because of variations in structural materials and their contents.

A module to represent the process of fire spreading by showers of embers, called spotting, will be added to HIGRAD–FIRETEC next year. The team is collaborating on the module with researchers at the University of California at Berkeley. “This is not as simple as it might sound,” Bradley comments. “We have to decide on the embers’ sizes, how far the winds take them, and the percentage of times they start new fires.”

Eventually, the team foresees a 24-hour national wildfire prediction program being established, with fire managers and even firefighters in the field linked to NARAC with laptop computers.

Putting wildfire simulation on a solid physics-based footing can only be good for firefighters, the public, and the environment.

—Arnie Heller

Key Words: Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS), fire model, FIRETEC, geographical information systems (GIS), high-gradient flow solver program (HIGRAD), Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, National Atmospheric Release Advisory Center (NARAC), TeraCluster2000 supercomputer, wildfires.

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