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WEATHER EFFECTS ON SMOKE AND WILDLAND FIRE

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On the Cover:

Plume on the 2013 Rim Fire, Stanislaus National Forest, California. Such towering plumes can function much like thunderclouds, creating their own weather. Photo: Forest Service.

The USDA Forest Service's Fire and Aviation Management Staff has adopted a logo reflecting three central principles of wildland fire management:

- *Innovation:* We will respect and value thinking minds, voices, and thoughts of those that challenge the status quo while focusing on the greater good.
- *Execution:* We will do what we say we will do. Achieving program objectives, improving diversity, and accomplishing targets are essential to our credibility.
- *Discipline:* What we do, we will do well. Fiscal, managerial, and operational discipline are at the core of our ability to fulfill our mission.

Firefighter and public safety is our first priority.

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ANCHOR POINT

By Tom Harbour
Former Director, Fire and Aviation Management
USDA Forest Service

THE FUTURE IS BRIGHT

Back in the summer of 2007, I wrote my inaugural Anchor Point article for *Fire Management Today*. The topic was "Our Challenge: Being a True High-Reliability Organization." In the article, I described a high-reliability organization as built on integrity, nurtured by culture, and refined under the fire of performance. I talked about the importance of doctrine and how our past shapes us, our present influences us, and our future challenges us. Nearly a decade later, as I share my final message with you as Director of Fire and Aviation Management for the Forest Service, the information remains relevant.

My message today: the future is bright! The impacts of wildland fire will continue to increase; the public's need and expectation for us to do our work professionally and effectively will also grow. There will be more discussions about how we do, or should do, our work. Nevertheless, the future of wildland fire management is bright because of you—the people who are dedicated to this honorable professional vocation of public service. You are energetic; you are wise. Yes, the future is bright because of you.

The future of our work is connected to the land. Whether we manage prescribed fire or wildfire, for our work to be successful, we do not work in a vacuum. Our work must be connected to the land on a landscape scale and in collaboration with our partners, in order for us to thrive and survive in today's complex, uncertain environment. To achieve resilience, we need a fundamental, expressive doctrine established in a context of mutually strong relationships. Doctrine and relationships are necessary for us to adapt to a world that has changed tremendously since I began work for the Forest Service in 1970.

I was a GS–2 when I began; I finished out my Forest Service career as Director of the agency's fire organization. When I have told people of my journey through my professional life, I have been humbled to recognize a unique set of circumstances (luck) that gave me the opportunity. My wife and family have sacrificed more than I have, but I am not unique; others must and will have this wonderful opportunity, as well.

I have frequently wondered if I have had sufficient courage and energy to change enough to lead to the future. I am encouraged when I see a new crop of leaders poised to deliver on promises that are only beginning to form. I am optimistic about our future. Although my career is done, there is no doubt in my mind that the "sun is rising" on another shift ready to tie in to the work that I have been a part of and ready to move the work forward.

The land and the human spirit have enduring meaning for me. The team we establish is critical to dealing with the pervasive risk of our work. "Constant Vigilance" must be our mantra. As noted by Eric Marsh and others, we must "BE" rather than seem to be (Esse quam videri).

I exit, but I do so with a mind and spirit filled with experiences that have spanned the breadth of human emotions and allowed me to think, consider, and act.

The work, this work, my work for over 45 years, will continue. I, likewise, plan to continue in some way, but in a much different role. My hope is that you will bear it up and carry on wisely and energetically. I look forward to that progress. I will be watching, hoping, and doing what I can to continue to help.

I am certain there is a renaissance of fire and aviation management coming in our world. I hope I have been of some small assistance in beginning to nurture that renaissance.

Bump up—see you on the next one! ■

Tom Harbour retired from the Forest Service in 2015 after a distinguished career of 45 years. The new Director of Fire and Aviation Management is Shawna A. Legarza, Psy.D.

WEATHER EFFECTS ON SMOKE AND WILDLAND FIRE

Preface to the Special Issue

Scientific understanding of how weather affects smoke and wildland fire has progressed since the turn of the millennium. Fourteen or 15 years ago, the wildland fire community couldn't get fire weather maps on the Internet. With today's research instruments, we can observe details of the atmosphere that we couldn't see before; we can see into the center of smoke plumes and right above the fire front, in some cases. With more powerful computers, we can model interactions between fire and the atmosphere in greater detail and produce forecasts of fire weather indices or smoke transport looking more than a week into the future. All this gives us new insights into fire and smoke, raises new questions about some of the things we see, and sometimes makes us reconsider what we previously thought we knew.

The tools that bring new scientific understanding to the field have also been improving and changing. Lidar remote-sensing systems can fit in a pickup truck and monitor smoke movement inside of smoke plumes from a few yards or miles away from the fire. Radiosondes have become inexpensive enough that incident meteorologists regularly release them on fires for immediate information on the atmosphere. Software previously limited to research because it took too long for operational purposes can now run fast enough for a fire behavior analyst or incident meteorologist to use on a laptop in the field. Desktop computer programs can now run on the Web, allowing access from anywhere, even on a smartphone.

This special issue of *Fire Management Today* highlights improvements in knowledge, technology, and tools related to how the atmosphere influences fire behavior and smoke impacts. There are articles on advances in smoke modeling (not only the transport but also the chemistry of smoke) in our understanding of how terrain influences airflow and fires, in our knowledge of convection and fire plumes, and in our perspectives on the concept of "critical weather patterns."

This issue also contains pieces on the changing roles of various weather agencies in research and operations and on how Red Flag Warnings and Watches work today. Some of the articles challenge entrenched conventional wisdom. The issue looks at where weather research and operations are likely to head in the next several years and what managers can look for down the line.

Not all articles in this issue are on topics directly related to fire weather. You will also find pieces on the Japanese balloon bombing campaign during World War II; the effects of social media on news stories about wildland fires; the career of Bea Day, a leader in the wildland fire community; and a new forestry journal featuring fire review articles. In addition, retired Director of Fire and Aviation Management Tom Harbour has signed off with his final "Anchor Point" piece for the journal. ■

WHO DOES WHAT: THE ROLES OF SCIENTISTS IN WILDLAND FIRE WEATHER

Robyn Heffernan

The role of meteorology in wildland fire management is varied. It takes an entire interagency team of highly qualified scientists to fill the needs of the wildland fire community. Employees of several Federal agencies, as well as people in the research community, have fire-weather-related roles such as operational forecasting, research advancement, standards development, training and education, and coordination. Fire weather is core to several programs within the five Federal land management agencies. Figure 1 outlines interconnections within the interagency fire weather community, described in detail below.

The National Weather Service has the lead role with regard to operational fire weather forecasting.

The National Weather Service (NWS) in the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) has the lead role with regard to operational fire weather forecasting; the NWS also produces air quality modeling (NWS 2014a,

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Robyn Heffernan is a science and dissemination meteorologist for the National Weather Service, National Oceanic and Atmospheric Administration, Washington, DC.

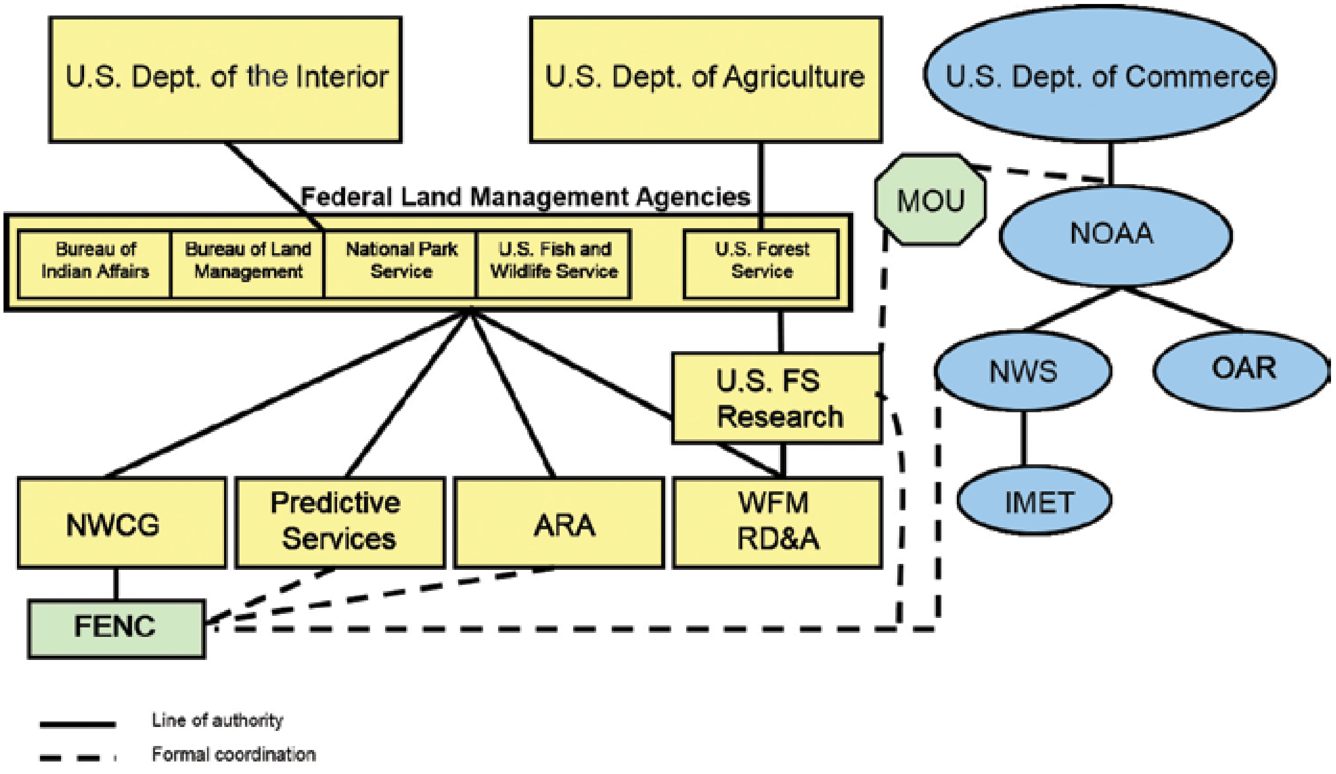

Figure 1—*Interconnections within the interagency fire weather community. ARA = air resource advisor; FENC = Fire Environment Committee; IMET = incident meteorologist; MOU = memorandum of understanding; NOAA = National Oceanic and Atmospheric Administration; NWCG = National Wildfire Coordinating Group; NWS = National Weather Service; OAR = Office of Oceanic and Atmospheric Research; WFM RD&A = Wildland Fire Management Research, Development & Application.*

2014b). In addition, the Federal land management agencies get jointly funded fire weather support from the Predictive Services program hosted by the Geographic Area Coordination Centers and the National Interagency Coordination Center. The U.S. Department of Agriculture has historically been a strong supporter of fire weather and air quality research through the Forest Service's meteorology research program. The Wildland Fire Management Research Development and Application unit is an interagency group that links fire management, research, and weather products. In addition to the operational and research programs, these entities work together through the National Wildfire Coordinating Group to provide national leadership in measuring and predicting the wildland fire environment.

National Weather Service

In general, the NWS offers basic meteorological services in support of wildland fire suppression, site-specific and onsite technical support, and other special fire management services. Specifically, the NWS issues Red Flag Warnings and Fire Weather Watches related to dry fuels, weather conditions, and other factors that contribute to extreme fire behavior and/or excessive fire starts, affecting initial attack. These products are critical in keeping firefighters safe every day.

The NWS offers daily Fire Weather Planning Forecasts with general, zone-based information for daily preparedness and planning purposes. These forecasts are often briefed live to fire managers and dispatch offices through virtual audio and Web-based meetings. On request, the NWS gives Spot Forecasts to support wildland fire and natural resource management.

In addition, the NWS plays a role in the National Fire Danger Rating System (NFDRS), giving 24-hour forecasts of required meteorological parameters. Entered into the system, the information allows the NFDRS software to predict the next day's fire danger indices. In addition, NWS digital services are now being used to produce NFDRS forecasts out to 7 days.

Predictive Services also offers a Daily Fire Weather Outlook throughout the fire season.

The NWS Storm Prediction Center (SPC) in Norman, OK, in addition to forecasting severe weather, offers fire weather services. Recognizing fire weather as a type of severe weather, the SPC produces Fire Weather Outlooks for the contiguous United States on day 1, day 2, and days 3–8. These outlooks describe critical combinations of dry fuels with large-scale weather conditions that favor extreme fire behavior and/or excessive fire starts.

The NWS doesn't confine its support for the wildland fire community to an office setting. Incident meteorologists are NWS forecasters who volunteer to offer fire weather services onsite at specific incidents. The NWS maintains a highly skilled cadre of incident meteorologists who are fully trained, certified, and able to serve on type 1 and type 2 incident management teams. Incident meteorologists also support other wildland fire operations, including prescribed fires and recovery efforts through burned area emergency response teams.

Predictive Services

The NWS produces fire weather forecasts that are critical to the Predictive Services program sponsored by the Federal land management agencies. The program arose following the extremely active 2000 fire season, which revealed the need for a more holistic approach to consolidating information about fuels, weather, fire danger, and situation and resources. The program has employees from all five Federal land management agencies in the disciplines of meteorology, fire analysis, and intelligence. The Predictive Services program gives decision support to wildland fire managers in managing and mobilizing fire management resources (NPSS 2009).

Predictive Services prepares a 7-Day Significant Fire Potential Outlook, a statistical assessment of significant fire potential by Predictive Services Area. The outlook includes a weather synopsis as well as fuels and resource discussions. The product is used across the wildland fire community for everything from fuels assessments for issuing Red Flag Warnings to air tanker allotment across the country.

Predictive Services also offers a Daily Fire Weather Outlook throughout the fire season. The daily outlook synthesizes fire weather information from a variety of sources, such as NWS and Forest Service meteorology research, into graphics showing significant fire weather parameters for a specific geographic area. Predictive Services offers fire customers daily recorded Web-accessible multimedia briefings on fire potential and fire weather forecasts, along with fire danger and resource information.

In addition, Predictive Services produces mid- and long-range projections of fire potential, called National Significant Wildland Fire Potential Outlooks. The outlooks incorporate all available weather, climate, and fire danger information from a variety of Federal, State, and local partners. Typically once each year, prior to the Western fire season, international partners from Natural Resources Canada and Mexico's Servicio Meteorológico Nacional coordinate with Predictive Services on a North American outlook.

In addition, Predictive Services issues Fuels and Fire Behavior Advisories to delineate areas of hazardous fuel conditions and projected active fire behavior. These products can be in effect from weeks to months. Predictive Services coordinates their production and period of validity with fire management personnel within the Geographic Area Coordination Centers and the National Interagency Coordination Center.

Other Roles

The Predictive Services program and the NWS are largely responsible for serving the operational fire weather needs of the wildland fire community. Many other entities contribute to the success of these operational services and provide essential research, development, and technology transfer of new science and applications.

Various agencies and programs cooperate in offering both operational services and research in the area of air quality. The U.S. Environmental Protection Agency, NOAA, and National Park Service, in coordination with tribal, State, and local agencies, developed a system called AirNow, giving the public easy access to national air quality information (AirNow 2014). The Forest Service's meteorology research program, in coordination with its partners in AirNow, has made great strides in developing research and operational air quality tools for wildland fire management. These tools are increasingly being integrated into fire management decision processes.

One recent innovation was the creation of the position of air resources advisor on wildfires with particularly critical impacts on air quality (NWCG 2014). In figuring out smoke risks and impacts, the air resources advisor works closely with the incident meteorologist and fire behavior analysts on incident management teams, as well as with a variety of regional, State, and local partners. Multiple partners put together a consolidated analysis and communication message related to the impacts of smoke and associated air pollutants on public health, transportation safety, and the health and well-being of firefighters.

Many advances in fire weather and smoke science came about under the National Fire Plan following the severe fire season of 2000.

Many advances in fire weather and smoke science came about under the National Fire Plan following the severe fire season of 2000. From 2000 to about 2008, the Forest Service's fire weather and smoke research program was organized under the Fire Consortia for the Advanced Modeling of Meteorology and Smoke (Riebau 2003; Potter and others 2006). Under a national research program, scientists combine theory, field work, and complex computer models to improve the scientific basis of fire weather, fire behavior, and smoke tools. They offer a valuable testbed for high-resolution modeling tools and fire or smoke forecasting.

The Wildland Fire Management Research Development and Application (WFM RD&A) unit, an interagency initiative, sponsors technology transfer from Forest Service research and the Joint Fire Science Program into operational decisionmaking by fire managers. The unit describes itself as "a primary point of contact for communication between scientists and participating field fire managers, as a liaison between research, wildland fire planning and operations, interagency wildland fire information technology groups, and as an advisor to program administrators at local, regional, and national levels" (WFM RD&A 2014). The WFM RD&A creates fire science applications, such as the Wildland Fire Decision Support System, that give decision support for wildland fire management (WFDSS 2012). The program also offers training in the use of cutting-edge fire science tools and applications and operates a National Fire Decision Support Center.

In 2012, the Forest Service and NOAA signed a memorandum of understanding to coordinate their research on fire weather, fire behavior, fire danger, smoke and air quality forecasting, and fire–climate effects. NOAA's fire weather research is conducted by the NWS and the Oceanic and Atmospheric Research line offices in collaboration with atmospheric science partners from private industry and academia. The Forest Service's Research and Development also studies atmospheric processes, including fire weather, fire danger, fire behavior, smoke emissions, air quality impacts, and climate.

The researchers in fire weather science have an amazing level of experience and a huge combined number of years in the field. Equally impressive is the required level of coordination among all of these scientists marching in the same direction while filling the diverse needs of the wildland fire community. The National Wildfire Coordinating Group plays a key role in the coordination of fire weather with the entire fire environment. The group's Fire Environment Committee provides national leadership in measuring and predicting the wildland fire environment. This includes the development and promotion of standards, tools, trusted data, and training to support fire weather forecasting, fire behavior prediction, fire danger rating, and predictive services.

Future Opportunities

The interagency fire weather community works together to offer accurate and relevant fire weather information that incorporates emerging new science and technology. Figure 1 outlines interconnections within the community. Safety is the community's first priority; however, the benefits and uses of weather information for the purpose of wildland fire management continue to grow. Therefore, the opportunities for scientists to make a difference in fire weather research will only increase.

As we look to the future, we can take advantage of current and emerging opportunities by using advances in science to create a unified message about the fire environment. Fire weather is one critical piece of the puzzle. The more we can continue to merge the results of fire weather research with results from research on fire danger, fire behavior, and smoke effects, the more we will accelerate advances in science and their transfer to operations.

Acknowledgments

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References

AirNow. 2014. About AirNow. Research Triangle Park, NC: U.S. Environmental Protection Agency. <http://www.airnow.gov/> (last accessed April 2015).

NPSS (National Predictive Services Subcommittee). 2009. Predictive Services Handbook—Updated 2009. Boise, ID: National Interagency Fire Center, National Predictive Services Subcommittee. <http://www.predictiveservices.nifc.gov/NPSG/NPSS.htm> (last accessed April 2015).

NWS (National Weather Service). 2014a. National agreement: Interagency Agreement for Meteorological and Other Technical Services. Fort Worth, TX: National Oceanic and Atmospheric Administration National Weather Service, Fire Weather Program. <http://weather.gov/fire> (last accessed April 2015).

NWS (National Weather Service). 2014b. National Fire Weather AOP: National Fire Weather Annual Operating Plan, 2014. Fort Worth, TX: National Oceanic and Atmospheric Administration National Weather Service, Fire Weather Program. <http://weather.gov/fire> (last accessed April 2015).

NWCG (National Wildfire Coordinating Group). 2014. Air resource advisor position description. Boise, ID: National Wildfire Coordinating Group, Smoke Committee. <http://www.nwcg.gov/branches/pre/ibc/ad_pds/coordination-support/thsp-ara.pdf> (last accessed April 2015).

Potter, B.E.; Larkin, N.K; Nikolov, N. 2006. Smoke, fire, and weather: What Forest Service research is doing to help. Fire Management Today. 66(3): 12–16.

Riebau, A.R. 2003. Fire Consortia for Advanced Modeling of Meteorology and Smoke – FCAMMS. 3rd International Wildland Fire Conference; 3–6 October 2003; Sydney, Australia. <http://www.fire.uni-freiburg.de/summit-2003/3-IWFC/Papers/3-IWFC-087-Riebau.pdf> (last accessed April 2015).

WFDSS (Wildland Fire Decision Support System). 2012. Wildland fire air quality tools. Boise, ID: Wildland Fire Management Research, Development & Application, Wildland Fire Decision Support System, U.S. Forest Service Air Fire Research Team. <http://firesmoke.us/wfdss/> (last accessed April 2015).

WFM RD&A (Wildland Fire Management Research, Development & Application). 2014. About WFM RD&A. Boise, ID: Wildland Fire Management Research, Development & Application, National Wildfire Coordinating Group. <http://www.wfmrda.nwcg.gov/> (last accessed April 2015). ■

SMOKE PLUMES: EMISSIONS AND EFFECTS

Susan M. O'Neill, Shawn Urbanski, Scott Goodrick, and Narasimhan K. Larkin

Smoke can manifest itself as a towering plume rising against the clear blue sky—or as a vast swath of thick haze, with fingers that settle into valleys overnight. It comes in many forms and colors, from fluffy and white to thick and black. Smoke plumes can rise high into the atmosphere and travel great distances across oceans and continents. Or smoke can remain close to the ground and follow fine-scale topographical features.

Along the way, the gases and particles in the plumes react physically and chemically, creating additional particulate matter and gases such as ozone (O_3). If atmospheric water content is high, smoke plumes can also create "superfog" (Achtemeier 2002). Over the past decade, researchers have studied the suite of trace gases and aerosols emitted by wildland fires, along with the physical and chemical reactions and transformations that occur within a plume.

Why Do We Care?

Smoke gases and particles constitute only a tiny fraction of the air (less than 0.1 percent of the atmosphere in any location, even under the worst conditions) (table 1). Overall, dry air is made up of 78 percent nitrogen (N_2), 21 percent oxygen (O_2), and about 1 percent trace gases (about 0.9 percent argon (Ar) and 0.1 percent other trace gases). Water vapor in the air ranges from almost nothing to 5 percent. Yet the trace amount of smoke in the air can have significant impacts, such as making the air smell bad; limiting visibility; and affecting the health of vegetation and animals, including humans. Smoke can affect public health, transportation safety, and the health and well-being of firefighters.

> Smoke can affect public health, transportation safety, and the health and well-being of firefighters.

Due to health and safety concerns, the Clean Air Act regulates aspects of atmospheric smoke. If smoke concentrations in a region exceed the national ambient air quality standards (NAAQSs), then the region is designated as "nonattainment." Nonattainment triggers regulatory actions, such as controls on smoke emissions; fees/charges for emissions; restrictions on industry; and, in some cases, restrictions on the use of fire. Currently, the NAAQS threshold for particulate matter finer than 2.5 micrometers in diameter ($PM_{2.5}$) is 35 micrograms per cubic meter (24-hour average); for ozone, the threshold is 75 parts per billion (8-hour average). Even at levels below these standards, smoke can significantly affect visibility, degrading vistas and creating transportation hazards. Smoke combined with high humidity can produce whiteout conditions known as superfog (Achtemeier 2002).

Wildland Fire Emissions

If fire were 100-percent efficient, the only products released would be carbon dioxide, water vapor, and heat. However, the combustion of wildland fuels is never 100-percent efficient. In addition to carbon dioxide and water vapor, the process transforms some of the fuel into ash, char, particulate matter, carbon monoxide, and other carbon-containing gases—a rich and complex mixture of gases and particles. Figure 1 shows the distribution of carbon emitted by

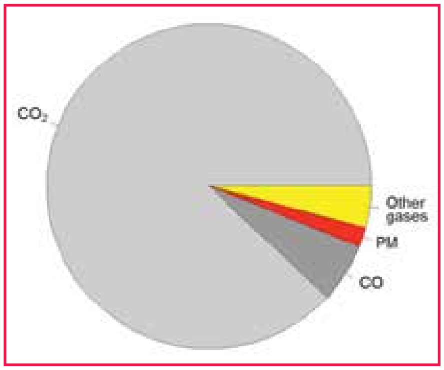

Figure 1—*The distribution of carbon emitted by a typical low-intensity understory prescribed fire in light fuels (based on Urbanski (2014)).* CO_2 *= carbon dioxide; CO = carbon monoxide; PM = particulate matter.*

Susan O'Neill is an air quality scientist for the Forest Service, Pacific Northwest Research Station, Seattle, WA; Shawn Urbanski is a research physical scientist for the Forest Service, Rocky Mountain Research Station, Missoula, MT; Scott Goodrick is a research meteorologist for the Forest Service, Southern Research Station, Athens, GA; and Sim Larkin is a research scientist and team leader for the Forest Service AirFire Team, Pacific Northwest Research Station, Seattle, WA.

