

Chapter 3

Fire Behavior and Heat Release as Source Conditions for Smoke Modeling



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Abstract Modeling smoke dispersion from wildland fires is a complex problem. Heat and emissions are released from a fire front as well as from post-frontal combustion, and both are continuously evolving in space and time, providing an emission source that is unlike the industrial sources for which most dispersion models were originally designed. Convective motions driven by the fire's heat release strongly couple the fire to the atmosphere, influencing the development and dynamics of the smoke plume. This chapter examines how fire events are described in the smoke

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modeling process and explores new research tools that may offer potential improvements to these descriptions and can reduce uncertainty in smoke model inputs. Remote sensing will help transition these research tools to operations by providing a safe and reliable means of measuring the fire environment at the space and time scales relevant to fire behavior.

Keywords Atmosphere models · Coupled fire · Energy release · Fire behavior · Fire progression · Remote sensing

3.1 Introduction

Many tools used to simulate smoke impacts from wildland fires evolved from tools used in the air quality community for assessing anthropogenic pollution impacts. As such, it has been necessary to describe a wildland fire event in terms common to these anthropogenic pollutant sources—often characterized as point, line, and area sources. Descriptions of a fire event, or of an individual burn period of interest, are often reduced to simply an amount of fuel consumed at a specified location during a period of time, perhaps with diurnal variability. As the sources of the emissions and energy that drive plume dynamics (Chaps. 4 and 5), fire behavior and associated heat release (this chapter) are critical links between fuels (Chap. 2) and downwind impacts (Chaps. 6 and 7).

Fire–atmosphere interactions are tied to the energy released by the combustion process that heats the surrounding air. This heating drives a convective circulation whereby the heated air expands, decreases in density, and is forced upwards by denser ambient air. The drawing in of ambient air to replace the buoyant updraft is referred to as entrainment and is determined by the conservation laws of mass and momentum. The spatial pattern of entrainment is governed by fireline shape, ambient winds, topography, and drag induced by vegetation structure. A sustained release of heat, such as from a wildland fire, induces a feedback that allows the scale of these convective circulations to grow and interact throughout the deepening layer of the atmosphere and form a plume. This chapter focuses on how to better capture the spatial evolution of this heat source in the description of fire events used in the smoke modeling process, and how these descriptions can be improved to reduce the error associated with forcing the fire emissions modeling process to conform to an overly idealized anthropogenic emissions source.

The description of a fire consists of both temporal and spatial components. Accurately describing the evolution of a fire through time connects the release of emissions to varying atmospheric conditions such as wind direction and atmospheric stability that can greatly affect transport and dispersion. The spatial component of a fire description is more complex: The atmosphere varies temporally and spatially, requiring that the fire location and the time component are correct. But a fire is much more than a passive emitter of pollutants to the atmosphere. Distribution of heat across the landscape creates feedbacks between the fire and atmosphere, altering

flow patterns and affecting downwind plume characteristics (Chap. 4). For a simple idealized source, Cunningham et al. (2005) illustrate how a buoyant plume interacts with a surface shear layer to yield variations in plume spread and depth (Fig. 3.1). For a larger fire, such processes interact across different scales to produce more complex plumes (Fig. 3.2), and that multiscale interaction can influence fire spread as well.

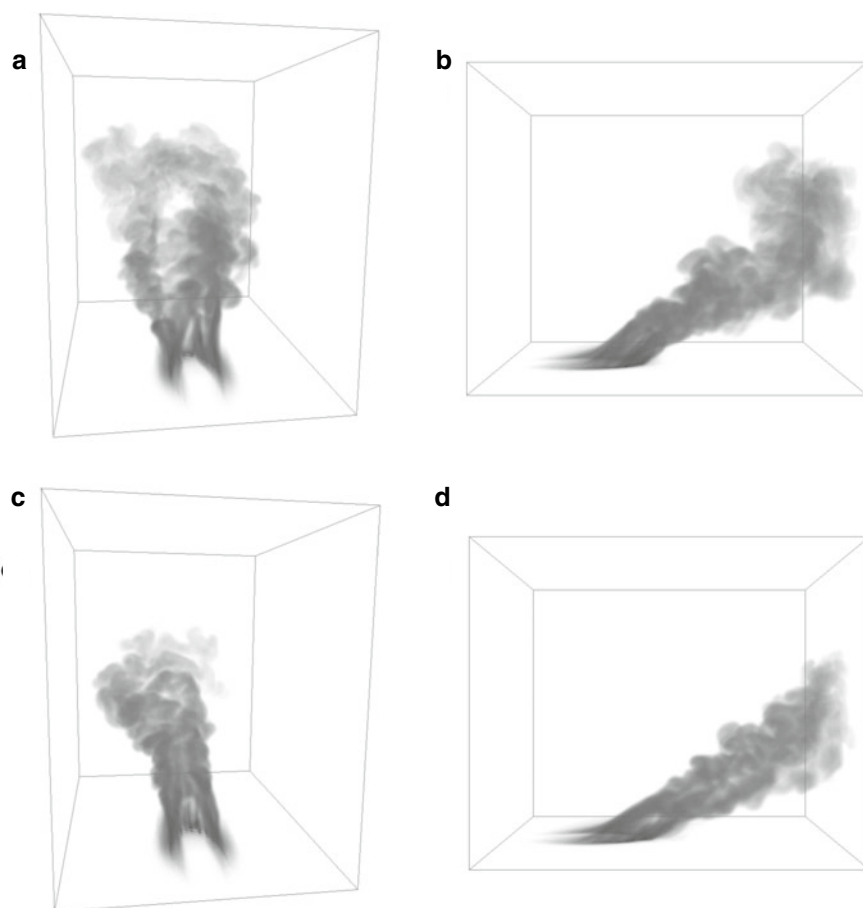


Fig. 3.1 Volume-rendered potential temperature at $t = 1100$ s for the realistic heat source large-eddy simulation. The upper two images are for the deep shear layer ($z_0 = 150$ m) case with views from **a** the inflow boundary and **b** lateral boundary. The lower two images are for the shallow shear layer ($z_0 = 50$ m) case with views in **(c)** and **(d)** identical to those in **(a)** and **(b)** respectively. Darker shades represent higher values of potential temperature. From Cunningham et al. (2005)