Table 1—*Gases and particles in the atmosphere, including those related to biomass burning.*

Chemical/particle		Description
Symbol	Name	
Ar	Argon	About 0.9 percent of the atmosphere.
BC	Black carbon	Particles from combustion that strongly absorb incoming solar radiation and emit longwave radiation.
CO	Carbon monoxide	Emitted from the incomplete combustion of biomass.
CO_2	Carbon dioxide	A primary product of biomass burning.
H_2O	Water	A primary product of biomass burning.
N_2	Nitrogen	About 78 percent of the atmosphere.
NH_3	Ammonia	A precursor of inorganic particle formation; trace amounts emitted from biomass burning.
NO_X	Oxides of nitrogen	NO and NO_2, precursors to ozone and particle formation.
NO	Nitrogen oxide	Part of NO_X; released from biomass burning as a function of the fuel nitrogen content and combustion phase.
NO_2	Nitrogen dioxide	Part of NO_X.
O_2	Oxygen	About 21 percent of the atmosphere.
O_3	Ozone	Created by the reaction of NO_X and VOCs in the presence of sunlight; regulated under the Clean Air Act.
OC	Organic carbon	Carbon and hydrogen compounds, oxygenated carbon/hydrogen compounds, and other trace elements; a major constituent of particulate matter from biomass burning.
PAN	Peroxyacetyl nitrate	Can sequester NO_X and travel long distances in the atmosphere; mixed back down near the surface, warmer temperatures break it apart, freeing up NO_X to generate more O_3 far from the fire.
$PM_{2.5}$	Particulate matter (aerodynamic diameter < 2.5 µm)	Fine particulate matter; can comprise organic and inorganic compounds; regulated under the Clean Air Act.
SO_2	Sulfur dioxide	A precursor of inorganic particle formation; trace amounts emitted from biomass burning.
SOA	Secondary organic aerosol	Particles formed by a series of physical and chemical reactions.
VOC	Volatile organic compound	Precursors of O_3 and SOA formation; hundreds identified from biomass burning, hundreds yet to be identified; examples: methane, ethane, benzene, furan, formaldehydes, methanol, monoterpenes.

a typical low-intensity understory prescribed fire in light fuels. Minor smoke constituents such as carbon monoxide, particulate matter, and “other gases” are mainly responsible for smoke impacts on visibility and air quality.

Over the past decade, scientists have made tremendous progress in identifying the “other gases” produced by wildland fires (fig. 1). Multiple research projects have gotten support from the Forest Service’s Research and Development, the multiagency Joint Fire Science Program, the U.S. Department of Defense Strategic Environmental Research and Develop Program, and others. Researchers have studied the composition of smoke from simulated fires in the large-scale combustion facility operated by the Rocky Mountain Research Station’s Missoula Fire Sciences Laboratory and from operational prescribed fires in the Southeastern and Southwestern United States. Recent advances in instrumentation and chemical analytical techniques have allowed scientists to identify nearly 200 volatile organic compounds (VOCs) in fresh smoke. The gases include methane, ethane, benzene, furan, formaldehydes, methanol, monoterpenes, and more. Despite such advances, a large percentage of VOCs remain unidentified, including 30 to 40 percent of them in forest fuels and over 70 percent of them in organic soils and duff.

Particulate Matter

Particulates released from fire are mostly carbon based and are typically referred to as organic carbon and black carbon. Organic carbon consists of carbon and hydrogen compounds, oxygenated carbon/hydrogen compounds, and other trace elements. Black carbon is the fraction of the particle that strongly absorbs incoming solar radiation and emits longwave radiation into the atmosphere. It is a product of combustion; in its purest form, it would be graphite. It has been identified as a short-lived climate forcer, bolstering the greenhouse effect; deposition of black carbon on snow accelerates snowmelt.

Smoke particles are quite small, making them very efficient at scattering light, thereby reducing visibility and generating “haze.”

Particles rarely exist solely as organic or black carbon. Instead, they form a continuum, ranging from pure graphite to mostly organic compounds. Smoke particles from wildland fires tend to have a higher percentage of organics than do particles from anthropogenic combustion sources, which tend to have a higher black carbon content.

New particles form in the atmosphere through gas-to-particle reactions involving VOCs, oxides of nitrogen (nitrogen monoxide and nitrogen dioxide), ammonia, and sulfur dioxide. Factors such as time, temperature, sunlight, and the proportion of gases in the atmosphere influence these reactions. The result is ultrafine particles; water vapor and other gas-phase species can easily attach and other reactions can occur, resulting in particle growth. These small particles can also grow through particle-to-particle coagulation.

Secondary organic aerosols are particles formed in the atmosphere through a series of gas-phase chemical reactions that lower the volatility of VOCs to the point where they can condense into or onto particulates. These organic compounds can continue reacting until the carbon is oxidized to carbon monoxide or carbon dioxide or until the particles are removed from the atmosphere through deposition. Cooler temperatures help semivolatile gases condense into particulates. As compounds react and age in the atmosphere, they tend to more readily attach to water, increasing the amount of water in the particulate. Most semivolatile compounds formed in the atmosphere remain to be identified. Secondary organic aerosols are an important area of current research.

Most smoke particles are quite small, often less than 1 micrometer in diameter. They are very efficient at scattering light, reducing visibility and generating “haze.” Smoke plumes lofted high into the atmosphere can also interact with cloud-forming processes.

Smoke and Ozone

Ozone is created in the atmosphere through the reactions of oxides of nitrogen (nitrogen monoxide and nitrogen dioxide) with VOCs in the presence of sunlight. Nitrogen dioxide undergoes photolysis (the separation of molecules by light) into nitrogen monoxide and oxygen, with the oxygen atoms (O) then reacting with the abundant oxygen in the atmosphere (O_2) to generate ozone (O_3). In an atmosphere without VOCs, the ozone would then react with nitrogen monoxide (NO) to regenerate nitrogen dioxide (NO_2) and oxygen (O_2). However, the abundant VOCs in the atmosphere provide for the regeneration of nitrogen dioxide without removing ozone.

Smoke plumes are rich sources of VOCs and also contain oxides of nitrogen (NO_X). The NO_X are a function of the nitrogen content of the fuel and the fuel combustion phase. Smoke plumes are said to be "NO_X-limited" in that the generation of ozone is limited by the amount of NO_X available. By contrast, many urban areas tend to be VOC-limited in that they have an abundance of NO_X in the atmosphere. In the simplest case, when smoke plumes mix with emissions from urban areas with lots of NO_X, the extra NO_X they get can generate more ozone.

However, smoke is smoky: it blocks solar radiation, hindering photolysis. Oxides of nitrogen can also be sequestered in peroxyacetyl nitrate, limiting the generation of ozone. However, peroxyacetyl nitrate can travel long distances in the atmosphere before mixing into the air back down near the ground, where temperatures are warmer. Warmer temperatures lead to thermal disassociation, freeing up NO_X to generate more ozone long distances away from a wildland fire.

Plume Interactions

Wigder and others (2013) analyzed measurements of fine particulate matter, carbon monoxide, and ozone at Mount Bachelor Observatory during 32 wildfires from 2004 to 2011. The observatory is located in central Oregon atop the mountain at 9,064 feet (2,763 m) above sea level. It is a remote site, with measurements that have identified episodes of Asian air transport and biomass burning across North America. Many of the air masses measured were local to Oregon; but wildfire events from British Columbia, California, Idaho, Montana, and Washington have also affected the site.

For smoke plumes with less than 2 days transport time, fine particulate matter ($PM_{2.5}$) increased over the period, indicating the generation of secondary organic aerosols. For older events, however, the generation of fine particulate matter was low, indicating that aerosol removal from the air could exceed generation. Only 13 of the 32 plumes measured had significant ozone generation. The two plumes that traveled over the Seattle metropolitan area had greater ozone generation but not necessarily the highest. Transport time did not necessarily equate to greater ozone generation.

Superfog

A major component of the emissions from the combustion of vegetation is water vapor. Although water vapor is not a pollutant, the emission of water vapor and particulate matter under the right environmental conditions can result in extremely low visibilities near a wildland fire. The very dense fog that results is called superfog, with visibilities of less than 10 feet (3 m) and often less than 3 feet (1 m) (Achtemeier 2002).

The water vapor and particulate matter in smoke can result in superfog, with visibilities of less than 10 feet.

Fog forms when water vapor condenses into tiny liquid water droplets suspended in the air. It normally occurs at a relative humidity of nearly 100 percent. The presence of particles in the air can boost the condensation process at humidities as low as 80 percent if the particles attract moisture. Such particles, referred to as hygroscopic, serve as cloud condensation nuclei.

The smoldering combustion of moist fuels such as organic soil, duff, and logs emits considerable amounts of water vapor and hygroscopic cloud condensation nuclei. When the warm, moist smoke mixes with cold air that already has a relative humidity approaching 100 percent, the result is a supersaturated atmosphere and the formation of superfog. The abundance of cloud condensation nuclei from the fire makes for very small condensed droplets. Small droplets are more effective at scattering light than larger droplets, leading to greater reductions in visibility.

Smaller droplets also have less mass and a slower settling velocity, letting them remain suspended in the atmosphere for longer periods of time. Achtemeier (2009) estimated the liquid water content of superfog to be about 23 times greater than in regular fogs. He also found that 1 percent of the particulate emissions from a wildland fire formed enough cloud condensation nuclei to shift the distribution of droplet sizes in superfog toward smaller droplets, reducing visibility to as low as 0.3 feet (0.1 m).

Achtemeier (2013) created a Superfog Index. Ranging from 0 to 100, the index represents the probability of superfog formation. The index increases rapidly at air temperatures of less than 55 °F (13 °C) when the relative humidity is 90 percent or higher. Figure 2 shows Superfog Index curves for two ambient relative humidity scenarios.

Fire managers should be aware of the possibility of superfog formation. Other critical questions to raise in assessing fog-related risk include the following:

- Do you have a smoldering fire that will burn all night?
- Is there a transportation route within 3 miles (4.8 km)?
- Is the wind direction toward the road?
- Do drainages lead from the fire to the road?
- Are temperatures predicted to be less than 50 °F (10 °C)?

Smoke in Complex Terrain

As the sun goes down, the surface of the Earth cools and inversions form within valleys, trapping smoke and causing smoke concentrations to be higher than they would be if the atmosphere were mixing in cleaner, fresher air. Nighttime drainage flows can also carry smoke for tens of miles down valleys, allowing smoke to affect areas at night that had little or no smoke impacts during the day.

The result is that smoke impacts in valleys near or downwind of fires can be significantly higher than in flat terrain. Figure 3 gives a satellite view of smoke pooled in valleys across northern Idaho and western Montana in September 2012, before daytime heating dispersed the smoke. New advances in fine-scale meteorological and smoke modeling can now simulate patterns of smoke dispersion, including inversions.

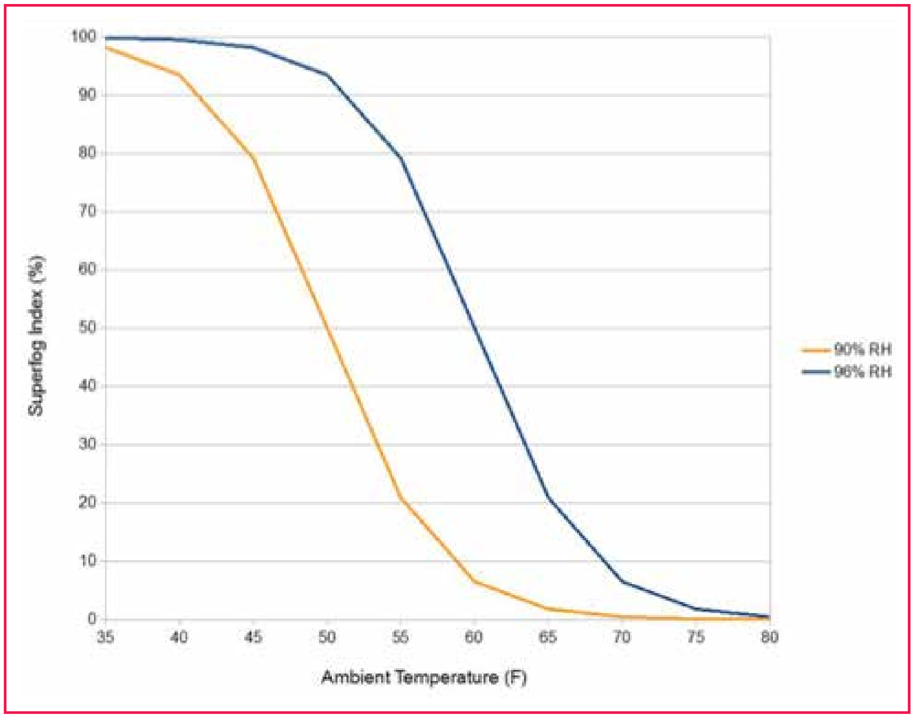

Figure 2—*Superfog Index indicating the probability of superfog formation as a function of ambient air temperature for two different relative humidity (RH) scenarios (yellow = 90 percent; blue = 96 percent) (adapted from Achtemeier (2013)).*

Figure 3—*Satellite view of smoke in valleys over northern Idaho and western Montana on September 13, 2012, at 1200 mountain daylight time, from the Moderate Resolution Imaging Spectroradiometer instrument aboard the National Aeronautics and Space Administration Terra satellite. Cities range from Missoula, MT, in the north; to Salmon, ID, in the south; to Butte, MT, in the east.*

The Challenge of Smoke

Smoke is challenging. It can be lofted high into the atmosphere to interact with cloud processes. It can smolder near the ground, depositing emissions.

The combination of aerosols and trace gases create their own chemical mix, with reactions that are as yet unidentified. Temperature and atmospheric water content interact with the smoke plume and fog processes. Smoke also blocks the transmission of solar radiation, hindering photolysis reactions.

Many of the trace gases emitted from wildland fires have yet to be identified, as do the intermediary products produced in a plume. With the outlook for more wildfires in the future, especially in a changing climate—and with tighter health standards—understanding these processes will become more critical in the years to come.

References

Achtemeier, G.L. 2002. "Super-fog"—A combination of smoke and water vapor that produces zero visibility over roadways. 12th Joint Conference on the Applications of Air Pollution Meteorology with A&WMA; 20–24 May; Norfolk, VA. Boston, MA: American Meteoroidal Society: 15–16

Achtemeier, G.L. 2009. On the formation and persistence of superfog in woodland smoke. Meteorological Applications. 16: 215–225.

Achtemeier, G.L. 2013. A Superfog Index based on historical data. International Smoke Symposium; 21–24 October; The University of Maryland University College, College Park, MD.

Urbanski, S.P. 2014. Wildland fire emissions, carbon, and climate: Emission factors. Forest Ecology and Management. 317: 51–60.

Wigder, N.L.; Jaffe, D.A.; Saketa, F.A. 2013. Ozone and particulate matter enhancements from regional wildfires observed at Mount Bachelor during 2004–2011. Atmospheric Environment. 75: 24–31. ■

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CONVECTION AND DOWNBURSTS

Joseph J. Charney and Brian E. Potter

Convection and downbursts are connected meteorological phenomena with the potential to affect fire behavior and thereby alter the evolution of a wildland fire. Meteorological phenomena related to convection and downbursts are often discussed in the context of fire behavior and smoke. The physical mechanisms that contribute to these phenomena are interrelated, but the phenomena are often misinterpreted or misunderstood in the fire/smoke context.

In this article, we discuss the physical mechanisms associated with convection and downbursts, and we discuss terminology used in reference to fire-driven convection. We identify the role the phenomena could play in fire behavior and smoke, according to the scientific literature. We also discuss some of the misinterpretations and misunderstandings that are common in the fire community.

Convection

Convection has two different but related definitions (N.a. 2016), depending on whether the word describes the general flow of heated material in a fluid or whether it refers to a meteorological phenomenon. The more general definition of convection is “the transfer of heat by the circulation or movement of the heated parts of a liquid or gas.” The meteorological definition is more specific: “the vertical transport of atmospheric properties, especially upward.”

According to the meteorological definition, convection does not contribute directly to fire behavior: convective heat transfer, as related to fire spread, falls under the first definition. Meteorologically, convection affects fire behavior indirectly by altering the flow of air through the combustion zone or by contributing to changes in the wind speed and wind direction in the immediate vicinity of the fire (that is, within about 3 to 300 feet (1 to 100 m)). In this article, we discuss meteorological convection and its role in fire behavior and smoke movement.

Meteorological convection is a very common and extensively studied feature of atmospheric motion. Convection is the mechanism by which many clouds and all thunderstorms form in the atmosphere. Even when no condensation occurs in a convective updraft, the updraft contributes to mixing of the air between the Earth’s surface and higher levels of the atmosphere. Weather forecasts routinely include assessments of the potential for convective clouds and thunderstorms to affect weather conditions during a forecast period.

A fire modifies the air directly over it by releasing heat and moisture into that air. A localized pocket of air that is warmer and moister than its surrounding environment at the same pressure is less dense and subject to an upward buoyant force. The effect of heating and moistening the air directly over a fire is that the air begins to rise.

The height to which the air rises and the vertical velocity it attains while rising are determined by a host of atmospheric conditions and processes that affect the buoyant force acting on the fire-modified air as it rises. The amount of buoyant force at a given altitude depends on the difference in density between the fire-modified air and the atmosphere at that altitude: larger differences in density increase the magnitude of the force. The maximum vertical velocity of the air can be determined by aggregating the buoyant force throughout the lower levels of the atmosphere, with a larger aggregated buoyant force corresponding to a stronger potential updraft. A common measurement that indicates the magnitude of the aggregated buoyant force is static stability, calculated as the vertical gradient of temperature over an atmospheric layer. Lower static stability corresponds to a larger vertical temperature gradient and indicates a larger aggregate

Meteorological convection is the mechanism by which many clouds and all thunderstorms form in the atmosphere.

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buoyant force as air rises through the layer.

Changes in the speed and direction of horizontal winds as a function of height also play an important role in how high the buoyant force can lift air. Greater wind shear leads to increased turbulence and mixing and typically reduces buoyancy (Moeng and Sullivan 1994). The result is greater mixing but often less lofting of air from the surface.

Pyroconvection, Pyrocumulus, and Pyrocumulonimbus

Pyroconvection, pyrocumulus, and pyrocumulonimbus are three terms often used by the fire and fire weather communities. Although the terms are often treated as interchangeable, each term has a specific and distinct definition that parallels its respective nonfire definition but with "related to fire" added (see, for example, AMS (2012a)). Thus, pyroconvection is the vertical transport of atmospheric properties driven by or enhanced by fire. Every fire, no matter how small, produces some degree of pyroconvection.

A pyrocumulus (or pyroCu, fig. 1) forms when moist rising air from pyroconvection reaches a condensation level, producing a cumulus cloud. The formation of a pyroCu is not uncommon on prescribed fires and agricultural burns and is not necessarily cause for concern.

A pyrocumulonimbus (or pyroCb, fig. 2) is an extreme manifestation of a pyroCu. It develops when upward moving air over a wildland fire is reinforced by instability in the middle troposphere such that a very deep convective cloud forms (Fromm and others 2008, 2010).

Only under rare circumstances would a pyroCu or pyroCb cloud generate a downburst that could alter fire behavior.

PyroCu and pyroCb are important for smoke lofting and transport, but studies have not established whether their formation signals a substantial change in upcoming fire behavior. In most cases, the character of pyroconvection is driven by earlier events that altered the energy released by the fire, such as a sudden change in fire size and intensity due to changes in surface winds, fuel load, or terrain.

Figure 1—*A pyrocumulus forming over a wildland fire. Moist rising air from pyroconvection reaches a condensation level, producing a cumulus cloud. Photo: Candace Krull, Forest Service.*

Figure 2—*A pyrocumulonimbus forming over a wildland fire. Upward moving air, reinforced by instability in the middle troposphere, results in the formation of a very deep convective cloud. The photo is of the 2013 Carpenter 1 Fire in Nevada. Photo: Zachary Parmentier, Forest Service.*

Downbursts

A downburst is an area of strong, often damaging winds produced by one or more convective downdrafts in a localized area (AMS 2012b). Convective downdrafts are a common occurrence during convective precipitation events, and they often lead to the formation of an outflow boundary and a change in surface wind speed, wind direction, and humidity. It is important for fire managers to be aware of the potential for outflow boundaries from any nearby convection to affect fire behavior and smoke. However, it is also important for fire managers to distinguish between convective downdrafts and downbursts.

A downburst is substantially less common than a convective downdraft, occurring when heavy precipitation evaporates in dry air beneath the base of a convective cloud (Wilson and Wakimoto 2001). Downbursts can contribute to very sudden changes in surface winds, moisture, and temperature (Byers and Braham 1949). The magnitudes of these changes are greater for a downburst than for a convective downdraft and are capable of affecting fire behavior (Fujita 1992).

In most cases, downbursts occur several miles away from the primary convective updraft (Wilson and others 1988). Downbursts usually require heavy precipitation, which can only occur when the updraft in the convective cloud produces significant condensation. For a downburst to form, the precipitation must fall into dry air and evaporate as it falls, which implies that it must fall somewhere other than into the (relatively moist) updraft that produced it. A meteorological environment capable of producing these characteristics would therefore have a horizontal wind that shifts the downburst to the other side of the updraft.

These requirements make it unlikely (though still possible) that a downburst produced by pyroconvection would reach the ground close to the fire. Only under rare circumstances would a pyroCu or pyroCb cloud generate a downburst that could alter fire behavior; it would occur only under the influence of a very particular wind shear configuration.

A cautious understanding of science and close collaboration between fire managers and meteorologists can help protect firefighters.

On two historic wildfires, however, fatalities are attributed, at least in part, to downbursts: the 2013 Yarnell Hill Fire and the 1990 Dude Fire. Both fires occurred with thunderstorms nearby. In the case of Yarnell Hill, the official investigation report suggests that downbursts only could have come from the nearby thunderstorms (ADFFM 2013). The documentation of the Dude Fire is less clear; it suggests that a nearby thunderstorm may have been intensified by the fire and subsequently produced a downburst (Goens and Andrews 1998). There are no clearly documented cases of pyroconvection alone producing a downburst.

Firefighters often state that downbursts occur soon after a visible change occurs at the top of a convective column during a fire (the so-called “plume collapse” or “capping”). The ingredients for downburst formation are the magnitude of the convective updraft, the amount of precipitation formed, very low relative humidity below the cloud base, and a supportive wind profile. There is no scientific evidence for downbursts forming as a result of visible features appearing at the top of a convective cloud. Additional research is needed to assess the credibility of cases in which plume collapse has been anecdotally associated with downburst formation and changes in fire behavior.

A Cautious Understanding

Fire activity clearly produces pyroconvection. However, what influence pyroconvection may have on the behavior of a wildland fire is not well understood, which makes it difficult to assess and predict. Clark and others (1996) found in a numerical modeling study that near-ground convection produced by a fire plays a role in the development of characteristic fire behavior patterns. However, the role of convection through deeper layers of the atmosphere (such as a pyroCb) in fire behavior is less clear. As indicated in Potter (2012), wildland fire studies that include an assessment of convection have yet to establish a clear quantifiable connection between convective characteristics (such as updraft strength and cloud depth) and fire behavior. Observational and numerical modeling studies of nonfire convection suggest that elevated updrafts are fed primarily by air entrained and mixed into the updraft well above the base of the cloud (Kain and Fritsch 1990; Kuang and

Bretherton 2006). The extent to which this applies to pyroconvection is not yet known.

Although convection-related phenomena have been extensively studied in meteorological field studies, in theoretical papers, and by using numerical models, there is still considerable uncertainty concerning precisely how they interact with wildland fires. Some of the anecdotal evidence for how these phenomena affect fire behavior does not agree with the meteorological understanding of the processes involved, and other possible connections have yet to be fully investigated and tested. A cautious understanding of the state of this science and close collaboration between fire managers and meteorologists can help protect firefighters from possible convective influences on fire behavior while the research community works to clarify the influences using improved modeling and observational tools.

References

AMS (American Meteorological Society). 2012a. Glossary of meteorology. Boston, MA. <http://glossary.ametsoc.org/wiki/MainPage> (last accessed September 2016).

AMS (American Meteorological Society). 2012b. Glossary of meteorology: Downburst. Boston, MA. <http://glossary.ametsoc.org/wiki/Downburst> (last accessed September 2016).

ADFFM (Arizona Department of Forestry and Fire Management). 2013. Yarnell Hill Fire serious accident investigation report. September 23. Phoenix, AZ.

Byers, H.R.; Braham, R.R., Jr. 1949. The thunderstorm. Washington, DC: U.S. Government Printing Office. 287 pp.

Clark T.L.; Jenkins, M.A.; Coen, J.; Packham, D. 1996. A coupled atmosphere–fire model: Convective feedback on fire-line dynamics. Journal of Applied Meteorology. 35(6): 875–901.