Fig. 3.2 Panorama image of the smoke plume above a prescribed burn at Magazine Mountain, Arizona, on February 27, 2004, revealing a complex structure of merging multiple updraft “cores” when the plume is viewed from the ground. From Achtemeier et al. (2011)

3.2 Current State of Science

3.2.1 *Representing Fire in Smoke Models*

Smoke models are numerical tools that provide information on the spatial distribution of pollutant species through time, such that the ecological, human health, economic, and societal effects of wildland fires can be simulated and assessed. Box models, Gaussian plume models, and Lagrangian particle and puff models, among others, are based on atmospheric transport and dispersion theory and may include complex chemical mechanisms for describing the generation of ozone and secondary organic carbon (Goodrick et al. 2012). Each tool must include a description of their emissions source, based on a representation of a wildland fire that includes fire behavior and heat release. For this assessment, we examine two smoke modeling tools commonly used on an operational basis in the USA and explore some additional models used within the research community.

3.2.1.1 Operational Tools

Operational tools are those models used for real-time decision making and planning for wildland fire management. With the exception of some planning applications, operational tools must make calculations faster than real time and be able to tailor outputs in order to effectively support decision making; for operational smoke models, the output is focused on surface pollutant concentrations rather than the full

three-dimensional (3D) distribution. In contrast, research tools are focused more on advancing our understanding of a phenomenon and thus operate without the faster than real-time constraint and provide a broader range of outputs that are useful to scientists but of little practical value to land managers.

VSMOKE

VSMOKE (Lavdas 1996) is a Gaussian plume model designed for estimating smoke impacts from prescribed fires in the southeastern USA. It is best suited for simulating the effects of a single fire within periods of constant or slowly changing fire behavior, emissions, and weather conditions, during which the smoke can be adequately depicted within a steady-state framework. The fire is treated as either a point source or a specific fire area that releases emissions and heat at a constant rate. The atmosphere is described by a mixing height, transport wind, and a stability class which is treated as steady state and spatially homogeneous. The stability class and heat release affect dispersion calculations through the determination of the plume rise as determined by the commonly used Briggs equations (Briggs 1982).

Because VSMOKE is designed for prescribed fires, the model accommodates a wide range of fire behaviors, such as fires dominated by combinations of backing and flanking fire rather than conditions dominated by head fire. This is accomplished through a parameter controlling the fraction of smoke released from the surface versus that released at the plume-rise height, or uniformly distributed between the surface and the plume-rise height to achieve a range of possible plume behaviors (Lavdas 1996) (Fig. 3.3). The user can assign the parameter, although a default value based on unpublished observations of prescribed fires is provided by Lavdas. Unfortunately, there is little work connecting variations of this fraction of emissions subject to plume rise to proportions of head, flank, and backing fire or other descriptions of firing method used.

BlueSky

BlueSky is a modular smoke modeling framework which links a series of processing steps containing datasets or individual component models to estimate smoke emissions and transport for smoke forecasts and decision support (Larkin et al. 2009). Figure 3.4 shows the array of models that can be incorporated into the BlueSky framework. The minimum fire information input data required by BlueSky are fire location and daily fire growth. This fire information is transformed into dispersion model inputs by identifying appropriate fuel loads for the location, applying a consumption model to estimate daily fuel consumption, and then constructing a time profile of heat and emissions release.

By default, wildfires use the Western Regional Air Partnership wildfire profile (Air Resources Inc. 2005) that allocates 68% of the emissions to an afternoon active

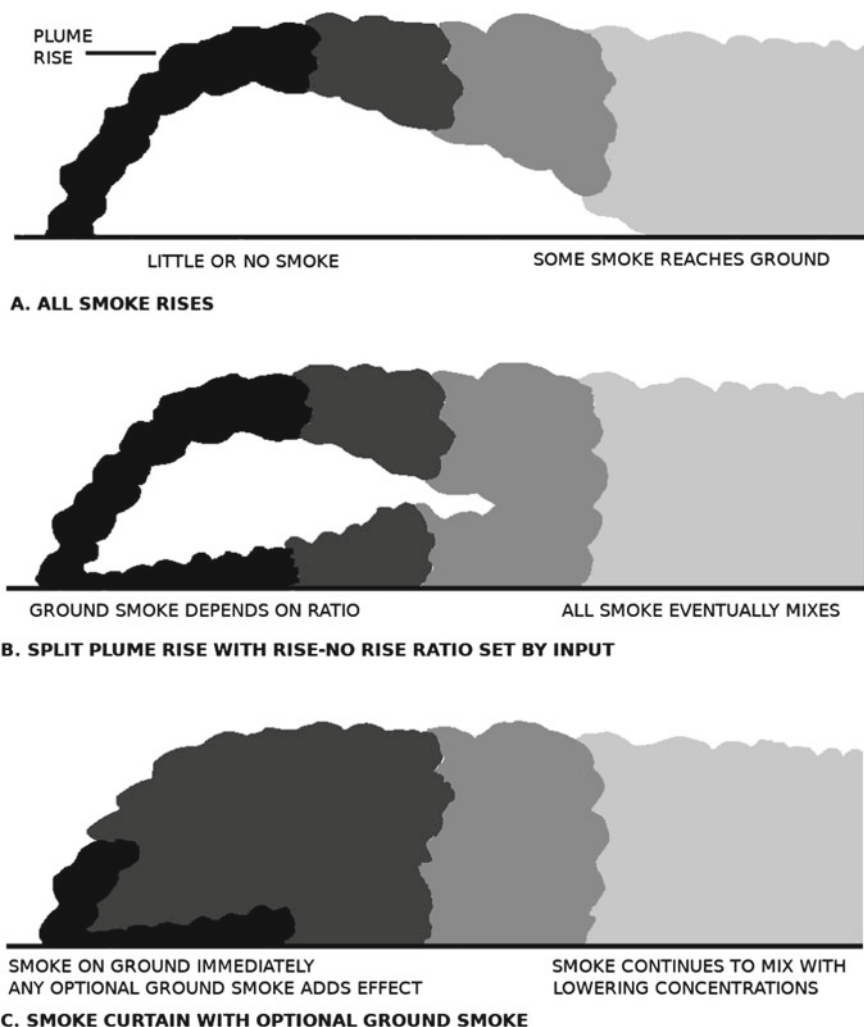


Fig. 3.3 Effects of plume rise options on ground-level smoke concentrations for VSMOKE. From Lavdas (1996)

burning period (1300–1700 h local time) along with a nocturnal smoldering component. Prescribed fires default to a time profile generated by the Fire Emissions Production System, which is based on simple rise and decay curves initially derived for estimating emissions from coniferous logging slash in the Pacific Northwest (Sandberg and Peterson 1984).

Validation efforts for older versions of the BlueSky framework found a tendency to underestimate near-field surface smoke concentrations while potentially overestimating far-field surface smoke concentrations (Riebau et al. 2006). Sensitivity studies found that predictions of surface smoke concentrations could be improved

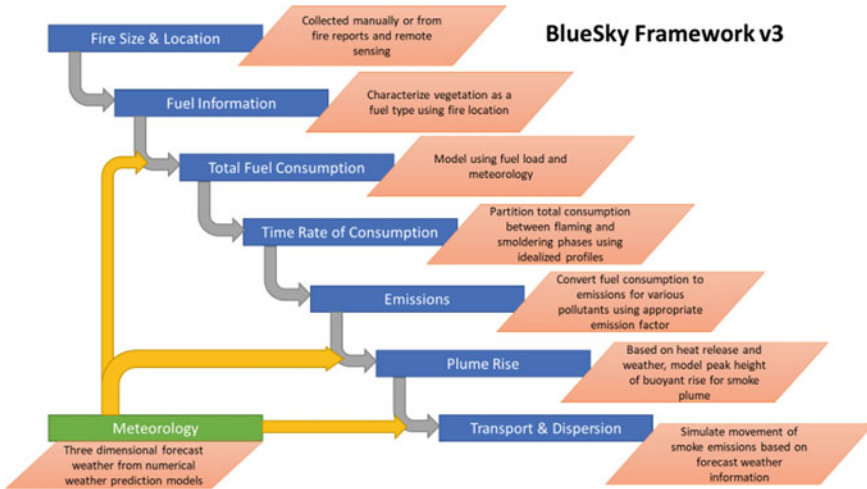


Fig. 3.4 Overview of BlueSky smoke modeling framework. Adapted from Goodrick et al. (2012)

by splitting fires into multiple emissions sources, effectively mimicking the concept of multiple updraft core plumes (Solomon 2007). A subsequent study of the 2008 northern California wildfires found that BlueSky predictions of $PM_{2.5}$ were in closer agreement with observations in both the near- and far-field (Strand et al. 2012). This simple application of the core plume concept with multiple updrafts is an example of a research tool transitioning to operations.

3.2.1.2 Research Tools

Although a wide range of research tools could be discussed in this section, our focus is on those tools that can provide insight into improving the representation of wildland fires within smoke dispersion models. This is not an exhaustive list, but a sampling of tools that are advancing our knowledge of the linkage between the fire and smoke dispersion processes.

DaySmoke

DaySmoke is a hybrid plume particle model that consists of four sub-models: an entraining turret model, a detraining particle model, a model of large-eddy parameterization for the mixed boundary layer, and a relative emissions model that describes the emission history of the prescribed burn (Achte-meier et al. 2011). The entraining turret model handles the convective lift phase of plume development and represents the updraft within a buoyant plume. This updraft is not constrained to remain within the mixed layer. A burn in DaySmoke may have multiple, simultaneous updraft

cores. In comparison with single-core updrafts, multiple-core updrafts have smaller updraft velocities, are smaller in diameter, are more affected by entrainment, and are therefore less efficient in the vertical transport of smoke.

The importance of multiple-core updraft plumes was demonstrated with the Brush Creek prescribed burn in eastern Tennessee on March 18, 2006, where visual observations identified between 1 and 5 cores throughout the duration of the fire (Jackson et al. 2007; Liu et al. 2010). DaySmoke simulations with 1 to 10 updraft cores produced estimates of hourly $\text{PM}_{2.5}$ concentrations in Asheville, North Carolina, ranging from 45 mg m^{-3} (single updraft core) to 240 mg m^{-3} (10 updraft cores). The simulation with 4 updraft cores produced an hourly peak $\text{PM}_{2.5}$ concentration of 140 mg m^{-3} , which agreed well with observations at the air quality monitor location in Asheville.