Fromm M.; Shettle, E.P.; Fricke, K.H.; [and others]. 2008. Stratospheric impact of the Chisholm pyrocumulonimbus eruption: 2. Vertical profile perspective. Journal of Geophysical Research. 113: D08203.

Fromm, M.; Lindsey, D.T.; Servranckx, R.; [and others]. 2010. The untold story of pyrocumulonimbus. Bulletin of the American Meteorological Society. 91: 1193–1209.

Fujita, T. 1992. The mystery of severe storms. WRL Res. Pap. Chicago, IL: University of Chicago.

Goens, D.W.; Andrews, P.L. 1998. Weather and fire behavior factors related to the 1990 Dude Fire near Payson, AZ. NWCG Wildland Fire Leadership Development Program.

Kain, J.S.; Fritsch, J.M. 1990. A one-dimensional entraining/detraining plume model and its application in convective parameterization. Journal of Atmospheric Science. 47: 2784–2802.

Kuang, Z.; Bretherton, C.S. 2006. A mass-flux scheme view of a high-resolution simulation of a transition from shallow to deep cumulus convection. Journal of Atmospheric Science. 63: 1895–1909.

Moeng, C.-H.; Sullivan, P.P. 1994. A comparison of shear- and buoyancy-driven planetary boundary layer flows. Journal of Atmospheric Sciences. 51: 999–1022.

N.a. (no author). 2016. Dictionary.com: Convection. Based on the Random House Webster's Unabridged Dictionary. New York: Random House, Inc. <http://www.dictionary.com/browse/convection?s=t> (last accessed September 2016).

Potter, B.E. 2012. Atmospheric interactions with wildland fire behaviour—I. Basic surface interactions, vertical profiles and synoptic structures. International Journal of Wildland Fire. 21: 779–801.

Wilson, J.W.; Wakimoto, R.M. 2001. The discovery of the downburst: T. T. Fujita's contribution. Bulletin of the American Meteorological Society. 82: 49–62.

Wilson, J.W.; Moore, J.A.; Foote, G.B.; [and others]. 1988. Convection Initiation and Downburst Experiment (CINDE). Bulletin of the American Meteorological Society. 69: 1328–1348. ■

TERRAIN-CONTROLLED AIRFLOWS

J.J. Sharples, R.H.D. McRae, C.C. Simpson, P. Fox-Hughes, and C.B. Clements

The presence of mountains—or even hills—in the path of an airmass can have important effects on the characteristics of the air. Temperature, humidity, wind speed, and wind direction can all vary greatly across complex terrain, and the variation of any of these factors will directly affect fire behavior. Indirect effects, such as through the modification of fuel moisture content, will also result. In this article, we discuss aspects of terrain modification of airflows that are relevant to wildland fire management.

Thermally Driven Diurnal Winds

During the day, parts of the landscape will warm or cool, depending on the terrain and the position of the sun. Varying on a diurnal (daily) cycle, these effects are most pronounced in mountainous terrain at sunrise and sunset. Basic thermally driven wind patterns, taught in fire behavior classes, have been known for quite some time. Whiteman (2000) gives a good overview of mountain wind systems. One of the important consequences of thermally driven winds for firefighters is the formation of a thermal belt. McRae and Sharples (2011) describe a simple process model that can be used in operations to assess thermal belt formation on midslopes (fig. 1).

Overall, thermally driven winds can add to the tactical challenges faced by incident management teams. During the critical times of dusk and dawn, crews working to suppress a wildfire must be aware that the fire's behavior could suddenly change. Thermally driven winds can also transport smoke that could cause problems for observers and make spot fire detection difficult. Such winds can also cause local problems for air operations and increase smoke exposure for fire crews and local communities.

Dynamic Channeling

Airflows over mountainous or hilly landscapes can be channeled by the topography in a number of different ways: downward momentum transport; forced channeling; and pressure-driven channeling (Whiteman and Doran 1993). Downward momentum transport happens when airflows in the upper atmosphere are mixed down to the surface, for example, by a large

> Temperature, humidity, wind speed, and wind direction may all vary greatly across complex terrain, directly affecting fire behavior.

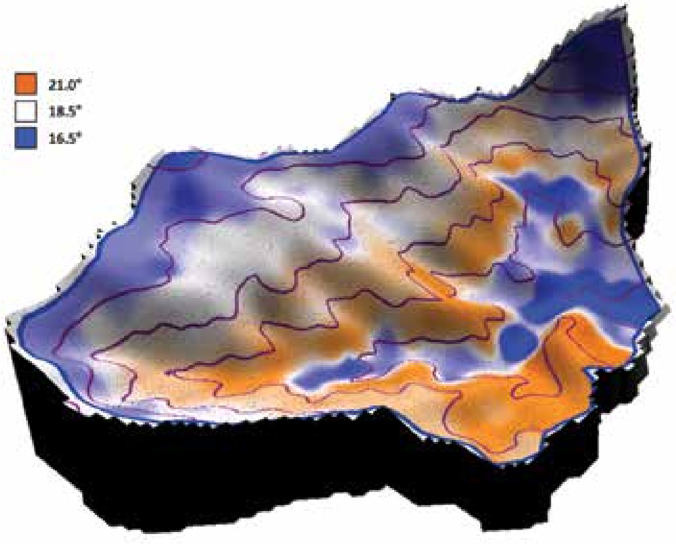

Figure 1—*Model output showing thermal belt formation over a catchment in southeastern Australia. Note the relatively warm midslopes. Temperatures are given in degrees Celsius; red = 69.8 °F; white = 65.3 °F; blue = 61.7 °F. Adapted from McRae and Sharples (2011).*

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At dusk and dawn, crews working on a wildfire must be aware that the fire's behavior could suddenly change.

fire. Because the momentum of the upper winds must be conserved, the surface winds will take on some of the direction of the winds aloft; the momentum of the upper winds is transported downwards. Valley winds driven by this downward transport of momentum are most likely to occur over terrain of mild relief under unstable atmospheric conditions.

Forced channeling results when the sidewalls of a valley cause mechanical deflection of an airflow. Wind funneling by the valley can also intensify the wind speed in the valley. The direction and strength of the resulting channeled flow depend on how the prevailing winds align with the valley. Valley winds will be strongest when the prevailing winds closely align with the along-valley direction. Under certain conditions, the winds within a valley can undergo an immediate reversal as the direction of the airflow changes across a line perpendicular to the valley axis (Kossmann and others 2001; Kossmann and Sturman 2002). With no more than a minor change in the ambient airflow across a mountain valley, firefighters can encounter an abrupt reversal of the main direction of fire spread and smoke movement.

Pressure-driven channeling can cause valley winds when a synoptic pressure gradient is superimposed on a valley. The direction of the winds in the valley depends on the along-valley component of the pressure gradient (fig. 2). An interesting consequence is that pressure-driven channeling can result in valley winds that flow in a direction opposite to the along-valley component of the prevailing winds (fig. 2, right panel). Pressure-driven channeling can produce confounding fire behavior in certain situations. Moreover, in contrast to forced channeling, valley winds resulting from pressure-driven channeling will reverse whenever the direction of the airflow crosses a line parallel to the valley axis (Gross and Wippermann 1987; Kossmann and Sturman 2003).

For most topographic configurations, it is still unclear which concept best describes the dynamically channeled airflows. Observations indicate that pressure-driven channeling is mainly responsible for the modification of large-scale winds in broad and long valleys, whereas forced channeling seems to occur mainly in small valleys, mountain passes, and saddles. The presence of thermal winds and the combination of different dynamic channeling mechanisms can further cloud the processes at play (see Sharples (2009) and the references cited therein). Dynamically channeled winds can therefore greatly increase uncertainty about the behavior of a wildfire and the movement of smoke above it.

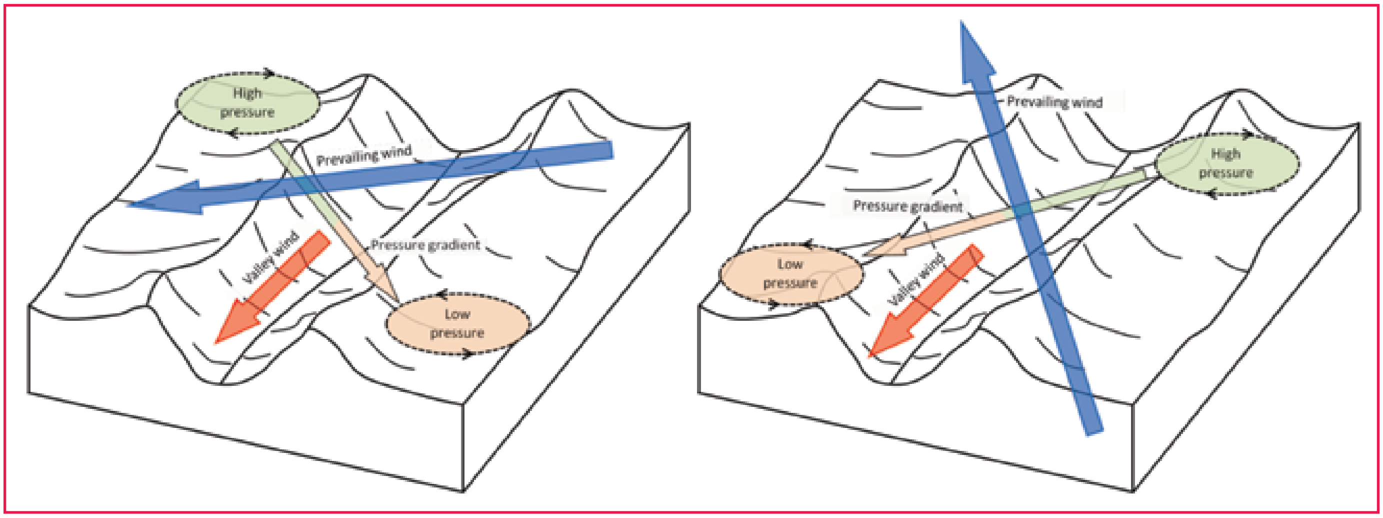

Figure 2—*Two cases of pressure-driven channeling for a valley in the northern hemisphere. On the left, the valley wind direction (red arrow) produced by pressure-driven channeling (gray/pink arrow) coincides with that produced by forced channeling. On the right, pressure-driven channeling produces a countercurrent within the valley to the prevailing wind direction (blue arrow). In each case, the valley wind follows the along-valley component of the pressure gradient.*

Foehnlike Winds

The *foehn effect* is observed globally. Its name derives from winds in the lee of the European Alps, but numerous other names have been given to similar winds. For example, the Chinook wind in parts of the United States and the bergwind of southern Africa are analogues to the foehn. Foehn winds are warm, dry, and strong winds that form in the lee of mountains or major hills. The defining characteristics of a foehn—low moisture content as well as high temperature and speed—all act to amplify fire behavior.

A foehn often begins as moist air is forced to rise over mountainous terrain. As it rises in elevation, it moves into a region of lower pressure, expanding and cooling as a result. Cooler air cannot hold as much moisture, so some of the moisture condenses into droplets, which fall as rain. As the water vapor condenses, it releases heat that warms the rising air. When the air descends on the other side of the mountains it retains the additional warmth and is drier because it lost moisture in the rain over the windward slopes.

Another foehn effect, less commonly recognized, occurs without rainfall over the windward slopes in mountainous terrain. If moister, lower level air is blocked by a mountain on its windward side, then drier, upper level air will flow in to replace it on the leeward side. As this upper air descends farther down the leeward slope of the mountain than it ascended on the windward side, it will warm overall. In some situations, the air may descend an additional several hundred feet on the leeward side, warming by roughly 0.5 °F (0.3 °C) for every 100 feet (30 m) of additional fall. Its relative humidity will also be lower. The Californian Santa Ana is an example of this type of foehn (Keeley 2004).

Figure 3 illustrates a foehn wind during a southwesterly flow over the island of Tasmania, Australia. The colored contours indicate vertical motion: red is upward motion and blue downward motion, with the airflow running left to right across the page. The topography is shown as a black silhouette. The large blue area of downward airflow, just right of center-figure, is a foehn wind. The background green/orange with white contouring is relative humidity. Thus, the relative humidity of the ascending air increases, while that of the strongly descending air decreases, markedly so at low elevation.

A minor change in the ambient airflow across a mountain valley can abruptly reverse the main direction of fire spread and smoke movement.

During foehn wind events, the air often flows down valleys and channels, its speed increasing as it is funneled through such features. Also, atmospheric stability effects can result in downslope winds that are stronger than winds on the upslopes. In the lee of mountains, all of these factors may act in concert to produce atmospheric conditions that are particularly hazardous in the context of wildland fire management.

Other Leeward Slope Effects

Other effects of topography on windflows are often most notable on the leeward side of mountains, where phenomena like flow separation and gravity waves, along with their associated turbulence, can have significant ramifications for wildfire development. In addition to the strategic challenge posed by foehnlike winds for firefighting operations, the leeward slopes in mountainous terrain can pose considerable challenges at the tactical level.

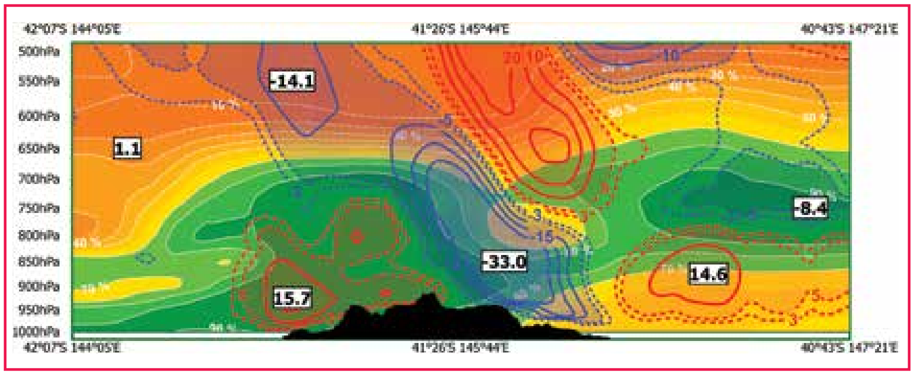

Figure 3—*Vertical cross-section southwest to northeast through Tasmania, showing the foehn effect operating in a southwesterly flow. White contours (in percent) indicate relative humidity, which is also contoured orange (dry) through green (moist). Red and blue contours represent vertical motion in cm s*$^{-1}$*, with red indicating ascent and blue descent.*

Countryman (1971) described a process by which a wildland fire burning on a leeward slope interacts with terrain-affected airflows and can spread laterally across the leeward slope. The heat of the fire creates an upslope wind that converges with the cooler, opposing background winds flowing over the ridge. The convergence of airflows produces conditions favorable for the formation of firewhirls in the lee of the ridge. A firewhirl is a vertically oriented, intensely rotating column of air above or near a fire. It can range in size from feet to miles in diameter (Forthofer and Goodrick 2011).

Extreme fire behavior consistent with the processes described by Countryman (1971) has been observed in the lee of a ridge on a number of occasions. McRae (2004) and Sharples and others (2012) used a variety of remote-sensing techniques to pinpoint instances of extreme fire behavior on the lee side of ridges during the 2003 Canberra bushfires in Australia. Similar behavior has been observed on other fires, such as the 2013 Wambelong Fire in New South Wales (fig. 4). In those cases, the fire spread laterally across the leeward slope, almost at right-angles to the background wind (fig 4a). In addition to the atypical lateral spread, spotting causes the fire to extend rapidly downwind of the leeward slope. The deep areal flaming (fig. 4b) that results from such events can produce vigorous pyroconvection and even large fire thunderstorms (Fromm and others 2006; McRae and others 2015).

> Dynamically channeled winds can increase uncertainty about the behavior of a wildfire and the movement of smoke above it.

The atypical lateral fire spread described above has been reproduced in both laboratory experiments (Sharples and others 2010) and coupled fire-atmosphere model simulations (Simpson and others 2013, 2014). The simulations also suggest that the lateral fire spread is driven by firewhirls that develop in the lee of a ridge. The vigorous pyroconvection associated with the lateral fire spread and the atmospheric turbulence associated with the leeward environment are conducive to mid- to long-range spotting downwind of the lee slope.

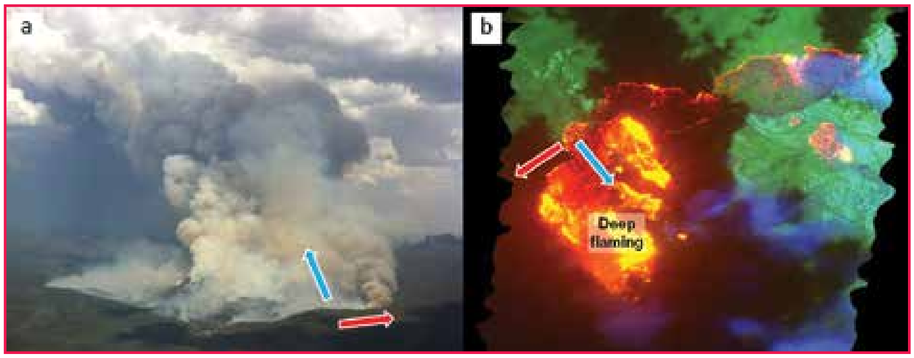

Figure 4—*An example of atypical lateral spread, which occurred in connection with the 2003 Wambelong firestorm in New South Wales, Australia. (a) Photo of a fire spreading transverse to the wind across a leeward slope. (b) Multispectral line scan image showing "deep flaming" downwind of this region of lateral spread. In each panel, the blue arrow indicates the main wind direction and the red arrow indicates the direction of lateral spread. Photo: Stephen Wilkes.*

Both the observational data and the model simulations suggest that atypical lateral fire spread depends on a number of environmental thresholds, including the background wind speed, the wind direction relative to the terrain aspect, and the terrain steepness (see, for example, Sharples and others (2013)). Broadly speaking, atypical lateral spread should be expected on steep (over 45- to 50-percent) leeward slopes with aspects within 30 to 40 degrees of the direction the wind is blowing when prevailing winds are over about 12 miles per hour (19 km/h). These environmental thresholds are likely due to a close association between the atypical lateral fire spread and the atmospheric turbulence required in the lee of a ridge. Operational products, including some under development, can help fire managers predict the occurrence of these atypical events by allowing regions where the environmental thresholds are exceeded to be mapped.

Understanding Terrain-Modified Airflows

Understanding how terrain-modified airflows fit into the broader weather picture is important for wildland fire management. Incident management teams now have access to a number of tools for anticipating the strategic challenges of the fire environment (for example, gridded weather forecast systems and models such as "WindNinja"), but it is important to acknowledge the limitations of these tools. If the grid resolution of the model is greater than the scale of the terrain features or if the model does not adequately account for the driving mechanisms, then important terrain-driven variations in winds might not be predicted. Unforeseen changes in the behavior of a wildfire could result, with implications for containment tactics and for firefighter and community safety.

> Understanding how terrain-modified airflows fit into the broader weather picture is important for wildland fire management.

References

Countryman, C.M. 1971. Fire whirls … why, when, and where. Report. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Forthofer, J.; Goodrick, S. 2011. Review of vortices in wildland fire. Journal of Combustion. 14: 984363.

Fromm, M.; Tupper, A.; Rosenfeld, D.; Servranckx, R.; McRae, R. 2006. Violent pyro-convective storm devastates Australia's capital and pollutes the stratosphere. Geophysical Research Letters. 33: L05815.

Gross, G.; Wippermann, F. 1987. Channelling and countercurrent in the upper Rhine valley: Numerical simulations. Journal of Climate and Applied Meteorology. 26: 1293–1304.

Keeley, J.E. 2004. Impact of antecedent climate on fire regimes in coastal California. International Journal of Wildland Fire. 13(2): 173–182.

Kossmann, M.; Sturman, A.; Zawar-Reza, P. 2001. Atmospheric influences on bushfire propagation and smoke dispersion over complex terrain. In: Pearce, G.; Lester, L., eds. Proceedings of the Australasian Bushfire Conference; 3–6 July 2001; Christchurch, New Zealand. New Zealand Forest Research Institute: Rotorua, New Zealand.

Kossmann, M.; Sturman, A.P. 2002. Dynamic airflow channelling effects in bent valleys. In: Proceedings of the 10th Conference on Mountain Meteorology; 17–21 June 2002; Park City, UT. Boston, MA: American Meteorological Society.

Kossmann, M.; Sturman, A.P. 2003. Pressure-driven channelling effects in bent valleys. Journal of Applied Meteorology. 42(1): 151–158.

McRae, R. 2004. Breath of the dragon—Observations of the January 2003 ACT Bushfires. In: Bushfire Conference 2004: Earth, Wind and Fire—Fusing the Elements; 25–28 May 2004; Adelaide, Australia. South Australian Department of Environment and Heritage.

McRae, R.H.D.; Sharples, J.J. 2011. Modelling the thermal belt in an Australian bushfire context. In: Chan, F.; Marinova, D.; Anderssen, R.S., eds. Proceedings of the 19th International Congress on Modelling and Simulation (MODSIM2011); 12–16 December 2011; Perth, Australia. Modelling and Simulation Society of Australia and New Zealand: 221–227.

McRae, R.; Sharples, J.J.; Fromm, M. 2015. Linking local wildfire dynamics to pyroCb development. Natural Hazards and Earth System Sciences. 15: 417–428.

Sharples, J.J. 2009. An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. International Journal of Wildland Fire. 18: 737–754.

Sharples, J.J.; Viegas, D.X.; Rossa, C.G.; McRae, R.H.D. 2010. Small-scale observations of atypical fire spread caused by the interaction of wind, terrain and fire. In: Viegas, D.X., ed. Proceedings of the VI International Conference on Forest Fire Research; 15–18 November 2010; Coimbra, Portugal.

Sharples, J.; Simpson, C.; Evans, J. 2013. Examination of wind speed thresholds for vorticity-driven lateral fire spread. In: Piantadosi, J.; Anderssen, R.; Boland, J., eds. Proceedings of the 20th International Congress of Modelling and Simulation Modelling and Simulation; 01–06 December 2013; Adelaide, South Australia.

Sharples, J.; McRae, R.; Wilkes, S. 2012. Wind-terrain effects on the propagation of large wildfires in rugged terrain: Fire channelling. International Journal of Wildland Fire. 21: 599–614.

Simpson, C.; Sharples, J.; Evans, J.; McCabe, M. 2013. Large eddy simulation of atypical wildland fire spread on leeward slopes. International Journal of Wildland Fire. 22: 282–296.

Simpson, C.C.; Sharples, J.J.; Evans, J.P. 2014. Resolving vorticity-driven lateral fire spread using the WRF-Fire coupled atmosphere-fire numerical model. Natural Hazards and Earth System Sciences. 14: 2359–2371.

Whiteman, C.D. 2000. Mountain meteorology fundamentals and applications. New York: Oxford University Press.

Whiteman, C.D.; Doran, J.C. 1993. The relationship between overlying synoptic-scale flows and winds within a valley. Journal of Applied Meteorology. 32: 1669–1682. ■

RED FLAG WARNINGS IN THE 21ST CENTURY

Heath Hockenberry

A Red Flag Warning (RFW) is the fundamental fire-weather-warning product of the National Weather Service. Various publications and online meeting notes show that RFWs originated in the late 1950s to early 1960s. Early sources defined the RFW as an indication of weather expected to be of "particular importance to fire behavior," to be rarely used.

Scope and Purpose

The RFW became particularly important after the devastating California wildfires of 1970. After that fire season, various working groups chartered under the Firefighting Resources of Southern California Organized for Potential Emergencies (FIRESCOPE) program used the RFW as part of their "Fire Weather Alert" program. According FIRESCOPE meeting notes, RFWs eventually replaced the need for products related to fire weather alerts in California (FIRESCOPE 1981, 1984a, 1984b). They delivered a consistent and coordinated message about critical local conditions related to fire weather and fuels.

Today, according to National Weather Service directives for Fire Weather Services, forecasters issue an RFW "when the combination of fuels and weather conditions support extreme fire danger and/or fire behavior" (NWS 2013). According to the National Wildfire Coordination Group, an RFW is used to "alert forecast users to an ongoing or imminent critical fire weather pattern" (NWCG 2004). In other words, an RFW is designed to alert land management agencies to the potential for widespread new ignitions or control problems with existing wildfires, both of which could pose a threat to life and property. Accordingly, the RFW is now far from rare. In fact, the National Weather Service issues an average of 15,000 RFWs each year.

> The Red Flag Warning became particularly important after the devastating California wildfires of 1970.

Criteria for Issuance

The National Weather Service decides on criteria for RFWs based on (1) meetings between the agency's local weather forecast offices and local users; and (2) historical analysis of fire danger and fire behavior within what are known as fire weather zones. Fire weather zones mirror the National Weather Service's public weather zones but can reach across public zones to better coincide with public land boundaries. Figure 1 shows a fire weather zone map of Idaho.

Figure 1—*Idaho Fire Weather Zone boundaries set by the National Weather Service for the Management Information Retrieval System.*

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The National Weather Service assigns red flag criteria to a fire weather zone from the ground up. Local meetings and conversations give users flexibility in defining criteria. The core parameters of an RFW include critical values of wind, relative humidity, lightning potential, and fuels data. These general parameters set the boundary conditions for selecting specific criteria. For example, fuels data—a general criterion—can take the form of 10-hour fuel moisture, fire danger adjective rating, or any other applicable fuels criterion.

Additionally, different combinations of wind and relative humidity values can be used to decide whether to issue an RFW. Local users provide the expertise on how the available fuels will respond to such weather factors. National Weather Service forecasters do not directly monitor fuels status; they get information about fuel dryness from local users and take it into account in deciding whether to issue an RFW. A forecaster will issue an RFW when critical fuels align with weather factors worthy of a warning.

The National Weather Service's directive and instruction series gives guidance on the criteria to use in issuing RFWs. According to the agency's own requirements, both weather and fuels information go into deciding whether an RFW is issued, making the RFW unique: it is the National Weather Service's *only* product based on both internal and external information. Most of the agency's other warnings are based on forecaster interpretation of hydrometeorological data alone.

Moreover, NWS policy does not dictate the type of fuels information to use in deciding whether to issue an RFW. This has resulted in a wide variety of RFW criteria in use across the country. In terms of consistency, local flexibility is both a strength and a weakness. The product is consistent with the end user interpretation of expected fire behavior and in resulting user actions. However, the product is inconsistent in terms of the actual criteria used to justify a warning. In addition, smoke output is not a consistent criterion for an RFW. Smoke parameters such as dispersion and ventilation rate are used in some areas to help decide whether an RFW is issued, but this is not a standard practice. Lightning occurrence is used in some parts of the country but not in others. Table 1 shows a small sample of the variety of RFW criteria for southern California. There are actually several dozen more combinations of criteria used as the basis for an RFW.

Public Perceptions of Red Flag Warnings

The RFW is first and foremost a wildland fire management tool and a firefighter safety product. One of the chief concerns about the RFW is its use by the general public. Both the fire weather alert and the RFW were originally intended to notify fire managers of imminent danger so they could take action to protect the public. The RFW was never intended as an actionable public product for people to use in protecting assets and moving to safety. Taking action in response to an RFW has been and remains a responsibility of local fire departments and agencies.

Table 1—*Various Red Flag Warning criteria from the 2014 California Annual Operating Plan, by area and National Fire Service fire weather zone in southern California.*

Area Description	Fire Weather Zones	Criteria
Southern California desert area excluding the lower Colorado River Valley	226–228, 230, 232, 260–262	Relative humidity ≤ 15% and wind gusts ≥ 35 mph for 6 hours or more, assuming fuel conditions are critical.
Lower Colorado River Valley	229, 231	Relative humidity ≤ 15% with sustained winds ≥ 20 mph or wind gusts ≥ 35 mph for 3 hours or more.
Antelope Valley and southeastern Kern County deserts	298, 299, 259	Relative humidity ≤ 15% and sustained (20-foot) winds ≥ 25 mph for a duration of 8 hours or more.
Central California interior (WFO Hanford)	289–297	RAWS sustained winds ≥ 25 mph or frequent gusts ≥ 35 mph AND relative humidity ≤ 15% for a duration of 6 hours or more. OR relative humidity ≤ 10% for a duration of 10 hours or more regardless of wind.

Source: California Wildfire Coordinating Group (2014).

Forecasters issue a Red Flag Warning "when the combination of fuels and weather conditions support extreme fire danger and/or fire behavior."

Nevertheless, fire managers need to pay careful attention to the public and social impacts of issuing these types of warnings. Every warning carries with it potential decisions to restrict public land use, mobilize firefighting resources, and organize evacuations. Media broadcasts of RFWs also raise public concerns, causing people to ask questions about a warning's meaning for them.

Unfortunately, National Weather Service forecasters do not have the same remote-sensing capabilities available for fire that they have for other types of severe weather. For tornadoes and severe storms, radar detection is precise and nearly instantaneous, allowing forecasters to predict the movement and intensity of the storms. Such precise intelligence does not yet exist for wildland fires, although innovations could change the situation. Such innovations include crowdsourcing through social media, advanced remote sensing, and advances in radar detection technology.

Future Improvements

Improvements in the use of RFWs depend upon advances in technology and remote sensing. Strictly speaking, RFWs are not predictions of wildland fire occurrence or behavior. They highlight a combination of conditions conducive to very high to extreme fire danger or new fire starts. As a result, RFWs are sometimes issued under dangerous conditions with no subsequent fire occurrence, creating perceptions of "false alarms." The belief has arisen that the National Weather Service issues too many RFWs.

However, an RFW depends on criteria-based weather conditions. Defined before fire season begins, the weather conditions depend on the status of fuels. Therefore, an RFW raises no more than the *potential* for widespread new ignitions or control problems with existing fires. It does not attempt to predict numbers of fire starts or a particular day's fire activity. An RFW is verified simply by matching preseason decisions about critical weather factors and fuels with the actual occurrence of those weather and fuels conditions.

Advances in remote sensing, on-the-ground intelligence, and radar sensing might lead to new ways of issuing the red flag product, thereby preventing perceptions of "overwarning." One option might be changing the RFW process to associate the warnings with actual fire detection. As the fire is detected or reported, the weather forecast office would examine the meteorological conditions and issue warnings based on the detected fire behavior and potential threat. Antecedent conditions would be covered and communicated purely through fire weather watches. This would produce an RFW program of the future, matching the guidelines of the 1960s, when issuing an RFW was indeed a rare event.

As technology improves in remote sensing and real-time fire behavior reporting, future RFWs may come to closely resemble a tornado/severe weather warning. This would create new impact-based warnings related to fire behavior, with increased direct public use. Nevertheless, the RFW will remain the National Weather Service's first and primary warning service to its land management partners.

References

California Wildfire Coordinating Group. 2014. California fire weather annual operating plan, 2014. <http://gacc.nifc.gov/oscc/predictive/weather/AOP/Entire_AOP.pdf> (last accessed March 2015).

FIRESCOPE (Firefighting Resources of Southern California Organized for Potential Emergencies). 1981. Proceedings of and meeting notes from California Division of Forestry FIRESCOPE Operations Team. January 26–27. <http://www.firescope.org/meetings/opsteam/1981/meeting1/docs-ops-jan-26-1981.pdf> (last accessed February 2015).

FIRESCOPE (Firefighting Resources of Southern California Organized for Potential Emergencies). 1984a. Proceedings of and meeting notes from California Division of Forestry FIRESCOPE Weather Specialists Team. July 2. <http://www.firescope.org/meetings/opsteam/1984/meeting4/docs-ops-july-11-1984.pdf> (last accessed February 2015).

FIRESCOPE (Firefighting Resources of Southern California Organized for Potential Emergencies). 1984b. Proceedings of and meeting notes from California Division of Forestry FIRESCOPE Operations Team. October 29–30. <http://www.firescope.org/meetings/opsteam/1984/meeting6/docs-ops-oct-29-1984.pdf> (last accessed February 2015).

NWCG (National Wildfire Coordinating Group). 2004. Glossary of wildland fire terminology. Boise, ID. <http://www.nwcg.gov/pms/pubs/glossary/> (last accessed September 2016).

NWS (National Weather Service). 2013. National Weather Service Directive Series, Instruction 10–401: Fire weather services product specification. September 30. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, DC. <http://www.nws.noaa.gov/directives/sym/pd01004001curr.pdf> (last accessed February 2015). ■

CRITICAL FIRE WEATHER PATTERNS

Paul Werth

Eyewitness accounts in journals and diaries have documented the relationship between weather and large wildland fire for over a hundred years. Even a hundred years ago, observers recognized short periods of up to several days in every fire season when wildland fuels were unusually susceptible to large fires, depending mainly on the weather. Show (1931) referred to these as "dangerous periods."

However, not until the 1960s were critical fire weather patterns that produced high fire danger and large wildland fires identified for the United States and Canada. Syverson (1962) recorded the first definition of critical fire weather patterns as the "critical day, week or month during which blow-up fires are experienced." Current fire behavior training courses define critical fire weather patterns as the atmospheric conditions that encourage extreme fire behavior, resulting in large and destructive wildland fires.

Critical Weather Elements

Early fire weather research focused on individual weather elements that occurred before and during large wildland fires. The early studies identified four critical weather elements common to wildland fires exhibiting extreme fire behavior: low relative humidity (low atmospheric moisture), strong surface wind, unstable air, and drought.

Four critical weather elements can contribute to extreme fire behavior: low relative humidity, strong surface wind, unstable air, and drought.

Low relative humidity adversely affects fire behavior by decreasing the moisture content of fine dead fuels, making them easier to ignite—and easier for them to carry fire. Fireline intensity (in kilowatts per meter), in rate of spread (meters per second), and the probability of spotting significantly increase when the relative humidity is low, sometimes so rapidly that there is little advance warning. Extreme fire behavior becomes more likely once regional threshold values for low relative humidity are exceeded; the values exceeded can range from 10 to 40 percent, depending upon fuel model.

The relationship between strong surface wind and large fires exhibiting extreme fire behavior has been well documented for hundreds of years. Wind affects wildland fire in a number of ways. It supplies additional oxygen to the fire, increasing fire intensity. It also preheats the fuels ahead of the fire and increases rate of spread by carrying heat and burning embers to new fuels (spotting). Subsequent fire weather research has documented strong cold front, thunderstorm, and foehn winds in connection with extreme fire behavior conditions.

With the advent of radiosonde data, researchers could investigate the influence of upper air temperature, relative humidity, and wind on wildland fire behavior. Crosby (1949) was the first to study the effect of atmospheric stability on fire behavior. He concluded that stable air dampened convection currents over a fire, whereas unstable air increased the speed and depth of the convection currents. Haines (1988) developed a lower atmosphere severity index based on the stability and moisture content of the lower atmosphere. The drier and more unstable the airmass becomes, the higher the Haines Index and the greater the threat of large wildland fire and extreme fire behavior.

In summary, unstable air amplifies the vertical growth of the smoke plume over a fire by bolstering the strength of the updrafts. This increases combustion rates by supplying more oxygen to the fire. As the height and strength of the smoke plume increases, the potential for gusty surface winds, dust devils, and firewhirls also increases. Spotting may become profuse all around the fire as large firebrands are lifted into the smoke plume. Unstable air also increases the probability of thunderstorms and strong downdraft winds.

Drought affects fuel availability by lowering the moisture content of live and dead fuels, making them more combustible. Drought conditions are not a prerequisite

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for large fires, but there is a close relationship between drought conditions, large wildland fires, and extreme fire behavior when low relative humidity and either strong wind or unstable air are present.

Critical Atmospheric Conditions

Critical fire weather patterns contain a combination of atmospheric conditions that significantly increase the threat of destructive wildland fires exhibiting extreme fire behavior. The patterns always contain air that is very dry for the region and season, resulting in unusually low relative humidity. Beyond that, they can be separated into two primary categories:

- Patterns that produce strong surface wind, and
- Patterns that produce atmospheric instability.

Strong wind with high relative humidity is not a critical fire weather condition, nor is unstable air combined with high relative humidity. When critical fire weather patterns occur during periods of drought, the threat of extreme fire behavior greatly increases due to low live fuel moisture in brush and timber fuels. However, in grass fuels, some of the worst fire behavior has occurred during moist periods, owing to increased fuel loadings.

The key to identifying a critical fire weather pattern is recognition that these patterns must produce unusually low relative humidity for the region, along with strong surface wind or unstable air. The fuels must also be available to burn for these patterns become an extreme fire behavior threat.

Critical Patterns in the Eastern United States

Schroeder and others (1964) and Brotak and Reifsynder (1977) studied wildland fires in the Eastern United States that had surface frontal systems and upper level troughs and ridges. They found that large fire growth tended to occur just before and after passage of colds fronts. At 500 hectopascals (about 18,000 feet above mean sea level), the favored area for large fire growth was between the upper ridge and trough axis. Dry cold fronts associated with fast-moving and weak upper level 500-hectopascal troughs can produce some of the most critical fire weather situations.

Critical fire weather patterns during the spring and fall fire seasons in the Eastern United States can be classified into two major categories: precold frontal and postcold frontal. The primary factor that decides which one is associated with critical fire weather is whether the area of unusually low relative humidity is located before or behind the cold front.

Figure 1 depicts an idealized example of a precold-frontal critical fire weather pattern. In this case, the area of unusually low relative humidity is located ahead of the cold front, often associated with strong westerly or southwesterly winds resulting in adiabatic warming and drying (warming at 5.5 °F per 1,000 feet (3.0 °C per 305 m) drop in elevation with declining relative humidity) in the lee of the Rocky Mountains. Moist air from the Gulf of Mexico or the Atlantic Ocean is pushed well to the east of the cold front by these warm, dry winds.

> Critical fire weather patterns produce unusually low relative humidity for the region, along with strong surface wind or unstable air.

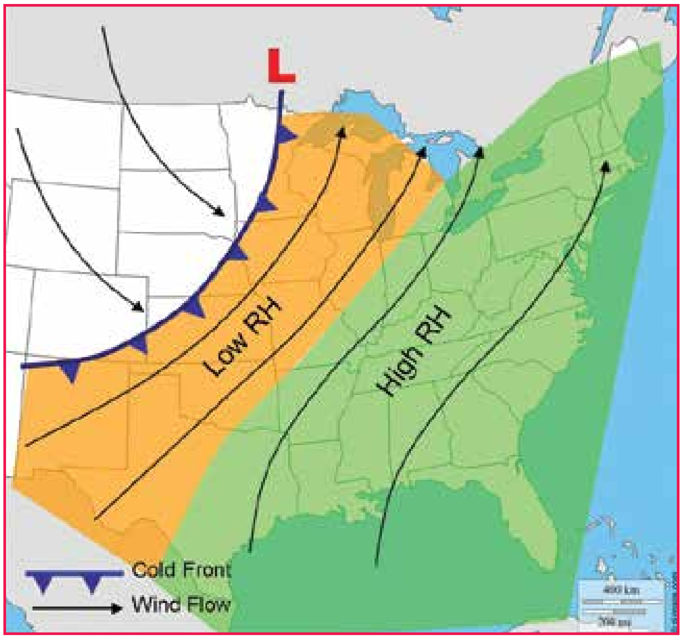

Figure 1—*Idealized example of a dry cold front with unusually low relative humidity ahead of the front.*

Of particular concern to firefighters is the unstable air located within the cold-frontal boundary and the 90-degree shift in wind direction, from the southwest to northwest, during the cold front passage. This shift in wind direction can rapidly change fire behavior as the right flank of the fire becomes a head fire. A gradual progression to a cooler, more stable air with higher relative humidity follows the passage of the cold front.

The Mack Lake Fire in Michigan on May 5, 1980, is a classic example of a wildfire that burned during a precold-frontal critical fire weather pattern. Ahead of the dry cold front, the relative humidity was unusually low at 24 percent, and the winds were gusting from the southwest at 15 to 25 miles per hour (24–40 km/h). The direction of fire spread drastically changed when the winds shifted northwesterly behind the front, and the relative humidity gradually rose.

The postcold-frontal critical fire weather pattern is depicted in figure 2. In this case, the area of unusually low relative humidity follows the passage of a dry cold front and is accompanied by strong northwest winds. This dry, stable air is contained in surface high-pressure systems originating from either northwestern Canada, the Hudson Bay area, or the Pacific Ocean after crossing the Rocky Mountains. Moist air ahead of the cold front, from the Gulf of Mexico or the Atlantic Ocean, is pushed eastward during frontal passage. Once the cold front approaches the Atlantic Coast, adiabatic warming and drying can occur as the northwesterly winds flow down the leeward slopes of the Appalachian Mountains.

The Sunrise Fire on Long Island, NY, on August 25, 1995, is an example of a fire that burned during a postcold-frontal critical fire weather pattern, with strong north winds and a relative humidity of less than 20 percent.

Critical Patterns in the Western United States

The study of critical fire weather patterns in the Western United States can be traced back to Syverson (1963), who investigated synoptic fire weather types in the northern Intermountain West, the Northern Rockies, and the northwestern Great Plains. He concluded that the greatest fire danger occurs just ahead of the upper trough in the area of low pressure at the surface, a pattern that Nimchuk (1983) later called the breakdown of the upper level ridge. Schroeder and others (1964), in their comprehensive study, concluded that critical fire weather in the Intermountain West is associated with upper troughs, jet streams, and surface dry cold fronts. They also stated that weather patterns producing foehn winds are most important along the Pacific Coast and the eastern slopes of the Rocky Mountains.

> The Mack Lake Fire in 1980 is a classic example of a wildfire that burned during a precold-frontal critical fire weather pattern.

Figure 3 shows an idealized version of the critical fire weather pattern associated with a breakdown of the upper level ridge. In this example, which is typical of the summer fire season in the Western United States, an upper level high pressure system at 500 hectopascals (depicted as a solid black line in figure 3) is centered near the Four Corners area (where Arizona, Colorado, New Mexico, and Utah join), with a ridge extending northward into eastern Montana. At the same time, an upper level trough is moving into Washington and Oregon. The sur-

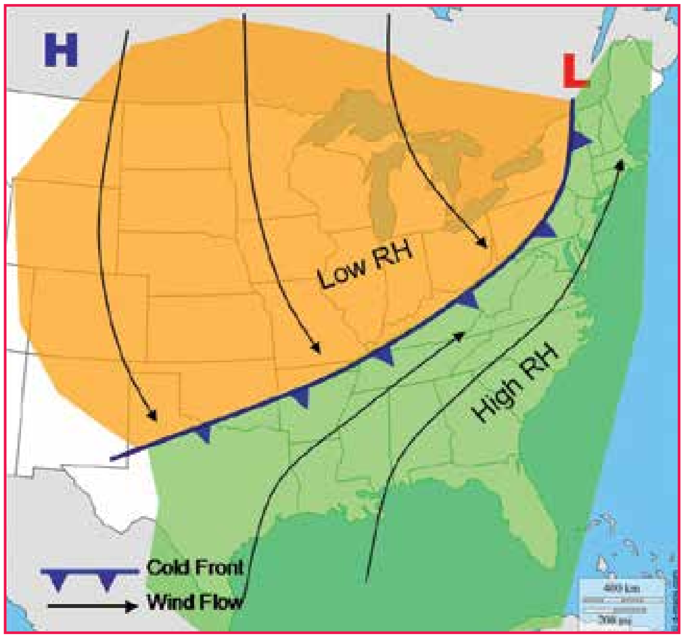

Figure 2—*Idealized example of a dry cold front with unusually low relative humidity behind the front.*

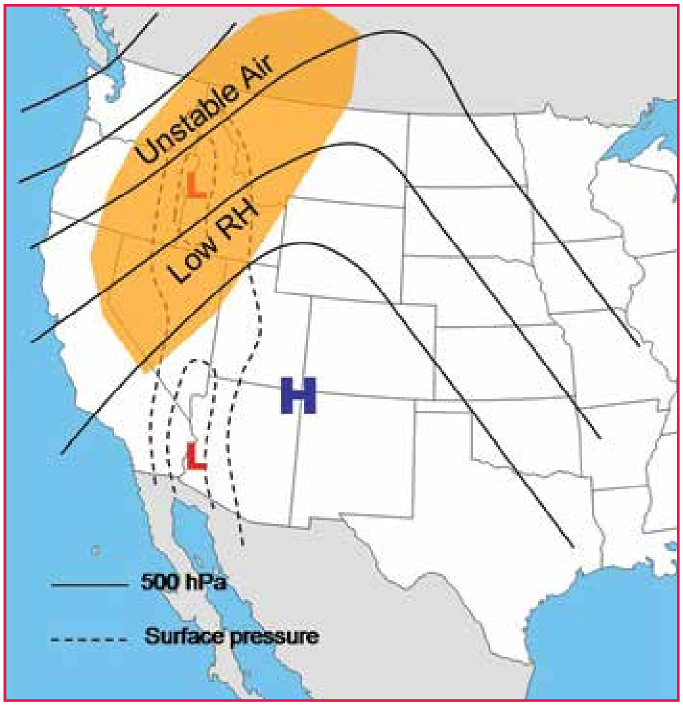

Figure 3—*Critical fire weather pattern associated with a breakdown of the upper level ridge, with a surface thermal trough and an area of unusually low relative humidity and unstable air.*

face pressure pattern (dashed black lines in figure 3) shows a thermal trough extending northward from the California/Arizona border into western Idaho. The thermal trough, resulting from intense surface heating, represents the area of hottest temperatures. Both the upper ridge and the surface thermal trough are being pushed eastward by the upper level trough. Between the upper ridge and the upper trough is an area of unusually low relative humidity and unstable air (shown in brown in figure 3). The unstable air results from cooling aloft due to descending 500-hectopascal heights and the hot temperatures in the thermal trough.

The concept of unstable air due to cooling aloft and heating below is taught in the National Wildfire Coordinating Group course "Intermediate Fire Behavior." The combination of unstable air and low relative humidity produces moderate to high Haines Index values and an elevated risk of extreme fire behavior and large fire growth. These conditions are also favorable for dry lightning if there is sufficient moisture aloft for thunderstorm development. Gusty surface winds can also occur as a result of downward momentum of strong winds aloft and/or outflow winds from thunderstorms. With summertime drought conditions lowering the moisture content of fuels, this critical fire weather pattern can produce all four weather elements necessary for extreme fire behavior and large fire growth: unusually low relative humidity, strong wind, unstable air, and drought.

> A critical fire weather pattern in the Western United States is the foehn wind, a strong, warm, dry wind on the lee side of mountain ranges.

The other critical fire weather pattern in the Western United States is the foehn wind, which is a strong, warm, dry wind on the lee side of mountain ranges. The name for foehn winds varies by region: East wind in western Washington and western Oregon; North wind in northern California; Mono wind in central California; Sundowner or Santa Ana wind in southern California; and Chinook wind along the eastern slopes of the Rocky Mountains. Whatever the name, foehn winds are all produced by strong surface pressure gradients across mountain ranges. Foehn winds are most likely from late summer through fall and winter, when the polar jet stream becomes stronger and cool, dry high-pressure systems begin to invade the Intermountain West.

Figure 4 is an example of a surface pressure pattern that produces Santa Ana winds in southern California. In this case, a strong surface high pressure system is centered in Utah and covers most of the Western United States. A strong pressure gradient over southern California, depicted by the tight spacing of isobars (black lines in figure 4), results in northeasterly winds (red arrow). As the stable flow of air is forced over the mountains of southern California, winds flow down the western (lee) slopes, accelerating and warming at the dry adiabatic lapse rate. This also lowers the relative humidity of the air. Well-established Santa Ana winds in the coastal areas of southern California can reach wind speeds of 50 to 60 miles per hour (80–97 km/h), with temperatures well above 90 °F (32 °C) and a relative humidity of less than 10 percent. Wind speeds can be even higher in mountain gaps and down canyons toward the Pacific Coast.

Fire behavior can rapidly become extreme during Santa Ana wind events, adversely affecting firefighter and public safety.

> Periods of critical fire weather occur in transition zones between high and low pressure systems, both at the surface and in the upper air.

Weather Patterns of Most Concern

Periods of critical fire weather occur in transition zones between high and low pressure systems, both at the surface and in the upper air. The surface pressure patterns of most concern are associated with cold fronts and terrain-induced foehn winds. The upper air pattern that is most critical is the area between the upper level ridge and the trough, a pattern called the breakdown of the upper level ridge.

Though regional variations in critical fire weather patterns exist, all contain weather elements that can produce extreme fire behavior and large fire growth. These elements are unusually low relative humidity coupled with strong wind and/or unstable air. Drought is an added factor because it significantly lowers the moisture content of live and large dead fuels, which increases fireline intensity and the threat of extreme fire behavior. If all four weather elements are involved in a critical fire weather pattern, the probability of extreme fire behavior and large fire growth drastically increases. Additional research is needed to better understand the many variations of these critical fire weather patterns and the dynamics of each that adversely affect wildland fire behavior.

Understanding weather's influence on wildland fire is essential to safe and effective wildland fire suppression. Fire managers and firefighters should be aware of critical fire weather patterns in the area where they are working. They need to understand how adverse weather associated with these critical patterns can produce extreme fire behavior, putting the safety of firefighters and the public at risk.