In applying the Fourier amplitude sensitivity test (FAST) to DaySmoke simulations of prescribed burning in the southeastern USA, the most important parameters for determining plume rise were the entrainment coefficient and number of updraft cores (Liu et al. 2010). Both of these parameters relate to the distribution of heat across the landscape as temperature gradients enhance turbulent mixing and therefore entrainment. Areas of elevated fire intensity indicate enhanced buoyancy and therefore stronger updrafts.

Although DaySmoke can represent multiple core updrafts, it has no method for determining the appropriate number of cores to include. Achtemeier et al. (2012) determined the number of updraft cores by linking DaySmoke to a cellular automata fire model, tested on an aerial ignition prescribed burn conducted at Eglin AFB on February 6, 2011, as part of the Prescribed Fire Combustion and Atmospheric Dynamics Research (RxCADRE) collaborative research project. Originally described by Achtemeier (2013), the fire model incorporates a two-dimensional wind flow model to represent coupled fire–atmosphere circulations and provides DaySmoke with the following input information: (1) 2-m winds for calculating indraft velocities and estimates for calculating initial plume updraft velocities, (2) location and number of updraft cores, (3) approximate initial plume diameter, and (4) relative emissions production. During the simulation of the RxCADRE burn, pressure anomalies were as low as -1.4 mb , and the number of updraft cores ranged from 1 to 6 but typically was 4. Figure 3.5 shows the distribution of fire and associated pressure anomalies.

The coupled DaySmoke simulation produced a strong vertical plume that extended 1000 m above the mixing height and resulted in the majority of the flaming phase emissions being injected above the mixed layer. The observed plume heights measured with a ceilometer verified the model results, as did minimal ground-level smoke concentrations measured by a small network of downwind particulate samplers (Achtemeier et al. 2012). Linking a fire model with the dispersion model allowed the simulated plume to provide burn managers with more accurate information for their ignition planning. Linking a fire model with a smoke plume model also improved descriptions of the fire as input into the smoke model (Achtemeier et al. 2012). Tools that more strongly couple the fire and atmosphere promise further benefits.

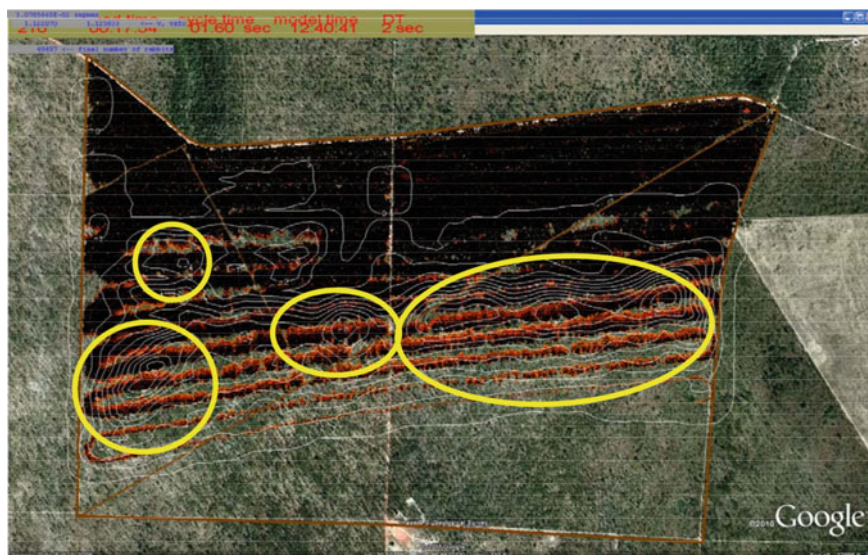


Fig. 3.5 Pressure anomalies (white lines) generated by the Achtemeier et al. (2012) fire model at 12:40:41. The yellow ellipses highlight centers that might correspond to updraft cores. From Achtemeier et al. (2012)

WRF-SFIRE

Kochanski et al. (2016) proposed an integrated system for fire, smoke, and air quality simulations by coupling WRF-SFIRE with WRF-Chem to construct an integrated forecast system for wildfire behavior and smoke prediction (Fig. 3.6). The Weather Research and Forecast (WRF) model is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications (Skamarock et al. 2008). WRF is designed to allow for incorporation of new functionalities: WRF-SFIRE and WRF-Chem are two extensions to the WRF model. WRF-SFIRE is a two-way, coupled fire–atmosphere model that estimates fire spread based on local meteorological conditions, taking into account feedback between the fire and atmosphere (Mandel et al. 2011, 2014). WRF provides a multi-scale domain, with fine scales for modeling fire behavior nested inside coarser scales for resolving the larger-scale synoptic flow.

WRF-Chem is a chemical transport model used to investigate regional-scale air quality by simulating the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with meteorology (Grell et al. 2005). In current operational modeling frameworks, prescribed fire activity and fire emissions are simplified to a single plume whose vertical extent is estimated by a simple plume-rise model. However, with the coupled WRF-SFIRE-Chem system, pyroplume development, smoke dispersion, and air quality impacts are comprehensively

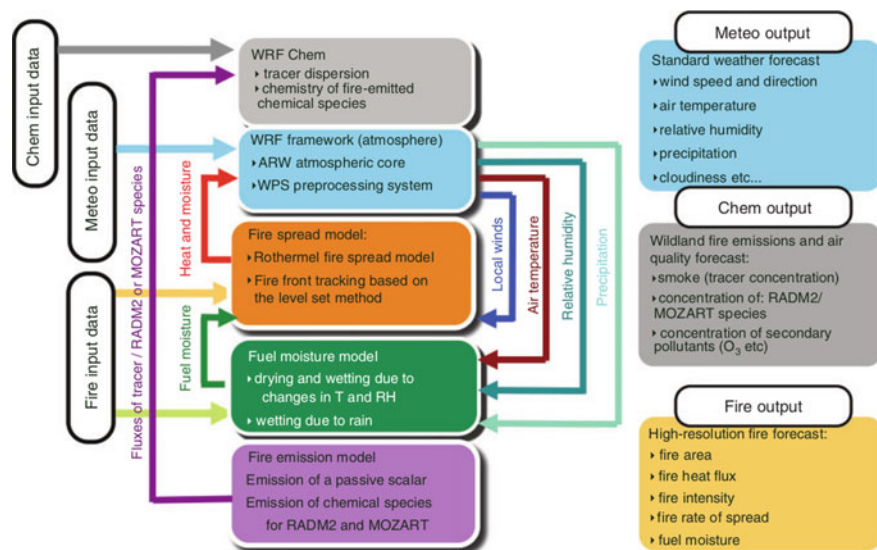


Fig. 3.6 Diagram of WRF-SFIRE coupled with fuel moisture model and WRF-Chem. From Kochanski et al. (2016)

modeled by one system that includes fire spread, heat release, fire emissions, fire plume rise, and smoke transport and dispersion with associated plume chemistry.

Application of the WRF-SFIRE-Chem system on two California fires, the 2007 Witch/Guejito fires and the 2012 Barker Canyon fire, yielded promising results (Kochanski et al. 2016). For the Witch/Guejito fire, simulated and observed local- and long-range fire spread and smoke transport agreed well, but ozone, $\text{PM}_{2.5}$, and NO concentrations were generally underestimated in the simulations. Simulated plume-top heights exhibited considerable variation throughout the day, with the standard deviation of time-averaged plume heights as high as 600 m. The simulations clearly exhibited multiple plume-rise peaks associated with multiple core updrafts and reinforced that a single Gaussian-shaped plume and injection height provides an unrealistic representation of a wildfire plume.

Simulations of several large 2015 wildfires in northern California highlighted the ability of the WRF-SFIRE-Chem system to capture feedback effects between smoke and weather (Kochanski et al. 2019). Smoke from the wildfires induced a positive feedback loop in which aerosols aloft in the smoke plume absorbed incoming solar radiation, warming the top of the plume. Less solar radiation was received at the ground, resulting in surface cooling. This warming aloft and cooling below develops a local smoke-enhanced inversion that inhibits the growth of the planetary boundary layer and reduces surface winds, resulting in smoke accumulation that further reduces near-surface temperatures. Such results are possible only in a system that fully integrates fire and smoke processes within the weather model.

MesoNH-ForeFire

Similar to WRF-SFIRE, the European MesoNH-ForeFire modeling system combines a fire area simulator and a mesoscale meteorological model to simulate fire-atmosphere interactions (Filippi et al. 2011). The fire area simulator is based on the spread model of Balbi et al. (2009) and describes the mean propagation velocity of the fire front as a function of slope, surface wind speed, and fuel properties. Initial application of MesoNH-ForeFire to real-case scenarios in predominantly Mediterranean Maquis shrublands yielded plume structures that agreed qualitatively with photographs of the plume, with distinct updrafts developing over each fire flank that merge over the head of the fire. Although the model produced some of the observed plume structures, the 50-m grid used in the atmospheric simulation limited the model's ability to reproduce finer-scale structures. In a more recent study using a finer grid resolution, MesoNH-ForeFire plumes compared well with Lidar-based plume observations (Leroy-Cancellieri et al. 2014). The more refined model grid improved the representation of the fire in space and time, resulting in improved forcing of the atmospheric processes governing plume behavior.

CAWFE

The Coupled Atmosphere Wildland Fire Environment (CAWFE) is an alternative system that employs a numerical weather prediction model designed specifically for simulating small-scale weather processes in complex terrain (Clark and Hall 1991; Clark et al. 1996, 1997; Coen 2013). Coupling of numerical weather prediction models to fire-spread simulations provides many benefits, as the coupling allows dynamic interaction among the components of the fire environment.

However, fire presents an interesting problem to many weather models, depending on their formulation and inherent assumptions. Models such as WRF are designed to simulate a broad range of weather phenomena ranging from hundreds of meters to tens of kilometers. This flexibility and scalability do not come without a cost. Models designed for these scales tend to dissipate energy at fine scales due to choices in numerical schemes used in its solver and grid refinement methodology. Thus, the model tends to dissipate energy at the scales that the fire is trying to add energy.

The fire component of CAWFE is a front-tracking approach similar to that of WRF-SFIRE. CAWFE simulations helped Coen et al. (2018) evaluate the relative roles of climate, fuel accumulation, and forest structure changes tied to fire exclusion, and nonlinear effects tied to dynamic coupling of fire environment components on the 2014 King fire (California). The CAWFE atmospheric formulation has shown promise in reproducing significant features of major wildfire events, such as a 25-km up-canyon run on the King fire (Coen et al. 2018), but its less dissipative nature may be more applicable for lower-intensity prescribed fires.

FIRETEC and WFDS-PB

FIRETEC (Linn et al. 2003) and the Wildland Urban Interface Fire Dynamics Simulator (WFDS-PB; Mell et al. 2009) are physics-based fire models that use a finite-volume, large-eddy simulation approach to model the atmosphere. FIRETEC (Linn et al. 2003) is a 3D model designed to simulate the constantly evolving relationships between wildland fire and its environment. FIRETEC describes a range of processes that drive fire behavior and how these processes interact with the overlying atmosphere (Fig. 3.9). Vegetation is described as a highly porous 3D medium characterized by bulk quantities (e.g., surface area-to-volume ratio, moisture content, bulk density) of the thermally thin components of the vegetation. FIRETEC and WFDS-PB have been used to simulate crown fires (Linn et al. 2012; Hoffman et al. 2016), bark beetle effects on fire behavior (Hoffman et al. 2013; Linn et al. 2013), and fireline interactions (Morvan et al. 2011, 2013). The primary drawback of such physics-based models is the very high computation requirements inherent in the fine resolution of the computational grid (1–2 m).