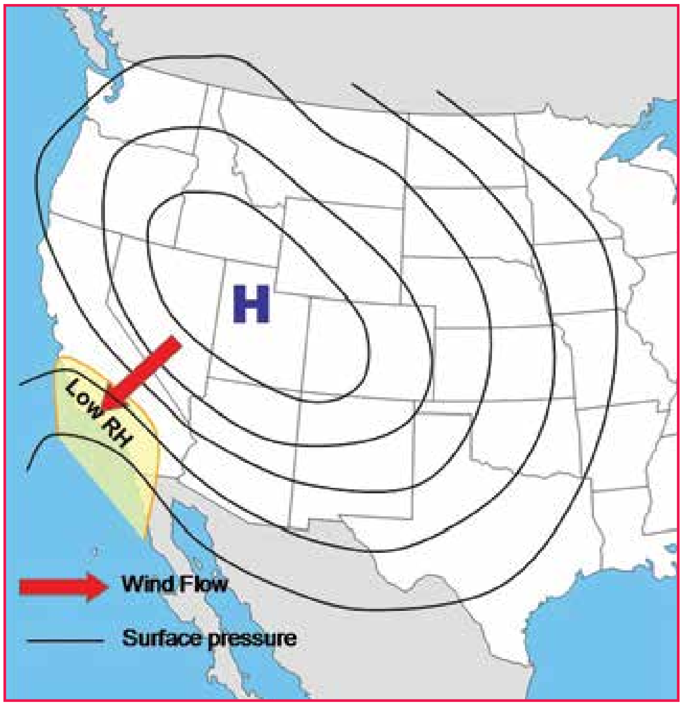

Figure 4—*A surface weather pattern that produces Santa Ana winds in southern California.*

References

Brotak, E.A.; Reifsnyder, W.E. 1977. An investigation of the synoptic situations associated with major wildland fires. Journal of Applied Meteorology. 16(9): 867–870.

Crosby, J.S. 1949. Vertical wind currents and fire behavior. Fire Control Notes. 10(2): 12–15.

Haines, D.A. 1988. A lower atmospheric severity index for wildland fires. National Weather Digest. 13: 23–27.

Nimchuk, N. 1983. Wildfire behavior associated with upper ridge breakdown. Rep. T/50. Edmonton, AB: Alberta Energy and Natural Resources, Forest Service.

Schroeder, M.J.; Glovinsky, M.; Hendricks, V.F.; [and others]. 1964. Synoptic weather types associated with critical fire weather. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Show, S.B. 1931. Meteorology and the forest fire problem. Monthly Weather Review. 59: 432–433.

Syverson, C.E. 1962. Prediction of the crisis period and the use of Red Flag Forecasts. Unpublished report on file with the USDA Forest Service Pacific Wildland Fire Sciences Laboratory, Seattle, WA.

Syverson, C.E. 1963. Fire weather synoptic types of the Northern Intermountain, Northern Rockies and the Northwestern Plains regions. Unpublished report on file with the USDA Forest Service, Pacific Wildland Fire Sciences Laboratory, Seattle, WA. ■

WEATHER, FUELS, FIRE BEHAVIOR, PLUMES, AND SMOKE—THE NEXUS OF FIRE METEOROLOGY

Scott L. Goodrick, Timothy J. Brown, and W. Matt Jolly

In a pair of review papers, Potter (2012a, 2012b) summarized the significant fire weather research findings over about the past hundred years. Our scientific understanding of wildland fire-atmosphere interactions has evolved: from simple correlations supporting the notion that hot, dry, and windy conditions lead to more intense fires, we have moved towards more mechanistic and physical descriptions of governing processes such as fuel moisture dynamics, wind-driven fire spread, the influence of vortices, and plume dynamics. Our advances are important not only for the sake of scientific knowledge but also for the sake of transferring new knowledge into applications for decisionmaking.

However, there is still much we do not understand. Potter (2012a, 2012b) offers ideas for future research that could prove particularly beneficial. How do vertical wind profiles and wind shear influence fire behavior? What atmospheric processes transport dry, high-momentum air from the upper and middle portions of the troposphere down near the Earth's surface, and how do these processes interact with the atmospheric boundary layer and, eventually, a wildland fire? At what scales does wind shear contribute most strongly to vortex formation? How does the heat and moisture released through combustion interact with ambient atmospheric stability? How do variations in sunshine influence fuel moistures, stability, and airflow in and around a fire?

Doppler radars allow us to examine the structure of the plume as well as winds at different heights within the plume.

Though by no means exhaustive, such research questions indicate that fire-atmosphere interaction research will require considerably more and different data than in the past. Fire-atmosphere interaction studies have relied on fairly simple fire metrics, such as area burned; change in fire perimeter or mean spread rate; and predominately surface weather observations of temperature, atmospheric moisture content, and wind speed as well as wind direction. Answering the questions raised by Potter (2012a, 2012b) will require more. We will need more detailed fire information, tracking not only the fire spread rate but also heat and moisture fluxes to the atmosphere, varying in both space and time. We will need more detailed weather information, moving beyond just surface conditions at a few locations to include local estimates of three-dimensional atmospheric structure and the evolution of those estimates.

This article focuses on what we can do to move forward with these and other research questions that require "more." First, the authors examine some of the technologies available for collecting the needed data and some of the field projects already working to collect such data. Next, the article outlines some of the advances in computing that are giving researchers new ways to examine fire-atmosphere interactions. However, this article is by no means a definitive look at technologies that will be important to fire-atmosphere research; the most important technologies may not have been thought of yet.

New Ways of Looking at Fires

Wildland fires are difficult to measure and study. High temperatures and high variability in both space and time make measuring fire attributes both difficult and dangerous. Remote sensing of wildland fires is an area of research that has emerged over the last two decades, with a variety of instruments capable of observing fires across a broad range of space and time scales.

Satellites provide some of the coarsest information in both space and time. The Hazard Mapping System of the National Oceanic and Atmospheric Administration (Rolph and others 2009) integrates information from a number of satellites

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Infrared imagery, both airborne and in situ, has evolved tremendously over the years.

to create daily maps of fire hotspots and smoke plumes. The finest spatial scale represented on these maps is 500 meters for detections by the National Aeronautics and Space Administration's MODIS instrument. Efforts have been made to estimate fire sizes from this coarse spatial data by relating satellite-measured brightness temperature to burned area, information that can be used to approximate fire progressions.

For the purpose of studying wildland fires, satellite remote sensing is of limited value because the data you get is high in either spatial resolution or temporal resolution but not both. Polar orbiting satellites travel in a low Earth orbit, achieving spatial resolutions as fine as 1 meter, but the satellites pass over a given location no more than every 1 to 3 days. Satellites in geosynchronous orbit continually view the same portion of the Earth's surface, updating each pixel of their image every few minutes. Spatial resolution of geosynchronous images is roughly 1 to 4 kilometers, for a coverage by each pixel of an area from about 250 to 4,000 acres (100–1,620 ha). The primary benefit from such products is a "big-picture" view of burning across an entire region, making this type of data a good fit for synoptic and climate studies.

Radar is another means of examining fires, specifically their plume structure. Hanley and others (2013) used data from National Weather Service NEXRAD radar to examine interactions between an approaching sea breeze front and a prescribed fire on the Apalachicola National Forest in Florida (fig. 1). The study related the passage of the front over the fire to observed plume structures and on-the-ground fire behavior to show how a sea breeze front can trigger erratic fire behavior. Doppler radars such as the NEXRAD allow us to examine the structure of the plume, as indicated by the base reflectivity, as well as winds at different heights within the plume. However, as distance from the radar increases, the lowest part of the plume observable by the radar increases in height, limiting the usefulness of radar in studying fire plumes. Portable radars help get around this limitation because not all fires are as conveniently located near a National Weather Service radar.

Similar in many ways to radar, Doppler lidar is another tool now being applied to examine fire-atmosphere interactions. For example, Charland and Clements (2013) used a ground-based scanning Doppler lidar to study airflow around the plume of a prescribed fire. The lidar revealed the development of a convergence downwind of the plume along with elevated radial velocities at the plume boundary that indicated fire-induced enhancement of the inflow into the base of the convection column. Hiscox and others (2006) used lidar data to estimate appropriate dispersion coefficients for smoke modeling, work previ-

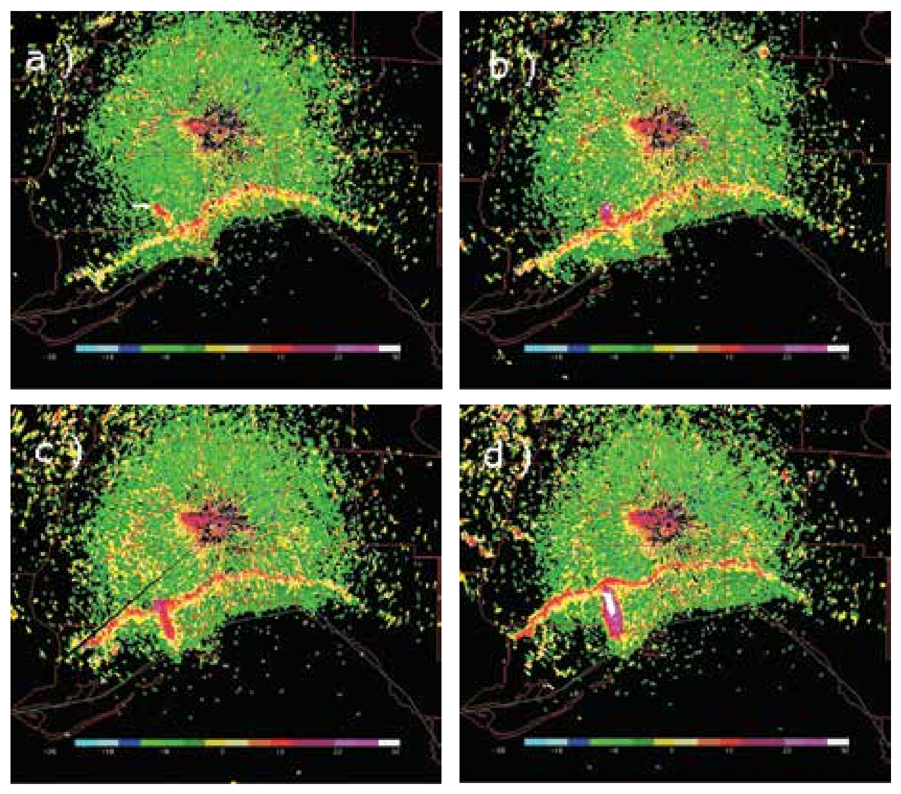

Figure 1—*Interaction of wildland fire with a sea breeze front on the Apalachicola National Forest in Florida on April 5, 2004, as shown by radar reflectivity (dBZ). The fire is located at the white arrow in (a), and the sea breeze front is the arc of elevated reflectivity in the lower half of each image. As the sea breeze front passes over, the fire changes in size and shape from 1828 UTC (a), to 1927 UTC (b), to 2025 UTC (c), and finally to 2124 UTC (d).*

ously conducted primarily through wind tunnel experiments.

Advances are also being made in characterizing the environmental conditions on a wildland fire. Fire researchers are placing sensor packages directly in the path of an approaching fire to measure the heat produced by the fire and the horizontal and vertical wind flows as fires approach and pass (Butler and others 2010). These packages can give researchers valuable information for use in evaluating wildland fire behavior models. They offer information about the rate of energy release from wildland fires and might improve our ability to better predict how fires interact with the atmosphere.

Infrared imagery, both airborne and in situ, has evolved tremendously over the years. It is another means of collecting detailed information about fire behavior. For over 40 years, wildland firefighters have used infrared sensors to detect, monitor, and direct fire suppression and mop up operations (Zajkowski and others 2003). Output from early airborne infrared sensors took the form of print imagery, useful for operations but of limited value for researchers. Some early infrared sensors were limited by saturation because they were not designed for the high infrared radiances typical of a wildland fire. More recent sensors have been specifically designed for wildland fire applications. The FireMapper thermal-imaging radiometer allows quantitative measurements of fire spread rates, fire temperatures, radiant energy flux, residence time, and fire line geometry (fig. 2) (Riggan and others 2010).

Like airborne infrared imagery, ground-based infrared imagery has advanced as a source of fire-related data for research. Coen and others (2004) studied the dynamics of crown fire by deriving a wind field from an infrared imaging camera using image flow analysis techniques. Their study helped to illustrate the link between convective updrafts and changes in surface airflow. Loudermilk and others (2012) combined lidar measurements of fuel structure and infrared imagery taken from a height of 7 meters to link fuelbed continuity and the heterogeneity associated with fuel types to fire behavior at the submeter scale. Infrared imagery has evolved into a tool that offers fire data across a range of space and time scales.

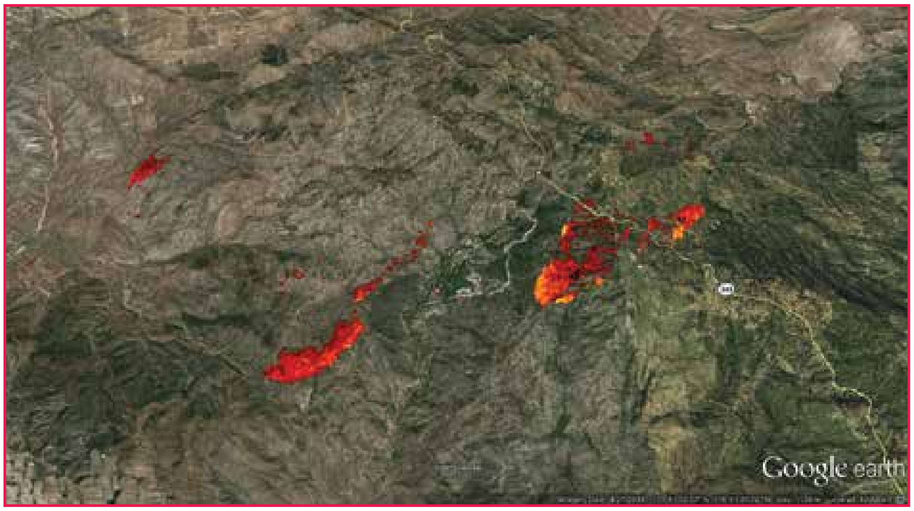

Figure 2—*FireMapper thermal image of the Esperanza Fire, showing ground surface temperatures as viewed from above on October 26, 2006, between 14:07 and 14:17 PDT.*

Prescribed Fires as Laboratories

The scientific study of wildfire dynamics is difficult because wildfires are not repeatable and the conditions that fires burn under cannot be controlled. It is difficult to know the prefire conditions since we do not have prior knowledge of when and where a wildfire will occur. Prescribed fires give researchers a level of control and repeatability not possible with wildfires.

Although prescribed fire has been used for studies such as the International Crown Fire Modeling Experiment (Alexander and others 1998), Wildfire Experiment (Radke and others 2000), and the FROSTFIRE experiment (Wilmore and others 1998; Coen and others 2004), studies are now being designed with a focus on fire–atmosphere interactions. In the FireFlux experiment, Clements and others (2007) examined the structure of a flaming front in a tallgrass prairie by capturing measurements of winds and heat fluxes during the fire's passage. These measurements were accompanied by nearby vertical profiles and surface weather stations recording time series of temperature, humidity, and wind.

> Prescribed fires give researchers a level of control and repeatability not possible with wildfires.

The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) expanded upon the ideas of FireFlux by conducting three sets of intensively measured experimental burns (in 2008, 2011, and 2012). The experiment was in simple fuelbeds—grass and shrubs—at Eglin Air Force Base in Florida. Over 90 scientists and technicians participated in collecting data on fuels, fire behavior, fire effects, meteorology, and smoke dispersion. The experiment was designed, in part, to collect datasets suitable for evaluating coupled fire–atmosphere models, smoke production and dispersion models, and fire effects models. Achtemeier and others (2012) published one of the first attempts at modeling one of the RxCADRE burns, a 1,650-acre (668-ha) aerial ignition. The simulation illustrated the complex interactions between fire and atmosphere and how they affect smoke plume structure (fig. 3).

Computer Models as Laboratories

Prescribed fires offer researchers a very modest level of control and reproducibility for their experiments, but this is nothing compared to the degree of control provided by the coupled fire–atmosphere models in use today. A coupled model is simply the joining of two models such that each model influences the other's results. In this case, a model of the atmosphere is joined to a model of a wildland fire such that the fire alters atmospheric temperatures, moisture, and winds, which in turn influence the evolution of the fire.

Prescribed fires give researchers nothing like the degree of control provided by the coupled fire-atmosphere models in use today.

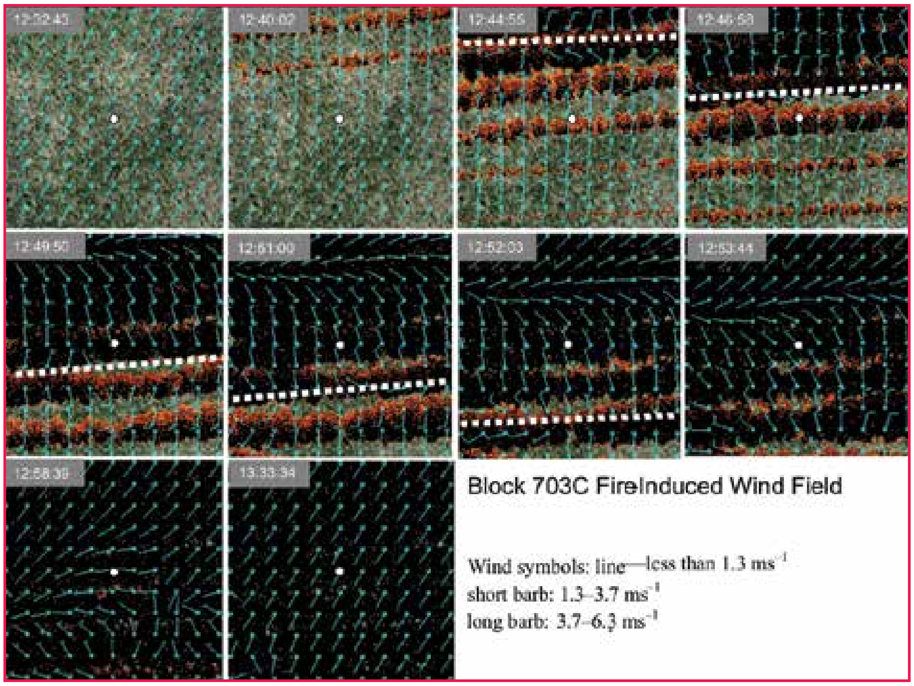

Figure 3—*Simulated time evolution of wind field during a simulated aerial ignition burn. The ignition pattern influences the wind field and the development of convergence zones (white dotted line), indicating an area of strong updrafts.*

Clark and others (1996) described one of the earliest examples of a coupled fire–atmosphere model, developed at the National Center for Atmospheric Research. The model merged a detailed atmospheric model with a fairly simple fire description based on the Rothermel (1972) spread model. Early results helped researchers understand some of the complex interactions that play a role in the development of fingers along a fire front. The model of Clark and others (1996) has evolved over the years into WRF–SFire (Mandel and others 2011) and CAWFE (Coen 2013).

Over the years, other coupled fire–atmosphere models have given more complete descriptions of the combustion portion of the problem. They include FIRETEC, developed at the Los Alamos National Laboratory (Linn and others 2002); and the Wildland Urban Interface Fire Dynamics Simulator, derived from the Fire Dynamics Simulator developed at the National Institute of Standards (Mell and others 2007; McGrattan and others 2010). Such models have been used to study a range of questions: how topography influences fire behavior (Linn and others 2007; Pimont and others 2012); how multiple fire lines interact (Morvan and others 2013); and how effective fuel treatments are (Cassagne and others 2011). Even without coupling, high-resolution atmospheric models have been useful in studying aspects of extreme fire behavior such as vortex dynamics (fig. 4) (Cunningham and others 2005).

Figure 4—*Idealized simulation of an airflow over a heat source, producing a pair of counterrotating vortices at the head of the fire (top). Aerial view from a real burn showing similar plume structures (bottom). Photo: Bret Butler, Forest Service.*

Interactions Between Terrain and Weather

Wildland fire behavior is dominated by fuel availability, terrain shape and orientation (topography), and local weather conditions. However, these factors are not independent, and topographic variations can heavily influence local weather conditions. Historically, wildland fires were simulated by assuming that wind speed and wind direction were constant across the entire burning area for a given time. Advances in wind modeling are significantly improving our ability to reduce coarse numerical weather model predictions, to predict fine-scale variations in wind speed and wind direction, and to depict solar-radiation-induced diurnal wind flow patterns (Forthofer and others 2014).

Furthermore, terrain can influence microclimates, which in turn can affect fine-scale fuel moisture and subsequent fuel availability (Holden and Jolly 2011). Ultimately, interactions between terrain and weather must be fully understood in order to use coarse-scale weather conditions to predict wildland fire combustion processes and subsequent fire–atmosphere coupling. Future work will improve and refine our ability to characterize microclimatic conditions and their influence on fire behavior.

Bringing It All Together

New technologies for looking at wildland fires and the structure of their plumes, coupled with advances in our ability to simulate wildland fires and their complex feedbacks to the atmosphere, are a solid foundation for answering a variety of fire-related questions. Lidar measurements of the flow field around fires can help researchers understand how vertical wind profiles and wind shear influence fire behavior. Advances in computer modeling will give insight into various questions regarding scale interactions and processes like vortex formation. Many of the questions posed by Potter (2012a, 2012b) as areas for fruitful future research are far more amenable to study now than they would have been in the past.

A 2015 project supported by the Joint Fire Science Program, still in the planning phase, is designed to yield novel critical observational data necessary to build and validate next-generation modeling systems for fire growth and danger, fuels consumption and emissions, smoke plumes, and smoke impacts. If fully funded, the project will be a multiagency, multiyear field campaign conducted across a variety of fuelbeds, including complex fuels, and over a variety of burn conditions, including large burns designed to simulate wildfires. This type of data collection is important because improvements are needed in both the underlying understanding and the overall accuracy of models central to operational decisionmaking in managing wildland fire and the resulting smoke.

Future work will improve and refine our ability to characterize microclimatic conditions and their influence on fire behavior.

References

Achtemeier, G.L; Goodrick, S.L.; Liu, Y. 2012. Modeling multiple-core updraft plume rise for an aerial ignition prescribed burn by coupling daysmoke with a cellular automata fire model. Atmosphere. 3: 352–376.

Alexander, M.E.; Stocks, B.J.; Wotton, B.M.; [and others]. 1998. The International Crown Fire Modeling Experiment: An overview and progress report. Preprints, Second Symposium on Fire and Forest Meteorology; 11–16 January 1998; Phoenix, AZ. American Meteorological Society: 20–23.

Butler, B.W.; Jimenez, D.; Forthofer, J.; [and others]. 2010. A portable system for characterizing wildland fire behavior. Proceedings of the 6th International Conference on Forest Fire Research (CD–ROM); 15–18 November 2010; University of Coimbra, Coimbra, Portugal.

Cassagne, N.; Pimont, F.; Dupuy, J.-L.; [and others]. 2011. Using a fire propagation model to assess the efficiency of prescribed burning in reducing the fire hazard. Ecological Modelling. 222(8): 1502–1514. doi:10.1016/j.ecolmodel.2011.02.004.

Charland, A.M.; Clements, C.B. 2013. Kinematic structure of a wildland fire plume observed by Doppler lidar. Journal of Geophysical Research: Atmospheres. 118(8): 3200–3212. doi:10.1002/jgrd.50308.

Clark, T.L.; Jenkins, M.A.; Coen, J.; Packham, D. 1996. A coupled atmosphere–fire model: convective feedback on fire-line dynamics. Journal of Applied Meteorology. 35: 875–901.

Clements, C.; Zhong, S.; Goodrick, S.; [and others]. 2007. Observing the dynamics of wildland grass fires. Bulletin of the American Meteorological Society. 88(9): 1369–1382. doi:10.1126/science.1244843

Coen, J.L. 2013. Modeling wildland fires: A description of the Coupled Atmosphere–Wildland Fire Environment model (CAWFE). NCAR Technical Note NCAR/TN–500þSTR. <http://nldr.library.ucar.edu/repository/collections/TECH–NOTE–000–000–000–866> (last accessed September 2016).

Coen, J.; Mahalingam, S.; Daily, J. 2004. Infrared imagery of crown-fire dynamics during FROSTFIRE. Journal of Applied Meteorology. 43(9): 1241–1259.

Cunningham, P.; Goodrick, S.L.; Hussaini, M.Y.; Linn, R.R. 2005. Coherent vertical structures in numerical simulations of buoyant plumes from wildland fires. International Journal of Wildland Fire. 14: 61–75.

Forthofer, J.M.; Butler, B.W.; Wagenbrenner, N.S. 2014. A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part I: Model formulation and comparison against measurements. International Journal of Wildland Fire. 23: 969–981.

Hanley, D.E.; Cunningham, P; Goodrick, S.L. 2013. Interaction between a wildfire and the sea-breeze front. In: Qu, J.J.; Sommers, W.T.; Yang, R.; Riebau, A.R. (eds.). Remote sensing and modeling applications to wildland fires. Beijing, China: Tsinghua University Press and New York: Springer: 81–98.