The WFDS model builds on the Fire Dynamics Simulator, which was developed by the National Institute of Standards and Technology to model structural fire. WFDS is intended to help understand fine-scale fire behavior within wildland fires and between wildland and developed areas. WFDS uses computational fluid dynamics to represent buoyant flow, heat transfer, combustion, and thermal degradation of vegetative fuels. This approach uses large-eddy simulation to solve the gas-phase equations on computational grids that are too coarse to directly resolve the detailed physical phenomena.

Computational costs can be lowered by implementing a “level-set method” to propagate the fireline (e.g., WFDS-LS; Bova et al. 2016). This numerical technique tracks the evolution of an interface between two locations (e.g., burned and unburned fuels), thus simplifying issues from merging and splitting fronts that are difficult to track (Mallet et al. 2009). Explicitly resolving gas-phase combustion is not necessary for smoke plume simulations of this scale if the heat release per unit area is known (Liu et al. 2019). Models such as WFDS can be used to inform our ability to design communities to withstand an approaching wildfire.

3.2.2 Remote Sensing

Although models provide one means of developing a more complete description of a fire for input into smoke models, empirical observations are also a vital source of information about individual fires and for fire model verification. Wildland fires are difficult to measure due to high temperatures, but many remote sensing techniques have emerged over the last 20 years that are capable of observing wildland fires across a broad range of spatial and temporal scales. This approach is often capable of deriving spatial and temporal distributions of heat release as inputs for smoke models.

3.2.2.1 Fire Area

Measurements of area burned are critical for estimating fire emissions, which are one of the largest sources of potential error in modeling (Soja et al. 2009). As described in Chap. 2, satellites provide a consistent means for estimating burned area. Two satellite platforms commonly used for estimating burned area are the Geostationary Operational Environmental Satellite (GOES) and Moderate Resolution Imaging Spectroradiometer (MODIS). The GOES product is geosynchronous with temporal resolutions of 5 min for the Fire Detection and Characterization Algorithm (FDCA) at the cost of relatively low resolution of 2 km. Despite geostationary satellites tending to have coarser resolution than polar orbiters, the more frequent observations have shown utility beyond just detection. For example, Liu et al. (2018) were able to extract near real-time rate-of-spread estimates for fires in Western Australia using data from the Himawari-8 satellite.

The polar-orbiting MODIS instruments provide improved spatial resolution of 500 m but at lower temporal resolution of 4 overpasses per day. The GOES and MODIS products capture the inherent tradeoff between spatial and temporal resolution which limits their current utility for describing the evolution of fire events. Satellite products successfully capture large wildfires that account for the majority of emissions (Soja et al. 2009), but are less useful for prescribed fires due to a low detection rate as most prescribed fires are of lower intensity and shorter duration (Nowell et al. 2018). Although satellite instruments and algorithms will continue to advance, alternative instrument platforms, such as aircraft and unmanned aircraft systems (UASs), provide better spatial and temporal resolution for select events.

3.2.2.2 Energy Release

Knowing the fire location is the first step in describing a fire for use in smoke models. The next piece is knowing the rate and amount of heat released. Measurements of Fire Radiative Power (FRP) detect the rate of radiant heat output from a fire, and FRP integrated over time provides an estimate of the fire radiative energy (FRE), which is proportional to the total mass of fuel biomass consumed (Chap. 2). In their review of fire meteorology, Kremens et al. (2010) outlined several methods for estimating the energy radiated by the combustion of fuels within each fire-affected pixel (Kaufman et al. 1996; Butler et al. 2004; Riggan et al. 2004; Ichoku and Kaufman 2005; Smith and Wooster 2005). The FRP and (by time integration) FRE are calculated by combining two infrared bands to estimate the mean radiant fire temperature and emissivity-area product for an individual pixel (Dozier 1981; Matson and Dozier 1981; Riggan et al. 2004).

In an examination of the 2013 Rim Fire (California), Peterson et al. (2015) employed FRP estimates from the GOES-14 satellite to study extreme fire spread and pyroconvection. Peaks in FRP during the Rim Fire likely coincided with the most intense burning (Fig. 3.7). Although diurnal variability in FRP is evident, it is equally evident that variation in FRP does not follow a simple diurnal distribution as

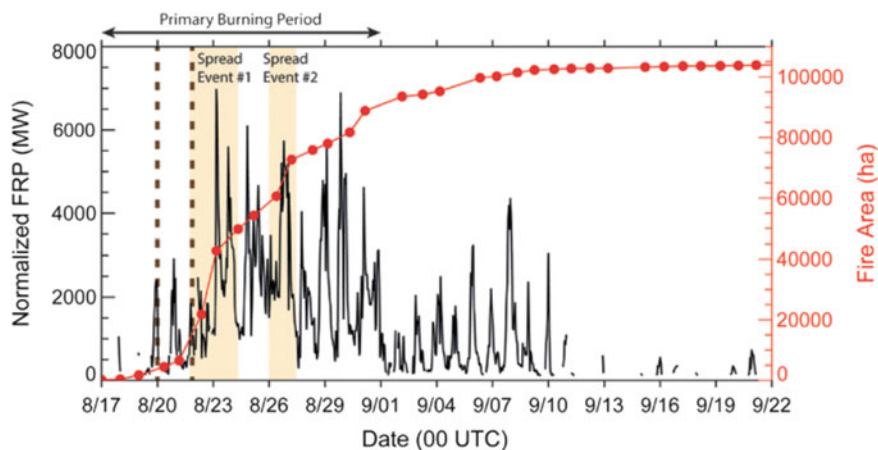


Fig. 3.7 Time series of normalized hourly FRP from GOES-West (black) and cumulative fire area derived from National Infrared Operations observations (red). Spread events 1 and 2 are highlighted with yellow shading, and the pyroCb events of 19 August and 21 August are denoted by dashed brown vertical lines. From Peterson et al. (2015)