Hiscox, A.; Napro, C.; Miller, D. 2006. On the use of lidar images of smoke plumes to measure dispersion parameters. Journal of Atmospheric and Oceanic Technology. 23: 1150–1154.

Holden, Z.A.; Jolly, W.M. 2011. Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. Forest Ecology and Management. 262: 2133–2141.

Linn, R.R.; Reisner, J.; Colman, J.J.; Winterkamp, J. 2002. Studying wildfire behaviour using FIRETEC. International Journal of Wildland Fire. 11: 233–246.

Linn, R.R.; Winterkamp, J. L.; Edminster, C.; [and others]. 2007. Coupled influences of topography and wind on wildland fire behavior. International Journal of Wildland Fire. 16: 183–195. doi:10.1080/13647830902977570.

Loudermilk, E.L.; O'Brien, J.J.; Mitchell, R.J.; [and others]. 2012. Linking complex forest fuel structure and fire behaviour at fine scales. International Journal of Wildland Fire. 21: 882–893.

Mandel, J.; Beezley, J.D.; Kochanski, A.K. 2011. Coupled atmosphere–wildland fire modeling with WRF 3.3 and SFIRE 2011. Geoscientific Model Development. 4: 591–610.

McGrattan, K.B.; Baum, H.; Rehm, R.; [and others]. 2010. Fire dynamics simulator (version 5) technical reference guide, mathematical model. Vol. 1. NIST, Spec. Pub. 1018–5.

Mell, W.; Jenkins, M.A.; Gould, J.; Cheney, P. 2007. A physics-based approach to modeling grassland fires. International Journal of Wildland Fire. 16(1): 1–22.

Morvan, D.; Meradji, S.; Mell, W. 2013. Interaction between head fire and backfire in grasslands. Fire Safety Journal. 58: 195–203.

Pimont, F.; Dupuy, J.L.; Linn, R.R. 2012. Coupled slope and wind effects on fire spread with influences of fire size: A numerical study using FIRETEC. International Journal of Wildland Fire. 21: 828–842.

Potter, B.E. 2012a. Atmospheric interactions with wildland fire behaviour—I. Basic surface interactions, vertical profiles and synoptic structures. International Journal of Wildland Fire. 21(7): 779–801.

Potter, B.E. 2012b. Atmospheric interactions with wildland fire behaviour—II. Plume and vortex dynamics. International Journal of Wildland Fire. 21(7): 802–817.

Radke, L.F.; Clark, T.L.; Coen, J.L.; [and others]. 2000. The wildfire experiment (WIFE): observations with airborne remote sensors. Canadian Journal of Remote Sensing. 26(5): 406–417.

Riggan, P.J.; Wolden, L.G.; Tissel, R.G.; [and others]. 2010. Remote sensing fire and fuels in southern California. Proceedings of the 3rd Fire Behavior and Fuels Conference; 25–29 October 2010; Spokane, WA. <http://www.fs.fed.us/psw/publications/riggan/psw_2010_riggan002.pdf> (last accessed September 2016).

Rolph, G.D.; Draxler, R.R.; Stein, A.F.; [and others]. 2009. Description and verification of the NOAA Smoke Forecasting System: The 2007 fire season. Weather and Forecasting. 24: 361–378.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT–115. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Wilmore, R.; Slaughter, K.; Theisen, M.; Roessler, J. 1998. FROSTFIRE research prescribed burn plan. Tech. Rep. Bureau of Land Management, Alaska Fire Service.

Zajkowski, T.; Queen, L.; VanBuren, D. 2003. Infrared field users guide and vendor listings. Salt Lake City, UT: USDA Forest Service Engineering, Remote Sensing Applications Center, RSAC–1309–RPT1. <http://nirops.fs.fed.us/docs/about-more/08-1309-RPT1.pdf> (last accessed September 2016). ■

COUPLED WEATHER–FIRE MODELING: FROM RESEARCH TO OPERATIONAL FORECASTING

Janice L. Coen and W. Schroeder

Large wildland fires are complex, dynamic phenomena that can encounter a wide range of fuels, terrain, and weather during a single event. They can produce intense firewhirls that snap mature trees and generate blowups. They can send 300-foot (100-m) bursts of flame shooting ahead of the fireline at speeds up to 100 miles per hour (160 km/h). They can spawn firewinds 10 times stronger than ambient winds, deep pyrocumulus clouds, and firestorms in which the fire-generated winds overwhelm ambient winds. Counterrotating firewhirls brought to the fire's head can combine at the tip and roll over, forming turbulent balls of flame that burst ahead of the fireline.

Given these complexities, the human mind cannot integrate all of the interacting factors that dramatically accelerate fire growth. Transient, dynamic fire behavior is not just a challenge for planning operations but also a threat to firefighter safety. Despite uniform training curricula and rigorous command-and-control structures, even seasoned firefighters can be tragically unprepared for complex and explosive fire behavior that can lead to burnovers. Burnovers do not result solely from unusual fire behavior; variance from operational procedures is often a contributing factor. But many burnovers occur "due to a lack of understanding of fire behavior or rapidly changing conditions that lead to burnover" (National Fire Academy 2011).

Traditionally, fire behavior models share several limitations. They diagnose rate of spread based on wind measured at a nearby surface weather station; the weather station indicates current conditions, not the future, and might be located miles away from the fire. Consequently, such tools are unable to anticipate how future weather will affect fire behavior, although the introduction of gridded surface weather forecasts is a step toward addressing some of these limitations. Moreover, traditional fire behavior models do not reproduce fire phenomena because they fail to include the interplay between fire and atmosphere, which is now known to be a fundamental aspect of fire behavior. Finally, without a mechanism to represent change over time, the current generation of tools cannot directly anticipate changes in fire behavior due to blowups, plume collapse or plume-driven behavior, or change in direction from wind shifts and cloud downdrafts. Thus, the wildland fire community has a restricted ability to explain or predict fire evolution and phenomena.

A New Class of Models

Models using a new paradigm—two-way coupled weather–wildland fire models—have shown increased realism. Coupled models combine wildland fire behavior modules with a numerical weather prediction (NWP) model that forecasts how weather varies over time and space, even in complex terrain. These components are connected in two directions: (1) evolving wind, along with fuel properties and terrain slope, directs where the fire grows and how fast; and (2) heat released by the fire modifies its atmospheric environment, thereby creating its own weather (such as fire-induced winds). Thus, coupled models complement current tools, such as the fire area simulator FARSITE and the Wildland Fire Decision Support System's Near-Term Fire Behavior (NTFB) model, in situations where those tools are weakest.

Researchers created the coupled weather–fire models based on their recognition that fires interact with the atmosphere surrounding them, producing many fundamental fire behaviors. Researchers applying such models have shown that fire–atmosphere interactions generate numerous wildland fire phenomena, including the commonly

> Transient, dynamic fire behavior is not just a challenge for planning operations but a threat to firefighter safety.

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observed bowed shape; the heading, flank, and backing regions; and firewhirls, along with other extreme behaviors. A prior *Fire Management Today* article condensed this new understanding for practitioners (Coen 2011).

Over the past decade, the National Center for Atmospheric Research's *CAWFE*™ coupled weather–fire modeling system was applied to over a dozen landscape-scale wildland fire events in varying fuel, terrain, and weather conditions (for examples, see the sidebar). CAWFE could simulate overall rate and direction of spread, distinguishing characteristics of fire events and transitions in fire behavior. *CAWFE* reproduced other fire phenomena and illuminated the conditions under which they form, such as distinctive shapes of the fire perimeter, flank runs, rotating plumes, and the splitting or merging of firelines. For example, under conditions where the horizontal wind increased with height, horizontal roll vortices (pairs of counterrotating updrafts laid forward on their side) formed along firelines, increasing the rate of spread where downdrafts coincided—or, alternatively, decreasing the rate of spread between rolls where updrafts coincided. Although data for such phenomena are not routinely collected during wildfire events, the fact that a coupled model reproduced such phenomena hints that a deeper understanding of an unfolding fire event might be possible, permitting greater foresight.

Case Studies Using *CAWFE*

Yarnell Hill Fire:
- Coen, J.L. 2015. Distilling and disseminating new scientific understanding of wildland fire phenomena and unfolding of large wildfires to prevent wildland firefighter entrapment. Proceedings of the 13th International Wildland Fire Safety Summit & 4th Human Dimensions of Wildland Fire Conference; 20–24 April 2015; Boise, ID. International Association of Wildland Fire, Missoula, MT.

High Park Fire:
- Coen, J.L.; Schroeder, W. 2015. The High Park Fire: Coupled weather–wildland fire model simulation of a windstorm-driven wildfire in Colorado's Front Range. Journal of Geophysical Research Atmospheres. 120: 131–146.

Little Bear Fire:
- Coen, J.L.; Schroeder, W. 2013. Use of spatially refined remote sensing fire detection data to initialize and evaluate coupled weather-wildfire growth model simulations. Geophysical Research Letters. 40: 5536–5541.

Esperanza Fire:
- Coen, J.L.; Riggan, P.J. 2014. Simulation and thermal imaging of the 2006 Esperanza wildfire in southern California: Application of a coupled weather–wildland fire model. International Journal of Wildland Fire. 23: 755–770.

Big Elk Fire:
- Coen, J.L. 2005a. Simulation of the Big Elk Fire using coupled atmosphere–fire modeling. International Journal of Wildland Fire. 14: 49–59.

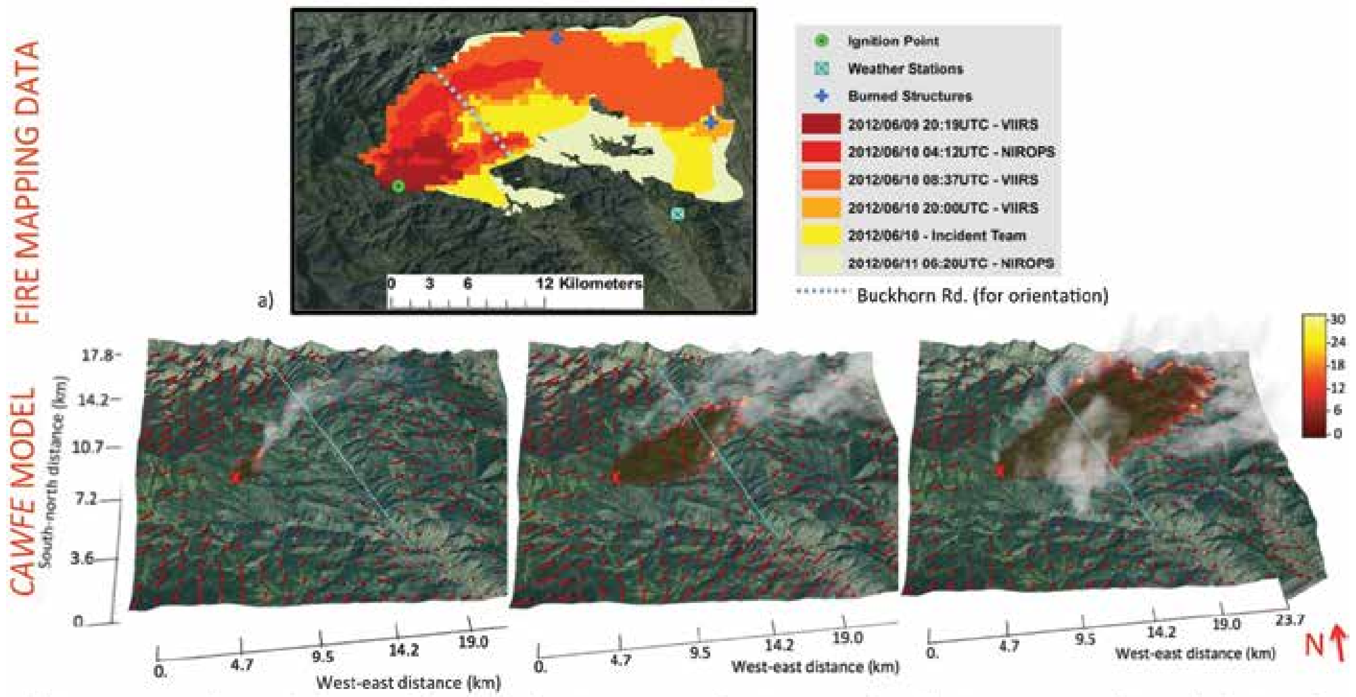
Testing Capabilities on Past Events

To retrospectively model an event, *CAWFE* ingests three kinds of information: terrain elevation data; a three-dimensional state of the atmosphere, either from gridded meteorological analyses (for cases in the past) or from a larger scale model forecast (for a prediction); and spatial data on fuel type, amount, and moisture content. The model then simulates several hours of weather at the reported ignition time and location, introducing either a point ignition (suitable for arson or a lightning strike); a line ignition (for a prescribed fire); or—for a more developed fire—a fire perimeter specified by fire mapping data at the time the observation was made. The fire's growth, the atmosphere's evolution, and the feedbacks between them at every step in time are simulated, showing the fire's progression; the fire plume; and the evolution of winds, clouds, smoke, and fire phenomena. For validation at the scale of large wildland fires, weather and fire simulation components are evaluated using weather data; documented events; and sequences of mapped fire extent, including incident team maps, FireMapper and National Infrared Operations (NIROPs) airborne infrared data, and satellite active fire detection data.

During wildland fires, some of the most difficult-to-anticipate fire behavior arises from complex mountain airflows, meteorological wind shifts, and plume-dominated fires growing under fire-induced winds. In such situations, transience and air accelerations are of utmost importance. Both are caused by heating or cooling due to vertical motion in a stratified atmosphere or water phase changes such as condensation into clouds or evaporation of precipitation. Such factors are beyond the capabilities of diagnostic tools such as WindWizard for airflow and BEHAVEPlus, FARSITE, or NTFB for fire behavior. The following studies have applied *CAWFE* to cases that exemplify these modeling challenges:

Models using a new paradigm—two-way coupled weather–wildland fire models—have shown increased realism.

- The June 2012 ***High Park Fire*** near Fort Collins, CO, exemplified the most destructive wildfires in Colorado history, during which prolonged drought and unseasonal Front Range windstorms overlapped. *CAWFE* simulated the first growth period, capturing atmospheric gravity wave breaking that produced strong, gusty surface winds that varied in time and space across the threatened forest (Coen and Schroeder 2015). Although simulated winds across a mountain peak 2.5 miles (4 km) upwind reached over 90 miles per hour (40 m s^{-1}), the fire lay in a sheltered valley in the hours after the first report, growing slowly orthogonal to the windstorm. Infrared mapping data confirmed this surprising behavior, the fire's subsequent splitting, and the fire's run eastward when it was exposed to the strong, gusty windstorm after climbing a mountain ridge. The simulation correctly captured the fire's extent within about a mile of observed perimeters (fig. 1).



b) 2019 UTC **9 June** (2:19 PM), the time of the 1st VIIRS data (brick red, in a). (X is the ignition point.)

Comparison: Simulated fire & mapped fire are both 4 km long wedges.

c) 0412 UTC **10 June** (10:12 PM 9 June), the time of the NIROPS map (red, in a).

Comparison: Simulation underestimated the leading edge by 2 km but showed the wide (5 km in simulation, 7 km in map) north-south burning area.

d) 0837 UTC **10 June** (2:37 AM), the time of the 2nd VIIRS data (dark orange, in a).

Comparison: The fire grew north to Poudre Canyon and east in the next 4.5 h. This was captured by the simulation but lagged the observations by 2–3 km.

Figure 1—*The High Park Fire during first growth period on June 9–10, 2012. (a) Fire mapping data from airborne and spaceborne sensors and incident team intelligence. (b)–(d)* CAWFE *simulation of fire heat flux (colored according to color bar at right, in kW* m^{-2}*) and wind vectors near the surface, at (b) June 9, 2:19 p.m. MDT, the time of the first Visible Infrared Imaging Radiometer Suite (VIIRS) data; (c) June 9, 10:12 p.m. MDT, the time of the NIROPS map; and (d) June 10, 2:37 a.m. MDT, the time of the second VIIRS data. The misty white field indicates smoke concentration. The X indicates the ignition location. Figure adapted from Coen and Schroeder (2015).*

- The 2013 ***Yarnell Hill Fire*** (fig. 2) exemplified how wind shifts can cause a fire to change direction, increase in intensity, and grow rapidly—an important firefighter safety hazard. *CAWFE* simulations of the day that 19 firefighter fatalities occurred captured two changes in fire growth direction. The first shift from northerly to easterly growth happened as the fire encountered an airflow between two buttes. The second, more dramatic shift to a southerly growth occurred when a gust front from a thunderstorm outflow crossed the modeled fireline at the observed time, driving it over the firefighters' location (shown by **X**; the fatalities occurred at about 4:45 p.m.) between 4:30 p.m. and 5:00 p.m.

- Although weather stations near the 2014 ***King Fire*** showed only weak to moderate winds, plume-dominated behavior drove the fire over 14 miles (23 km) into and up Rubicon Canyon in 1 day, a result not produced using operational tools. A *CAWFE* simulation reproduced this run, driven by fine-scale circulations in the narrow valley and fire-induced winds. The simulated fire grew to the west because it did not include actual suppression that occurred on the western (left) flank (fig. 3).

- *CAWFE* simulations captured distinctive elements of the Santa Ana-driven ***Esperanza Fire*** in 2006. The captured elements included rapid growth up and over Cabazon Peak; an airflow that drove the fire downslope into an unnamed drainage; the fire's climb up into the San Jacinto Wilderness; the fire's bifurcation into two heads (one

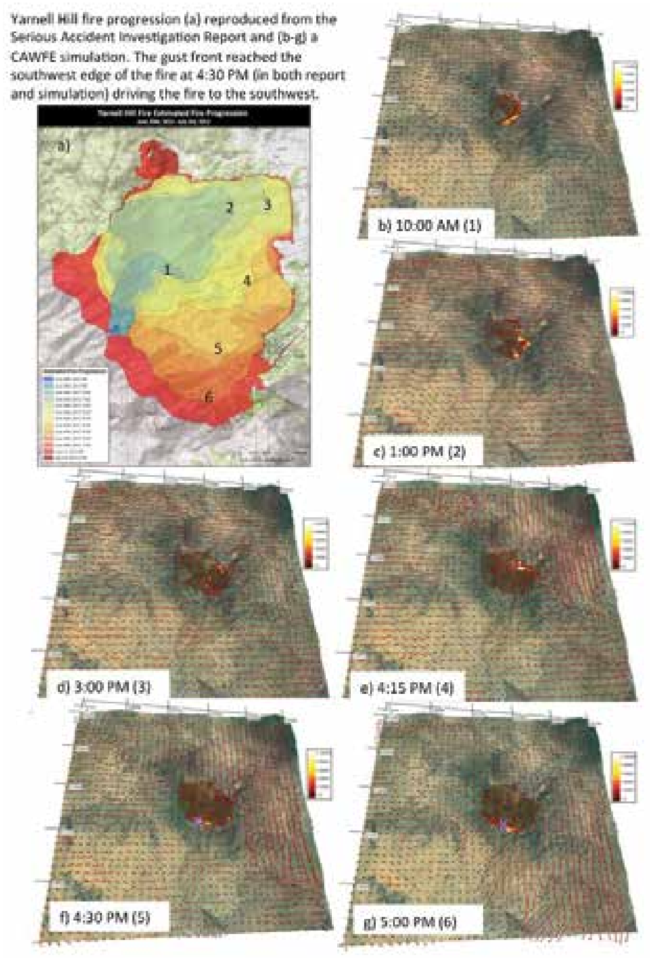


Figure 2—*Fire progression on June 30, 2013, during the Yarnell Hill Fire as mapped in the serious accident investigation report (left, courtesy T. Foley) and as simulated by* CAWFE *(right) at six times corresponding to periods shown in the progression map at left. Simulation snapshots show the sensible heat flux (W m*$^{-2}$*), colored according to color bar at right, and the near-surface wind (arrows point downwind; longer arrows indicates stronger winds). The gust front—indicated by the line of strong northeasterly winds—reaches the southern edge of the fire at 4:30 p.m. (as reported and in the CAWFE simulation), driving the fire to the southwest through the firefighter deployment site (**X**). Figure adapted from Coen (2015).*

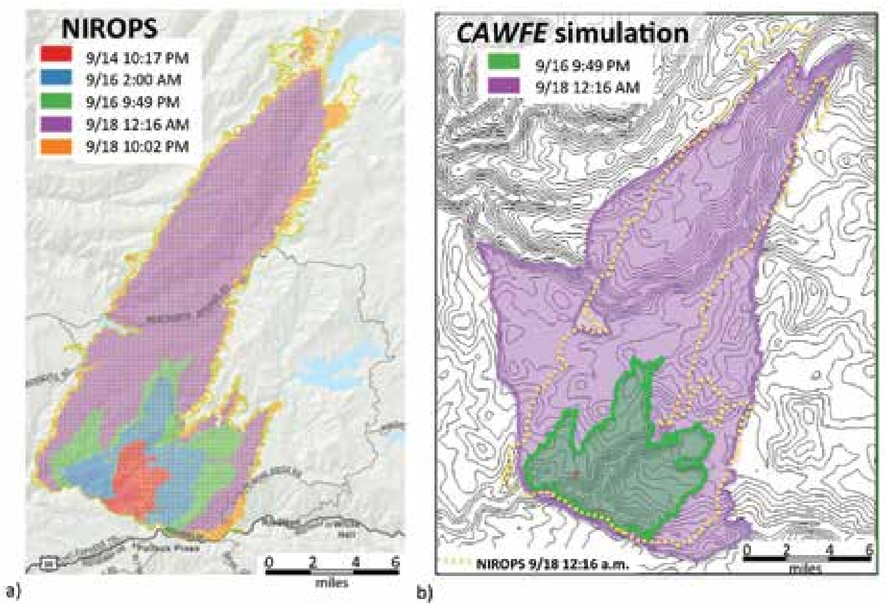


Figure 3—*(a) Progression of the King Fire on September 14–18, 2014, as mapped by NIROPs. (Figure courtesy of USDA Forest Service and CalFire.) (b)* CAWFE *simulated fire progression, with the fire initialized using the September 16, 2014, NIROPs fire map until September 18 at 10:02 p.m. The NIROPS-mapped fire extent at that time (dotted yellow line) is shown for comparison.*

wind-driven heading region running downwind across drainages and a second plume-driven heading region that drew itself up through the fatality site); fire runs up canyons perpendicular to both the fire's flanks and the wind; and feathering of the fireline at the leading edge (Coen and Riggan 2014). Such features were confirmed by FireMapper imagery. By contrast, alternative approaches using weather station data and weather model input into FARSITE predicted a weak growth, largely within Banning Pass, that failed to reach the fatality site (Weise and others 2007).

For each of the four fire events, *CAWFE* simulations recreated much of its unique unfolding by capturing the terrain-induced airflow effects; the fire's forces on the air, altering winds; and the role of winds in directing the fire spread. *CAWFE* showed that it can (1) simulate the weather near fires, notably the near-surface wind speeds, including how they vary spatially and over time and are affected by terrain, the fire, and cloud downdrafts; and (2) reproduce fire spread characteristics and, more importantly, critical fire/wind interactions that determine fire shape and important fire phenomena.

Predicting the Future

Wildfires present a difficult weather forecasting challenge. To anticipate how a wildfire will evolve, a model must predict how weather—and factors that depend on weather, such as dead fuel moisture—vary over time, how a fire's behavior responds, and how weather and fire interact. In 2004, *CAWFE* modeled Colorado wildfires in faster-than-real-time (Coen 2005), illuminating numerous forecasting challenges. For example, a fire may continue for weeks or months while the accuracy of NWP forecasts decreases over time; a forecast for the next day might be reliable, but little accuracy remains in a forecast 10 or more days out. Very high-resolution NWP forecasts, such as these *CAWFE* simulations, quickly lose reliability and are useful for only up to 24 to 36 hours. Thus, a forecast initialized at the time of a fire's ignition could lose fidelity (in both weather and predicted fire location) by the time of fire growth. A single model forecast has often been unable to accurately span a fire's lifetime. Compounding the problem, models cannot foresee everything; firefighting could be affecting natural fire growth, and spotting could be creating new fires. Although research may suggest a size distribution of embers, a distribution of landing spots, and the likelihood that an ember is burning and will ignite another fire upon landing, predicting exactly where this will occur is beyond a model's capability. These forecasting challenges have precluded real-time coupled weather–fire forecasting to date.

New satellite active fire detection sensors and products have created new opportunities. The Visible Infrared Imaging Radiometer Suite (VIIRS), launched in October 2011 on the Suomi National Polar-orbiting Partnership, has improved active fire detection products compared to previous polar orbiting systems, such as the 1-kilometer Moderate Resolution Imaging Spectroradiometer (MODIS). Routine VIIRS active fire data for the United States are on a dedicated Website hosted by the Department of Geographical Sciences at the University of Maryland (<http://viirsfire.geog.umd.edu/>), and active fire maps for the United States are available online (<http://activefiremaps.fs.fed.us>). VIIRS offers global coverage every 12 hours or less at nominal spatial resolutions of 375 meters and 750 meters (Justice and others 2013). Figure 4 contrasts how MODIS and VIIRS would each detect the 2014 King Fire. Compared to MODIS, which often shows scattered pixels containing fire, VIIRS 375-meter fire data allow for improved—and often earlier—detection of smaller and/or cooler fires and clear delineation of large-fire flaming fronts.