described for the Western Regional Air Partnership and Western Governors Association (Air Resources Inc. 2005). The co-occurrence of high FRP on days with weaker atmospheric stability is likely tied to a greater vertical extent of the smoke plumes and an enhanced probability of smoke injection into the free troposphere (Val Martin et al. 2010; Peterson et al. 2014).

Satellites are not the only remote sensing platforms from which fire information can be derived. One example of an aircraft-based platform, the FireMapper thermal-imaging radiometer, allows quantitative measurements of fire-spread rates, fire temperatures, radiant-energy flux, residence time, and fireline geometry (Riggan et al. 2010). Figure 3.8 is a FireMapper thermal image of the Esperanza Fire (California) depicting thermal anomalies indicative of biomass burning on October 26, 2006, between 14:07 and 14:17 PDT (Fig. 3.9).

Coen and Riggan (2014) examined the Esperanza Fire to test the CAWFE model and examined how dynamic interactions of the atmosphere with large-scale fire spread and energy release affect observed patterns of fire behavior as mapped by FireMapper. This is a case of FireMapper being used to verify a model projection of fire behavior. The CAWFE simulation correctly depicted the fire location at the time of an early-morning incident involving firefighter fatalities. Periods of deep plume growth were also well captured by the model and verified by FireMapper, highlighting the importance of fire–atmosphere coupling in reproducing the evolution of a fire.

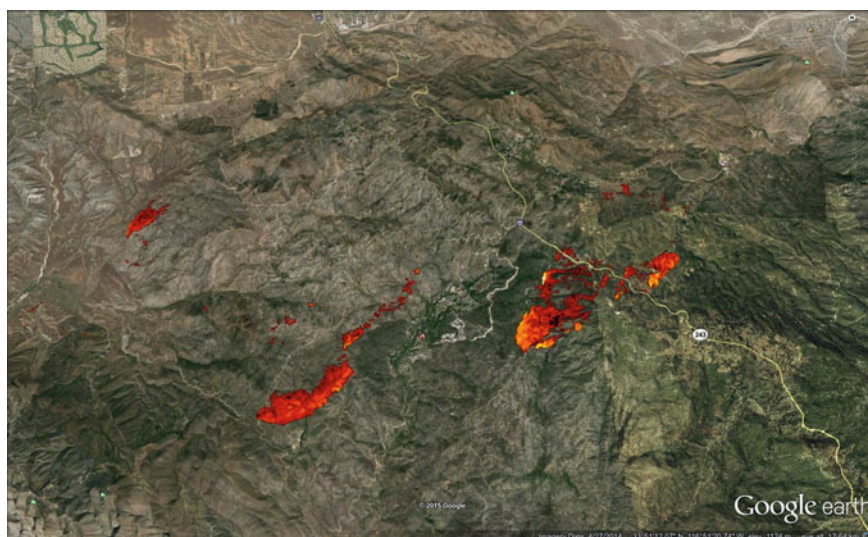


Fig. 3.8 FireMapper thermal image of the Esperanza Fire (southern California), showing thermal anomalies indicative of biomass burning on October 26, 2006, between 14:07 and 14:17 PDT. Higher fire intensity is indicated by orange and yellow pixels. From Riggan et al. (2010)

3.2.3 *Effects of Management Actions*

3.2.3.1 Prescribed Fire

A shortcoming of many fire behavior tools is their inability to consider interactions between multiple lines of fire (e.g., counter-firing operations); operational tools do not account for convective heating or interactions between multiple heat sources and are typically limited to describing fire behavior for a point ignition spreading in a homogeneous environment (Furman et al. 2019; Hiers et al. 2020). Fire operations are planned to accomplish multiple, specific objectives. Prescribed fire objectives often include maintaining fire within a limited range of intensities (e.g., rates of spread, flame lengths) to minimize damage to the resource but supply enough heat to aid in smoke transport and dispersion. A key part of the burn plan is developing sufficient heat to generate a plume that rises above the mixed layer such that surface impacts to nearby communities are minimized (Achtemeier et al. 2012).