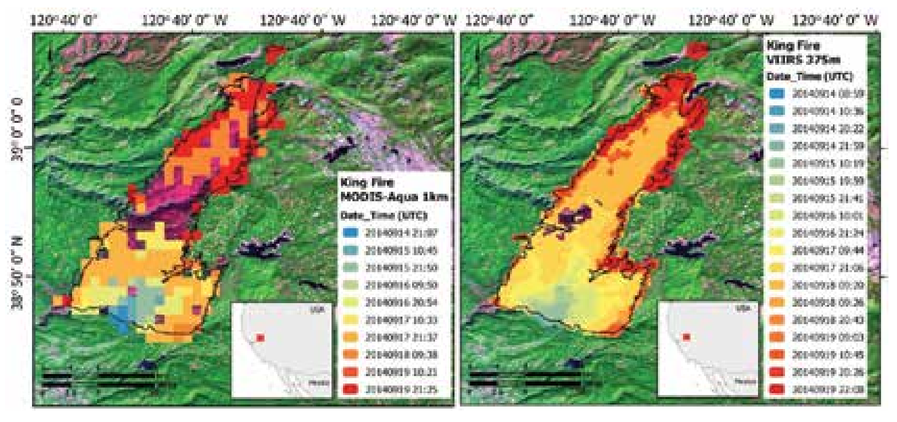


Figure 4—*King Fire spread mapped using (a) 1-kilometer Aqua MODIS data and (b) 375-meter VIIRS satellite active fire detection data. The data cover the fire from first detection through September 19, 2014. The black outline represents the burned area mapped using Landsat 8 30-meter data.*

To have a good forecast at any time during even a long-lived fire, *CAWFE* was adapted to ingest a map of a fire already in progress and then to continue. In a sequence of simulations throughout the 2012 Little Bear Fire, Coen and Schroeder (2013) showed that after ingesting the fire map, *CAWFE* simulated the fire evolution well for at least the next 12 to 24 hours—a critical requirement because a new VIIRS map of the fire extent would be available by then (fig. 5). Figure 5 shows the NWP technique of cycling—initializing a sequence of frequently launched simulations with updated weather data and, in this application, fire extent data. Coen and Schroeder (2013) suggested that cycling yields a good 24-hour forecast from first detection until the fire is extinguished—even if the fire persists for weeks or months. *CAWFE* is being transitioned into operational forecasting use on wildland fires through grants and contracts with research and operational agencies.

Researchers applying weather–fire models have shown that fire–atmosphere interactions generate numerous wildland fire phenomena.

Tradeoffs

By integrating the weather and fire behavior forecast, coupled weather–fire models further intertwine two related roles: the weather forecaster and the fire behavior analyst. Whereas weather agencies traditionally deliver weather forecasts to land management agencies, which develop fire-related products, coupled models pose organizational challenges by blending weather and land management agency activities. In addition, the tradeoffs associated with coupled models include higher complexity, broader training, and more computing requirements, even though *CAWFE* can simulate fires as big as several tens of thousands of acres at very high resolution on a single processor faster than real time.

However, the potential benefits are significant. Research has shown that coupling very high-resolution weather forecasting with fire behavior models to capture fire–weather feedbacks can reproduce many of the distinguishing characteristics of large fires. Thus, although wildland fire behavior has often been described as unpredictable because it appears to be so complex and rapidly changing and therefore beyond a human's ability to integrate all the associated factors, laws of fluid dynamics determine the outcomes—the shape and extent of a fire perimeter, including splitting and merging, blowups, and apparently inexplicable growth due to mountain airflow effects and wind shifts. When these laws of fluid dynamics are formalized as computer

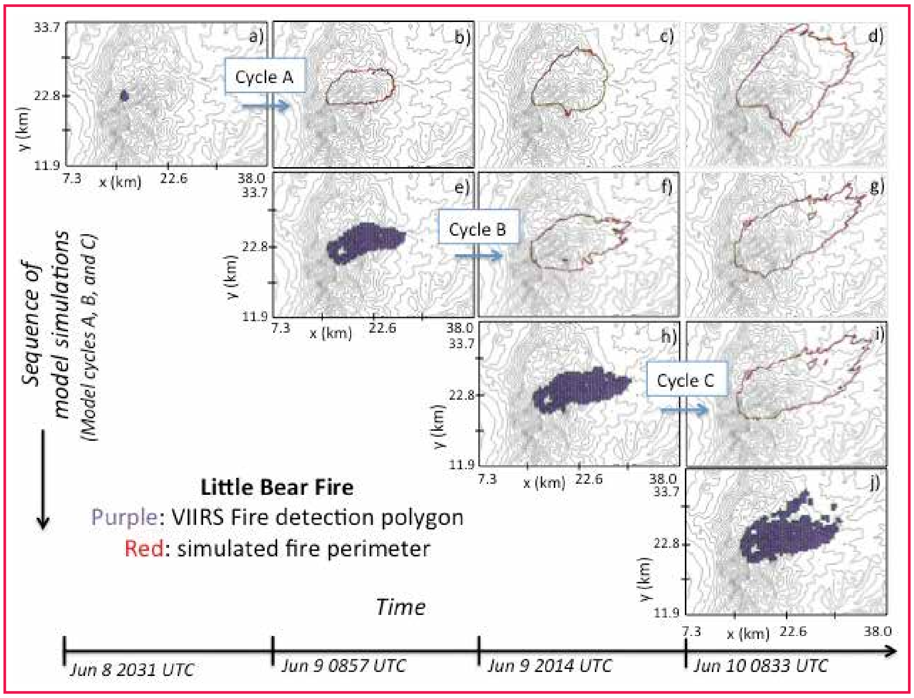


Figure 5—*Simulation of the Little Bear Fire using a cycling approach. From left to right, time increases in increments of 12 hours for each column. From top to bottom, each row represents a different, updated* CAWFE *coupled weather–fire simulation (modeled fire extent shown by the red outline), initialized with a more recent VIIRS-derived active fire detection (purple fill). Each simulation is run until June 10, 08:33 UTC, the time of the fourth VIIRS image. Reproduced from Coen and Schroeder (2013).*

For each of four fire events, *CAWFE* simulations recreated much of its unique unfolding.

programs known as weather models with fire components, they largely reproduce past fires. Performed in a predictive manner, they forecast fire behavior to a much greater extent than is currently believed possible. The improvement comes through simulation of the spatial and temporal evolution of weather at the right scale and inclusion of fire-atmosphere feedbacks that create fire-induced winds. The "right" resolution of hundreds of meters is 20 to 100 times finer than forecast models at the National Centers for Environmental Prediction (NCEP) and an order of magnitude finer than NCEP's finest weather forecast product, the 1.33-km CONUS/1.5-km Alaska fire weather nested run of the North American Mesoscale modeling system.

CAWFE has matured to the point where it can reproduce the evolving extent, shape, and distinctive features of landscape-scale fire events, notably in complex mountain environments, on plume-dominated fires, and under changing conditions of weather and fire behavior. Under such circumstances, existing tools often underperform. Integration with active fire detection data has overcome a longstanding obstacle to using coupled weather-wildland fire models predictively: that a fire event outlasted the period for which a forecast remained good, with unforeseen events derailing the forecast. As coupled models are transitioned into operations, such tools could simulate airflow in complex terrain at hundreds of meters resolution (finer than current or anticipated operational models at NCEP) and feedbacks from wildland fires, anticipating behavior heretofore considered to be unpredictable.

CAWFE has matured to the point where it can reproduce the evolving extent, shape, and distinctive features of landscape-scale fire events.

Acknowledgments

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References

Coen, J.L., 2005. Applications of coupled atmosphere-fire modeling: Prototype demonstration of real-time modeling of fire behavior. 6th Symposium on Fire and Forest Meteorology; 24–27 October 2005; Canmore, Alberta, Canada. CD–ROM.

Coen, J.L. 2011. Some new basics of fire behavior. Fire Management Today. 71(1): 37–42.

Coen, J.L. 2015. Distilling and disseminating new scientific understanding of wildland fire phenomena and unfolding of large wildfires to prevent wildland firefighter entrapment. Proceedings of the 13th International Wildland Fire Safety Summit & 4th Human Dimensions of Wildland Fire Conference; 20–24 April 2015; Boise, ID. International Association of Wildland Fire, Missoula, MT.

Coen, J.L.; Riggan, P.J. 2014. Simulation and thermal imaging of the 2006 Esperanza wildfire in southern California: Application of a coupled weather-wildland fire model. International Journal of Wildland Fire. 23: 755–770.

Coen, J.L.; Schroeder, W. 2013. Use of spatially refined remote sensing fire detection data to initialize and evaluate coupled weather-wildfire growth model simulations. Geophysical Research Letters. 40: 5536–5541.

Coen, J.L.; Schroeder, W. 2015. The High Park Fire: Coupled weather-wildland fire model simulation of a windstorm-driven wildfire in Colorado's Front Range. Journal of Geophysical Research Atmospheres. 120: 131–146.

Justice, C.O.; Román, M.O.; Csiszar, I.; [and others]. 2013. Land and cryosphere products from Suomi NPP VIIRS: Overview and status. Journal of Geophysical Research Atmospheres. 118: 1–13

National Fire Academy. 2011. 2nd National Fire Service Research Agenda Symposium report. National Fallen Firefighters Foundation. 2nd National Fire Service Research Agenda Symposium; 1–3 June 2011; Emmitsburg, MD. <http://www.everyonegoeshome.com/wp-content/uploads/sites/2/2014/03/report2.pdf> (last accessed September 2016).

Weise D.R.; Chen, S.; Riggan, P.J.; Fujioka, F.M. 2007. Using high-resolution weather data to predict fire spread using the FARSITE simulator—A case study in southern California chaparral. Proceedings of the 7th Symposium of Fire and Forest Meteorology; 23–25 October 2007; Bar Harbor, ME. Pap. 8.2. Boston, MA: American Meteorological Society. <https://ams.confex.com/ams/pdfpapers/126873.pdf> (last accessed August 2015). ■

SOCIAL MEDIA: ROCKING THE WILDFIRE WORLD

Mary Ann Chambers and Joseph G. Champ

Expressions of community gratitude for firefighters are common. Photo: Mary Ann Chambers, Forest Service.

Before the rise of social media sites such as Facebook and Twitter, public information officers on wildfires depended on traditional mass media, including newspapers, television, and radio, to get important messages about dangerous wildfires to the public. That is not the case anymore. Our research confirms that social media are changing everything. Firefighters and others with wildfire-related roles, such as journalists, are also affected.

To find out how social media are changing the way people collect and circulate information about wildfires, we interviewed journalists, news directors, public information officers, incident commanders, and firefighters (25 participants in all). They all agreed that the way information about wildfires is gathered and disseminated is changing.

With the availability of new media channels, we wondered whether news releases were going the way of the dinosaur.

One of our original goals was to examine the role of the news release in this new age of social media. With the availability of new media channels, we wondered whether news releases were going the way of the dinosaur. But we found news releases still in use, largely because social media information is still difficult to verify. The official news release is still a trusted source. For journalists, news releases are rarely the start of a story, but they offer valuable background for a story.

However, we also found that firefighters are now knowingly and unknowingly giving information to journalists who are desperate for something new. Journalists want their copy to differ from what their competitors are reporting and from the offerings of an incident management team.

A Direct Line From the Fire to the Public

Public information officers now have many tools for getting out their messages. Newspapers and radio are no longer the big guns. However, when asked which method is best for general wildfire-related communication, most public information officers agreed that no one method works for everything.

"Depends," said one respondent. "Sometimes it is very remote and the press is not right there. [A] press release can still be a good choice because it has all the info, contacts, etc."

Traditional media sources such as television can start conversations among their many viewers, thereby defining a topic of discussion across a large area. Some call this setting an agenda.

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But on large fires, many people we interviewed gave us a different story. Public information officers indicated that they have had up to 250,000 followers on Facebook, all hungry for information. With that many followers, a public information officer might find him- or herself in a position once exclusively occupied by traditional media sources. Increasingly, the public information officer has the power to get important information about the management of a wildfire directly to the public.

Firefighters are also tweeting and Facebooking about their work on fires, raising concerns about the information that they and other employees are sharing. Firefighting is a dangerous job; incident management teams want firefighters to concentrate on their work, not on social media. Incident management teams also want to convey unified messages with important information for the public. Public information officers still want firefighters to contact them if they are approached by a journalist.

Journalists Troll For Benefits

It is not all bad news for journalists. Public information officers might be able to speak directly to the public though social media and possibly set the agenda without having to go through the media. But journalists—in the words of one news director interviewed—are still "committing journalism." Journalists understand that their roles are changing, and they are looking for ways to distinguish their stories and content, both on social media and in traditional formats, from those of the land managers.

When asked which method is best for general wildfire-related communication, most agreed that no one method works for everything.

Most journalists we interviewed said that their employers had hired social media experts to help them make the most of social media. Social media tools allow journalists to collect data, photos, and even video from firefighters and other eyewitnesses by trolling social media sites. Journalists do not have to wait for information from official sources; they can get it faster, allowing them to better compete with other news organizations.

However, our research revealed that journalists need to exercise caution. It is difficult to verify information on social media sites. One journalist admitted to searching the social media for information but said "it was a worry for me to use an unknown source." Yet an editor told us that a survey had revealed that readers understood the unreliability of early information but wanted it anyway and expected journalists to correct it as new information emerged.

Social media tools allow journalists to collect data, photos, and even video from firefighters and other eyewitnesses by trolling social media sites.

Despite the changes wrought by rapidly evolving social media platforms, our research showed that two realities have not changed for journalists in their fire coverage. First, reporters need access to the wildfire scene, allowing them to tell great firsthand stories, thereby differentiating their content from a managing agency's information on social media. Second, journalists still use news releases in their coverage of wildfires. A news release is never the start of a story for any of the journalists we interviewed; a story usually starts with a social media post they see, usually on Twitter. However, they value traditional communication tools as verifiable data sources that contain solid statistics, contacts for fire management, and background information.

Although journalists value the accuracy of news releases, they dislike the often slow delivery process. News releases are also no longer solely for journalists, thanks to rapid online distribution capabilities. As one interviewee put it, "When you send those press releases, you send them to a large email list. If people ask to be put on that list, we are bound to do that." Elected officials, neighbors, local storekeepers, and many others are getting news releases at the same time journalists are getting them. So what was once exclusive copy for the eyes of journalists alone is now simultaneously available to anyone who asks for it.

Firefighters and Incident Commanders: Mixed Reviews

The firefighters we interviewed received training from their agencies on the use of social media, but they were mainly told what *not* to do, not what they *could* do. They offered differing opinions about using social media on wildfires. Some worried that it could upset the families of fire victims. In one case, a firefighter explained, “a wife found out about someone being injured before you could notify her in a respectful and kind way.”

Other firefighters agreed that there have been inappropriate posts, but they also thought that social media outlets offered a truer picture of what happens on a fireline. “I think it is a great thing, actually,” said one firefighter. “It gets things out there and shows people what we do.” But the reality of fast and widespread communication suggests that firefighters need to be extra careful about where and what they post.

Like public information officers, incident commanders realize that it is difficult to control the use of social media; they often find themselves reminding firefighters about their mission. According to one incident commander:

> I have concerns about it [social media]. But I am not naive enough to think that we can do anything about it, but to remind people [firefighters and other employees] that we are public servants and we need to be mindful about what we are putting out there. It’s here to stay. Things can get viral. I usually give a spiel about taking pictures of people’s houses that have burned and how those things can be damaging and hurtful. They’re out there to swing a tool and do a hose lay and they really should not have time to be standing around and taking pictures.

Journalists use official fire information to confirm the information they get from other sources for their stories. Photo: Mary Ann Chambers, Forest Service.

Journalists value news releases as verifiable data sources, but they are never the start of a story.

According to another incident commander, there has been operational use of social media to communicate among crews, and incident command teams are using “quick response codes” to spread information among firefighters and allow them to report safety concerns. Quick response codes are like bar codes on grocery products, but they can contain much more data as well as links to social media sites.

Firefighters interviewed also informally contacted other crews using tweets and Facebook about road closures and what they were doing on an incident. As one firefighter put it, “It is a good way for us to communicate. It’s easier, ’cause we can go on our Facebooks and we can contact crews in this region and have a pretty good idea of what is going on.”

Firefighters and Journalists: Still Strange Bedfellows

Despite advances in social media, everyone we interviewed agreed that face to face is usually the best way to communicate. But it is not always easy. One firefighter told us he sees the media as being in the way and acting unsafely. Many journalists ask for more access to incidents, and firefighters characterize them as obstructionists who need to be blocked from access. “They know their job is to sell,” one firefighter said, “and if I were in charge, I’d never let them on a fire.”

Firefighters want journalists to know that they are not public information officers and that they have many bosses. Therefore, they may not have answers to all of the questions journalists ask. Incident commanders want journalists to know that safety always comes first, but journalists do not always seem to understand. "We can't just send a bunch of crews out to a 50-foot wall of flame," said one incident commander. "It takes many people to support the firefighters on the line."

Meantime, firefighters and incident commanders are well aware that journalists are trolling for information shared on social media. They remind their peers and subordinates to be cautious about what they post.

Firefighters Beware!

Although many firefighters and incident commanders we interviewed believe that journalists should not have free run of incidents, they also know that reporters are trolling their Facebook posts and Twitter feeds, which could be just as troublesome. In response, some agencies require employees to act responsibly both on and off the job when they post information on social media about their work. Inappropriate posts can be grounds for dismissal.

Some agencies are encouraging firefighters to share their posts and pictures on the agency's Facebook page or Twitter feed. Although this infringes upon the self-publishing spirit of social media, agencies hope it will keep firefighters out of trouble. They also want a unified message about issues concerning wildfires and other land management activities.

How to Roll With the Social Media

Firefighters should know that trust still counts. For everyone we interviewed, personal relationships still matter, even in this new media age. Even though they search for information on the Web, journalists told us that they prefer local sources, such as the volunteer firefighters from their own communities, who are usually the first to respond to an incident. Trust is the main reason why social media have not totally supplanted news releases and other official sources of news about incidents.

For everyone we interviewed, Twitter and Facebook are the most popular social media venues. But other communication sites are gaining ground, such as Instagram and Vimeo. It is important that agencies keep up with developments in the social media world, which are sure to change over time.

Even without a steady flow of news, journalists have no choice but to "commit journalism." Public information officers need to give them information as quickly as they can. Social media can help; the ease of online editing and publication allows public information officers to offer smaller, focused elements of the larger story. As long as the information is verified, it can be released, with no need to wait to complete a single large report.

Incident management teams should find ways to give the media better on-the-ground access. Journalists are usually highly trained in the eyewitness accounts desired by an interested public. Allowing them to do their job frees up agencies to do theirs—fighting fires.

Firefighters and other agency employees need more training concerning social media and what is appropriate and inappropriate. If they are going to post anyway, agencies might as well have firefighters help by posting things that will get important positive messages out. For their part, journalists need to be cautious about gathering data from unknown sources. They should wait for trusted sources whenever possible.

More research is needed. In our exploratory qualitative research, we aimed at investigating an emerging phenomenon—the rapidly evolving world of social media and its influence on communication about fighting wildfires. It is time to apply other methods to new situations so we can continually improve our understanding of an important process.

A Foot in Both Worlds

Social media can be extremely valuable tools on wildfires. But news releases still give journalists important verifiable information. And other classic communication tools, such as interviews, community meetings, and eyewitness accounts, allow everyone to have that face-to-face contact they crave.

Our research revealed that the use of social media in wildfire communication will only grow. But the traditional ways are far from dead. At least for the near future, we will have to keep one foot in the old world and the other in the new if we are to succeed in this important area of wildland fire management. ■

New Forestry Journal Features Fire Review Articles

Martin E. Alexander

Current Forestry Reports is a new journal published by Springer that contains indepth review articles by international experts on significant developments in the field of forestry, including wildland fire management. By providing clear, insightful, and balanced contributions, the journal highlights and summarizes key topics of major importance to researchers and managers of forestry resources.

To help accomplish the journal's purpose, international authorities serve as section editors in a dozen key subject areas across the broad field of forestry, including fire science and management. The section editors, in turn, select topics for which leading experts in their respective specialty areas contribute comprehensive review articles that emphasize new developments and recently published papers of major importance. An international editorial board reviews the annual table of contents, suggests articles of special interest to their country/region, and ensures that topics are current and include emerging research.

Current Forestry Reports is published on a quarterly basis. Volume 1, issue 2, features five contributions related to fire science and management:

- The Flammability of Forest and Woodland Litter: A Synthesis—by J. Morgan Varner, Jeffrey M. Kane, Jesse K. Kreye, and Eamon Engber;
- Theory and Practice of Wildland Fuels Management—by Philip Omi;
- Empirical Support for the Use of Prescribed Burning as a Fuel Treatment—by Paulo Fernandes;
- A Review of Recent Forest and Wildland Fire Management Decision Support Systems Research—by David L. Martell; and
- Community Wildfire Preparedness: A Global State-of-the-Knowledge Summary of Social Science Research—by Sarah McCaffrey.

For more information, go to: http://link.springer.com/journal/40725 ■

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BEING REALISTIC ABOUT RISK

Barbara B. Day

I remember wanting to work for the Forest Service at a young age. It started when I saw an engine crew visit a Camp Fire Girls summer camp I attended every year. Something about that grabbed my attention.

It wasn't until I was out of college that I actually began my relationship with the Forest Service. The year was 1985, and I was hired late in the field season to mark timber on the Twin Falls Ranger District, Sawtooth National Forest, ID.

I came back to the district for the 1986 field season and went through the S–130 and S–190 fire training courses with the Sawtooth Interagency Hotshot Crew to get my first red card. Later that season, I was able to fill in with the crew and ended up on the Anderson Creek Fire on the Boise National Forest in Idaho. I don't remember a lot about that fire, but I do remember that a deuce-and-a-half (2-1/2-ton cargo truck) rolled off the road with everyone aboard, killing four members of the Jemez Eagles Crew 4 from the Jemez Pueblo in New Mexico.

That was my first dose of reality about the dangers of the job. But it didn't deter me from following my career path over the next 30 years.

I graduated from college in 1984 with a degree in education and had trouble finding a teaching job. I moved to Arizona and got hired as a temporary employee by the Tonto National Forest as an assistant on a type 6 engine on the Cave Creek Ranger District. I received a career appointment in 1990 as an engine captain on the same district and stayed on the Tonto for the next 20 years in various positions, including as the engine captain for the type 3 engine on the Payson Ranger District and as assistant district fire management officer on the Tonto Basin Ranger District. I ended my stay on the Tonto as the assistant forest fire management officer.

Bea Day is the fire operations risk management officer for the Forest Service, Southwestern Region, Albuquerque, NM.

Bea Day discussing an incident in New Mexico. Photo: Bea Day, Forest Service.

In 2008, I moved to the Cibola National Forest as the forest fire management officer. In June 2016, I took a position in the Southwestern Regional Office as the fire operations risk management officer.

Throughout my career, I've been active on several incident management teams in the Southwest. I am currently the incident commander for Team 1, a type 1 incident management team.

My first assignment as an incident commander was on a type 2 incident management team on a fire on the Valles Caldera in New Mexico in 2013. Little did I know as a new firefighter back in 1986 that I would have the incredible experience of interacting with the Jemez Pueblo and protecting many sacred sites of the very tribe that lost four firefighters on the Anderson Creek Fire. I have been in the profession long enough to come full circle to places I knew and people I met early in my career. Now I'm making decisions on the course of action to follow, whether it's on a fire or in a program.

I was honored and very humbled to receive the 2014 Forest Service Fire Management Officer of the Year Award from my peers. I'm committed to leaving a legacy of mentoring the next generation of leaders to find better ways of doing business and become absolutely committed to taking care of our own.

After the Yarnell Hill incident and after attending the L–580 Gettysburg Staff Ride (which, by the way, is one of the best

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leadership training opportunities out there), I was asked by a line officer what I would do differently. I said that I would be more honest—honest about the "why" of what we do; honest with the firefighters on the ground about the possibility of not coming home; honest with myself about my limits.

Often, we (the wildland fire community in general) are not honest about the risks inherent in the job we do. We say that we've mitigated the risks, but have we? We develop the 215A, writing out everything possible that might happen, along with risk mitigations; and then we walk away feeling good that we have a plan. But having a plan doesn't mean that you're any safer. The risks are still there and people can still get hurt or killed. Have we really been honest with ourselves and with the troops about why we are implementing this plan? That is what we, as an agency, need to improve on. We should not be afraid to be honest about the risks we face. ■

We should not be afraid to be honest about the risks we face.

Success Stories Wanted!

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A FIRE MANAGEMENT ASSESSMENT OF OPERATION FUGO

Jameson Karns

"Look what I found, dear!" Elsie Mitchell excitedly shouted to her husband, who was parking the family sedan.

Pastor Archie Mitchell and his wife Elsie had driven with a group of Sunday school children on May 5, 1945, from Bly, OR, to nearby Gearheart Mountain. The Mitchells were new to Bly and wanted to foster relations with the children of their congregation by hosting a morning picnic.

Elsie Mitchell, who was 5 months pregnant, had been exploring an adjacent creek with a group of five children and had discovered a peculiar object. Some of the children began to play with the strange gadget.

After receiving no response, Elsie called out a second time.

"Look what I found, dear!"

Pastor Mitchell never made it to his wife. The object suddenly and instantaneously incinerated Elsie and the children. The picnickers were the first casualties of one of the largest incendiary attacks of modern history (Webber 1975).

World War II has been termed the war of fire (Pyne 1982). Images of infernos are at the forefront of historical memory when one thinks about the catastrophes of the Second World War. Pictures of ash and rubble are associated with the horrific bombings of Tokyo, Berlin, and London. This perspective of incendiary warfare omits the U.S. mainland as a front in the war but not as a target.

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The Japanese incendiary operation, named Operation FuGo, succeeded in sending over 9,000 explosives-laden balloons over the Pacific, all designed to cause wildfires and destruction in the Western United States (Mikesh 1973). Although the attack triggered the restructuring and modernization of American wildland fire suppression, such efforts were not needed to defeat the threat: abnormal weather conditions caused the attack to fail. Yet in American wildland fire history, FuGo remains a unique and often disregarded event.

The Japanese Attack

Following the Battle of Midway and the Doolittle Raid on mainland Japan in 1942, the Japanese public's demand for retaliation led Japanese officials to devise an inventive and ambitious offensive attack by incendiary balloons. The objectives were to spark widespread destruction in America's Pacific coastal forests and arouse public panic and hysteria (Mikesh 1973). The Japanese military had studied the use of balloons in warfare as early as the mid-1930s. But the program was suspended and not resumed until the onset of World War II, when Major

Military personnel combat forest fires in western Oregon during World War II. Photo: Les. T. Ordeman, Forest Service; courtesy of the Forest History Society, Durham, NC.

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Otsuki, known as the “Father of FuGo,” received joint funding from both the army and the navy.

The first balloon bombing of America was set to take place in March 1943 (Mikesh 1973), with the release of FuGo balloons by two Japanese submarines dispatched to the American coast for the purpose. Before reaching the American coastline, the submarines were diverted to carry food and supplies to starving Japanese soldiers elsewhere in the Pacific. The decline in Japanese naval capacity following the Battle of Midway led to a grounding of any sea-based project. FuGo would have to assault the American West from over 5,000 miles (8,000 km) away on mainland Japan.

The project would have remained grounded altogether had it not been for the discovery by Otsuki, meteorologist Hidetoshi Arakawa, and others working at the Meteorological Observatory in Tokyo of “rivers of fast moving air” at an altitude of 30,000 feet (9,100 m) (Mikesh 1973). Of importance to Arakawa and military engineers was the discovery of a particular jet stream above mainland Japan that flowed eastward towards America. The jet stream over Japan created an excellent point of entry for incendiary balloons and a route by which the balloons could reach the United States in 3 to 4 days.

Notwithstanding its potential as a conveyor of destruction, the newly found jet stream had its shortcomings. The most favorable conditions for conveying FuGo’s balloons were from November to March, during the North American winter. That would prove critical in FuGo’s defeat.

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The first wave of paper balloons was launched on November 3, 1944, in honor of Emperor Meiji’s birthday, and further launches continued until the end of April 1945 (Mikesh 1973) (fig. 1). In total, 9,300 incendiary balloons, each of which carried multiple bombs, were launched toward targets of value in the United States.

Although the attack was ineffective militarily, it did have some success. One of the objectives was to spread panic, and the deaths of Elsie Mitchell and the Sunday school children made national headlines.

Yet the most tactically successful bombing would remain classified for decades. On March 10, 1945, a balloon bomb damaged the power generators of the Hanford Engineering Works production facility in Washington (Keating and Harvey 2002). Unknown to the Japanese and the American public, Hanford Engineering was one of the most important facilities of the American war effort because it housed a top-secret reactor that was responsible for supplying plutonium to the Manhattan Project. Less than half a year after this event, plutonium from Hanford was deployed in an atomic bomb over the city of Nagasaki.

The American Response

Because the military knew so little about the Japanese attacks, the U.S. Department of Defense took charge of wildfire suppression operations throughout the nation. The military plan emphasized three points: the incorporation of military tactics and equipment into wildland fire suppression; the control and

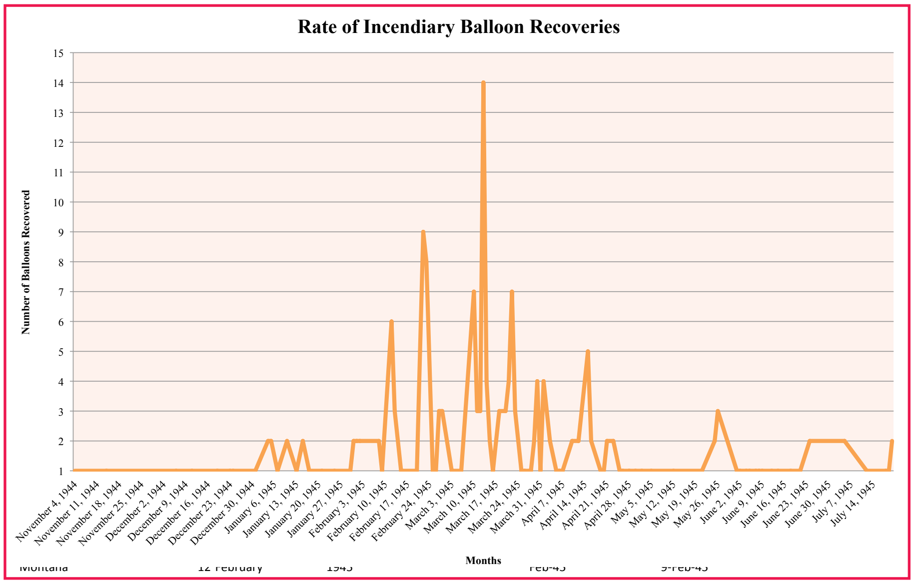


Figure 1—*The rate of balloon recoveries in the United States suggests that the FuGo attack was heaviest from February through April 1945, peaking in March. Source: National Archives (1945b).*

unification of all land management agencies involved in fire suppression; and the control and dissemination of information about wildfires and FuGo (fig. 2). “Project Firefly” was the military’s main line of defense against FuGo, primarily conducted under the Western Defense Command, Ninth Service Command, and Fourth Air Force (Mikesh 1973).

Firefly took a militarized tactical approach to fire suppression, treating each wildfire as a possible instance of foreign aggression, to be countered with the same tactics and equipment used against enemies in Europe and the Pacific. Firefly called upon the USDA Forest Service, “the largest single forest protection agency” (National Archives 1945c), as its primary vehicle for combating FuGo and for deploying over 3,000 military personnel throughout the West (National Archives 1945d).

Fire intelligence for the entire nation was reported to and processed at the top-secret headquarters in Missoula, MT (fig. 3) (National Archives 1945a), which also housed Firefly’s smokejumping and firefighter training facility. All land management agencies reported to this center, which dispatched resources to incidents. In a way, the center presaged today’s National Interagency Coordination Center in Boise, ID.

One of the most significant Firefly initiatives was to put military equipment to use in fire suppression. Military-grade equipment was “business as usual” for military personnel but not for the Forest Service. The agency had plenty of tools for manual labor, such as shovels, pulaskis, and saws; but all mechanized equipment came from the military (National Archives 1945c).

The most tactically successful bombing would remain classified for decades.

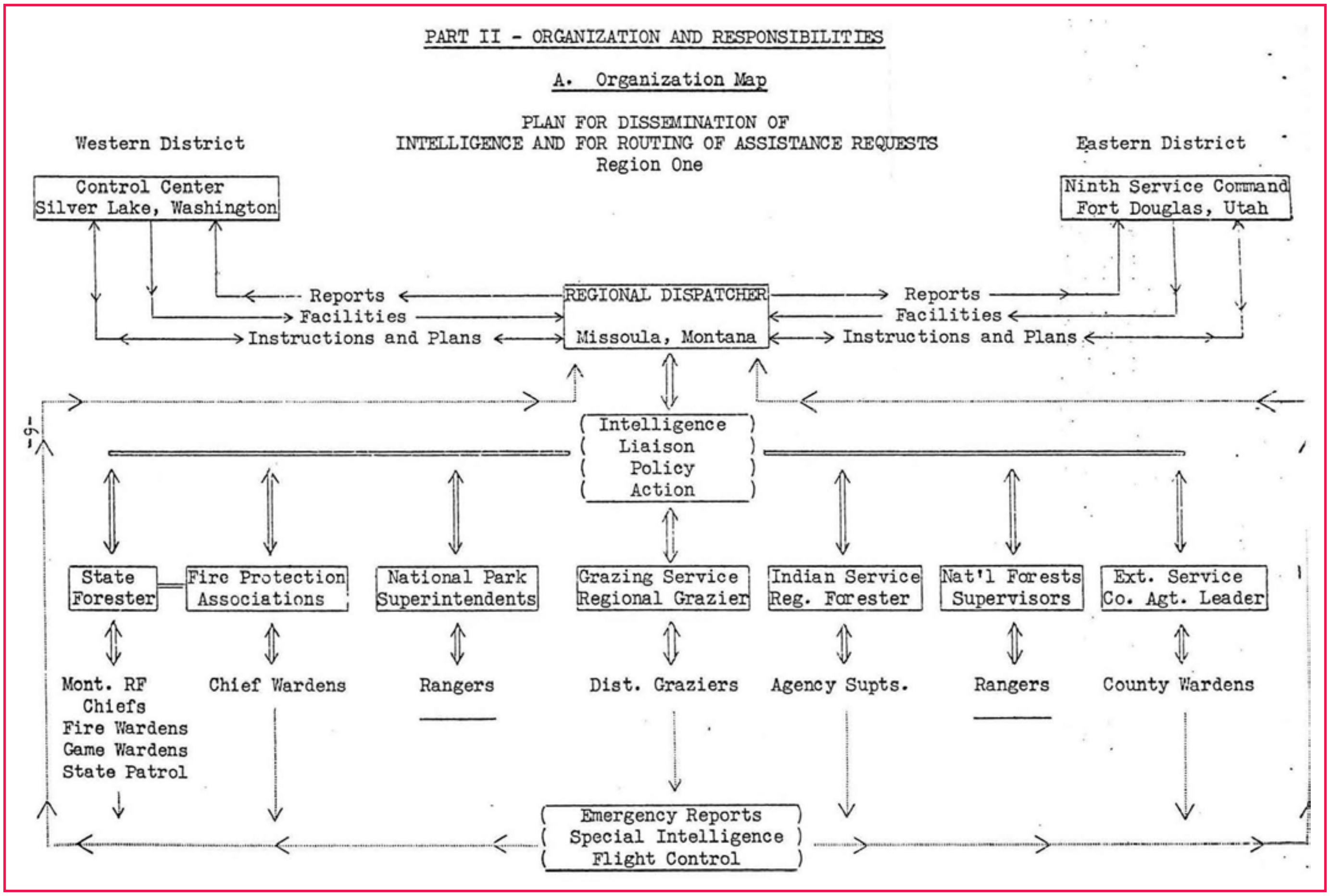


Figure 2—*Organizational chart for Project Firefly showing the chain of command for land managers in reporting wildland fires, reflecting the militarized flow of intelligence under Project Firefly. Source: National Archives (1945a).*

Under Firefly, the Forest Service learned to attack fire using methods and formations associated with modern warfare. According to fire historian Stephen Pyne, the dynamic of using both smokejumpers and ground-based crews was similar to using "commandos" and "shock troops" on the field of battle (Pyne 1982). Smokejumpers could rapidly reach tactically vital and remote areas. Ground-based crews, with their larger personnel complements, could sustain themselves for longer periods of time and, if necessary, be reinforced or relieved by other crews. Both types of units offered specialties and limitations.

The military supplied a normative formula for the disbursement of equipment to Forest Service "troops" (National Archives 1945b):

- One C–47 for each 250 ground troops,
- One C–47 for each 25 paratroops,
- Two C–64s for general fire use,
- Eight L–5s for observation and patrol,
- One personnel truck for each 25 men,
- One-and-one-half supply trucks for 25 men,
- Staff cars and jeeps for officer personnel,
- One rolling kitchen for each 250 men,
- Two bulldozers for each 250 men,
- One semitrailer and tractor for each dozer,
- One shop (field) repair truck for each two dozers,
- One ambulance for each 250 men,
- One tanker for each 250 men,
- One mobile radio unit for each 250 men,
- One semiportable radio for each 250 men, and
- Ten walkie-talkie radios for each 250 men.

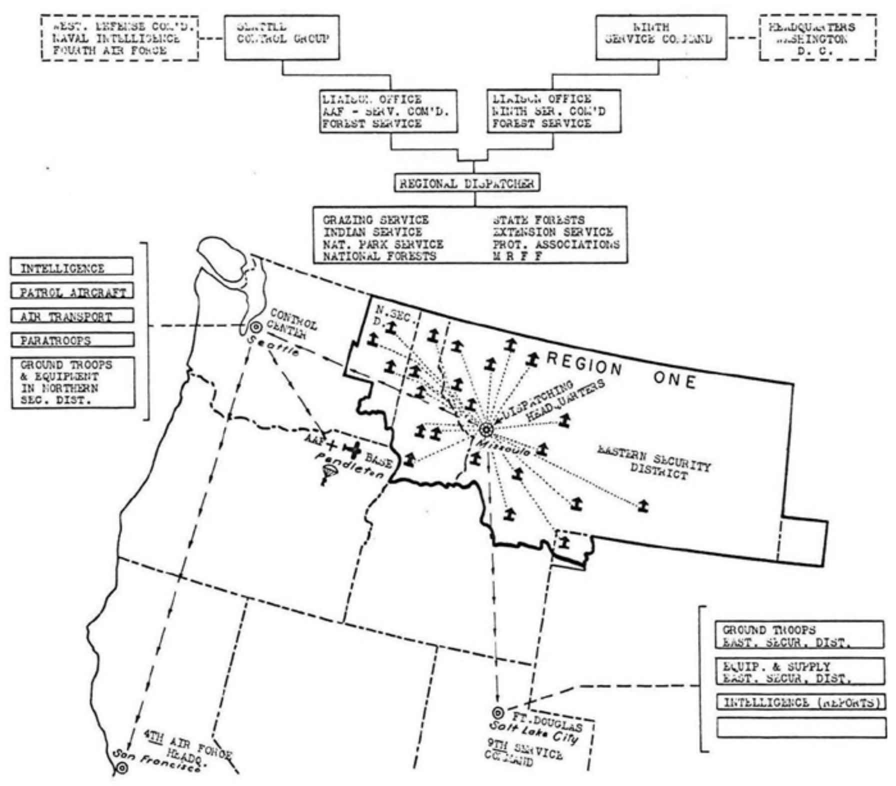


Figure 3—*Map showing the flow of intelligence and the structure of fire dispatch from a top-secret dispatch-and-operations base in Missoula, MT, under overall U.S. military command. Source: National Archives (1945a).*

By introducing such equipment and methods to fire suppression, the military permanently shaped the capabilities and expectations of land management agencies. In 1943, fire suppression had relied primarily upon manual labor, pack animals, and fire lookouts. By 1945, firefighters were using bulldozers and airplanes to suppress wildfires.

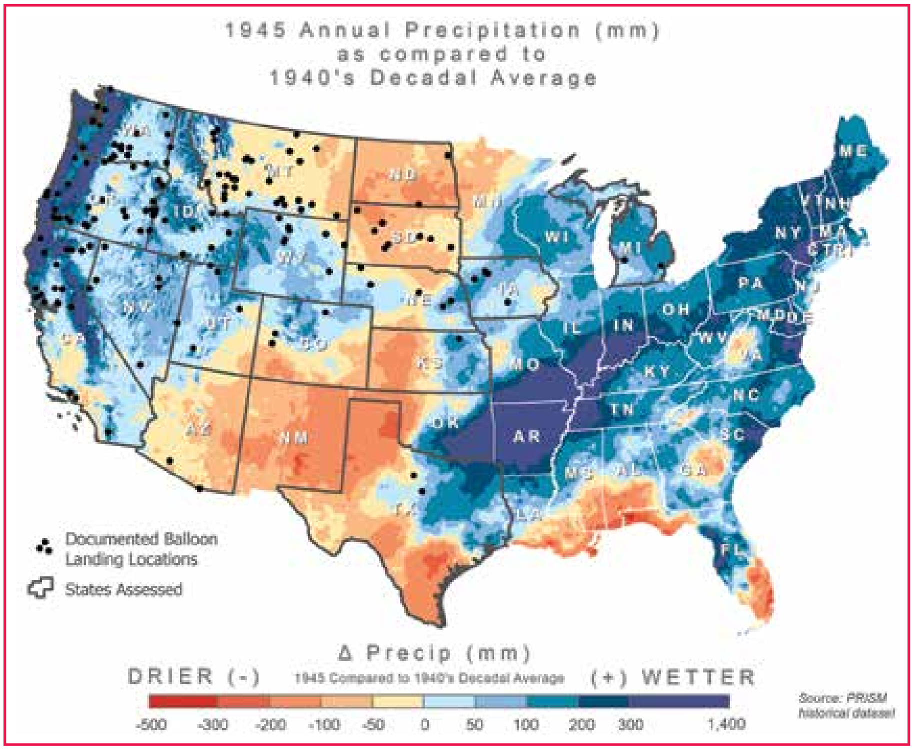
Aircraft became pivotal for rapid deployment by eliminating topographical obstacles and making any area relatively accessible to personnel, to equipment, and to fire retardant and suppressant. Accordingly, aircraft have been called the single most influential instrument in fire suppression tactics (Pyne 1982). Strategically, agencies that used aircraft came to symbolize modernity and technological achievement, which they used to advertise and advance their various causes (Wohl 2005).

The FuGo Failure

The rate of balloon touchdowns supported predictions by Japanese meteorologists (fig. 1). FuGo's incendiary balloon bombs found many of their intended West Coast targets. Of course, the variability of jet stream currents carried many balloons far off course into Mexico, Canada, and the interior United States.

Historians have not produced a full scientific explanation for FuGo's failure. However, the environmental and physical conditions that prevailed during the period when FuGo balloons touched down support the theory that FuGo was simply "rained out" (fig. 4).

FuGo was constrained by its singular avenue of delivery—the jet stream. This "river of air" is strongest from November through



Source: PRISM historical dataset

Figure 4—*Map showing precipitation in 1945 as compared to the decadal average, along with incendiary bomb balloon recovery sites. The year was exceptionally wet in the Pacific Northwest; although many balloons found their targets, the fuels were far too wet for the incendiary bombs to cause large fires. Constructed based on bombing locations confirmed by the U.S. National Archives and Mikesh (1973) and GIS metadata from Oregon State University, PRISM Climate Group, and the Northwest Alliance for Computational Science and Engineering.*

March. In the Pacific Northwest, November through March is also the period of greatest precipitation. As the fortunes of war would have it, Operation FuGo could not have been deployed at a more disadvantageous time for the Japanese.

The regions that FuGo targeted received disproportionately more precipitation in 1945 than in any other year of the decade (fig. 4). Most of these areas received 4 to 10-plus inches (10–25+ cm) of precipitation more than the normal amount. When the balloons touched down in the winter and spring of 1945, the Pacific Northwest was effectively in a state of supersaturation, and nearly three-quarters of the balloon touchdowns were in areas that had received record levels of precipitation. Widespread fire ignition would have been impossible under these circumstances.

Lasting Effects on Wildland Firefighting

Unusually high levels of precipitation defeated the largest incendiary bombing campaign on American soil. Nature defended the American homeland from FuGo.

In response to an unknown enemy and with no means of forecasting the record precipitation levels that would doom FuGo anyway, the American military revamped and reorganized the Nation's fire suppression capabilities to meet the FuGo attack. Even though the troops under Project Firefly never really battled FuGo, they witnessed a revolution in methods of firefighting.

Firefly created a militarized mechanized approach with lasting effects. Pyne (1982) had good reason to label this period the "age of mechanization" for fire suppression. Casting wildland fire as a foreign combatant in a military setting has become a mainstay of American culture, policy, and practice.

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References

Keating, J.K.; Harvey, D.W. 2002. History of the plutonium production facilities at the Hanford Site Historic District, 1943–1990. Richland, WA: U.S. Department of Energy.

Mikesh, R.C. 1973. Japan's World War II balloon bomb attacks on North America. Smithsonian Annals of Flight. 9: 1–84.

National Archives. 1945a. Control of forest fires to Joint WSF-WDC Plan Covering Defense Against Japanese Balloons. Annex H. Record Group 160. Documents and Studies. College Park, MD.

National Archives. 1945b. Cooperative Fire Control Plan, Army and Forestry Agencies, Region One Zone. Annex H. Record Group 160. Documents and Studies. College Park, MD.

National Archives. 1945c. Lyle F. Watts, Chief, Forest Service, to Assistant Chief of Chief of Staff. Annex H. Record Group 160. Documents and Studies. College Park, MD.

National Archives. 1945d. Forest Service to Army Assistant. Annex H. Department of Defense. Motion Picture Combat Bulletin. Documents and Studies. College Park, MD.

Pyne, S.J. 1982. Fire in America: A cultural history of wildland and rural fire. Volume 1. Princeton, NJ: Princeton University Press.

Webber, B. 1975. Retaliation: Japanese attacks and allied countermeasures on the Pacific Coast in World War II. Corvallis, OR: Oregon State University Press.

Wohl, R. 2005. The spectacle of flight: Aviation and the Western imagination, 1920–1950. New Haven, CT: Yale University Press. ■

Wildland/Urban Interface Watchouts

(Six Minutes to Safety, Operational Engagement Category)

The primary consideration is to first ensure firefighter and public safety. It is a must to assess potential fire behavior, ingress/egress routes, nature of the threat, hazardous materials, and available water supplies before engaging in the protection of any structures. The first step in conducting a safe operation is to assess whether the firefighting operations can be conducted safely.

Consider the “Wildland/Urban Interface Watchouts” in completing a risk analysis for the urban interface area to be protected. Remember, there are three categories of structures:

- Those that are not threatened,
- Those that are threatened, and
- Those that have already been lost or are too dangerous to protect.

Wildland/Urban Interface Watchouts

Poor access and narrow, one-way roads. A rapidly spreading fire could trap apparatus and personnel before they can turn around or move away from the flames and smoke.

Observe bridge limits. Exceeding bridge limits could lead to bridge failure, with a resultant blocking of ingress/egress routes that could result in the loss of an escape route or loss of equipment.

Inadequate water supply. Without a reserve supply of water, the fire can overtake an area before the fuels can be cleared away.

Natural fuels are located 30 feet or closer to structures on level ground. Remember, structures on slopes require greater clearance.

Structures located on canyon slopes or in “chimneys” on slopes of 30 percent or more with continuous flashy fuels. The resulting rate of spread of any fire can quickly extend beyond control.

Extreme fire behavior. Situations involving crowning, large flame heights, and erratic fire behavior can extend in an unpredictable manner beyond the control of any number of personnel.

Strong winds of 25 miles per hour (40 km/h) or more. Winds increase the chance of spotting over the heads of firefighters and trapping them between both fire areas. Winds also cause greater preheating of fuels in the path of a fire front.

The need to evacuate the public, livestock, pets, and/or animals. This critical activity can pull personnel from the firefighting activity and can distract attention from fire behavior at a time when the greatest alertness is needed.

Propane and above ground fuel tanks that are next to wooden structures or close to vegetation.

Powerlines and poles. What is their location in relation to the structures that are being protected? Watch for both overhead and downed powerlines.

Local citizens are attempting suppression activities. Lack of knowledge in fire suppression may lead to unsafe tactics.

Airtanker retardant drops and helicopter bucket operations. Establish communications and keep fire personnel out of the drop zone.

Source

Incident Response Pocket Guide: 12–16.

Editor’s note: *The piece is adapted from Six Minutes for Safety, a Website maintained by the interagency Wildland Fire Lessons Learned Center. (http://www.wildfirelessons.net/communities/community-home/librarydocuments?communitykey=dea3bee5-27db-4b8e-80c9-b95ed205777a&tab=librarydocuments)*

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