The widely used Briggs plume-rise schemes used in air quality forecasting assume the plume rises through a passive environment that does not consider the complex ways a fire and the environment interact (Moisseeva and Stull 2020). Neglecting such interactions can lead to overestimation of plume rise and underestimation of surface smoke concentration for “highly tilted” plumes characterized by weak buoyancy and strong winds (Achtemeier et al. 2011), or underestimation of plume rise

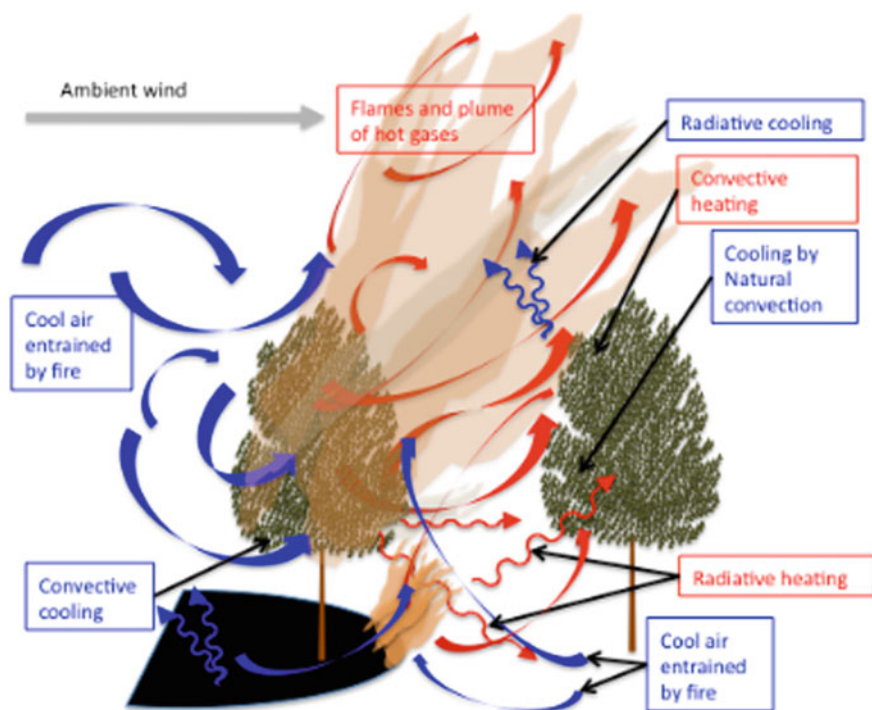


Fig. 3.9 Multiple interactive physical processes are integrated in FIRETEC simulations. From Furman et al. (2019)

and subsequent overestimation of surface smoke concentration for strongly buoyant plumes (Achtemeier et al. 2012).

Using FIRETEC, Furman et al. (2019) examined whether a coupled fire–atmosphere model could reproduce a range of fire phenomena common to prescribed fires. They examined questions that current operational tools are ill-suited to answer, including:

- How does distance between lines of fires and multiple ignition points affect fire intensity and plume lofting?
- How does spot ignition moderate fire intensity compared to line ignition?
- How does unit boundary ignition affect fire behavior and fire effects in the interior of the burned area?
- How do mid-story vegetation and other forest structure variables influence wind fields and resulting fire behavior?

Furman et al. (2019) evaluated different ignition patterns for prescribed fires in longleaf pine (*Pinus palustris*) forest fuels. Figure 3.10 illustrates FIRETEC results that depict general fire phenomenology associated with multiple ignition lines ignited

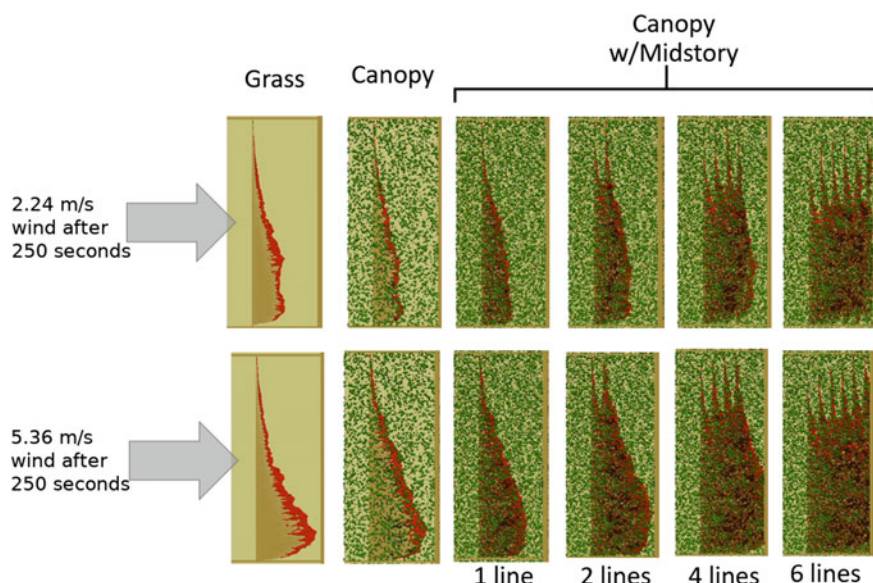


Fig. 3.10 Baseline fire scenarios modeled with FIRETEC. The images are bounded by the fuel breaks and therefore do not show the entire computation domain. From Furman et al. (2019)

by all-terrain vehicles (ATVs). Higher fire behavior and mid-story/canopy consumption in response to an increased number of simultaneous ignition lines (Fig. 3.10) is common knowledge among experienced prescribed fire managers. However, the effects of line spacing on convective lift and subsequent plume lofting were not as well known (Figs. 3.11 and 3.12). These FIRETEC simulations revealed that the ATV-ignition strip-head fires reached greater plume height and volume than the plastic sphere dispenser (or “ping pong ball”) aerial ignition, as the small individual ignitions of the aerial ignition were widely dispersed and burned together more slowly than solid lines ignited by the ATVs.

A new simulation tool called QUIC-Fire (Linn et al. 2020) is designed to rapidly simulate fire–atmosphere feedbacks by coupling the 3D rapid wind solver QUIC-URB to a physics-based cellular automata fire-spread model (Fire-CA). QUIC-Fire uses 3D fuels inputs similar to those used by the CFD-based FIRETEC model, allowing this tool to simulate the effects of fuel structure on local winds and fire behavior. Preliminary comparisons between QUIC-Fire and FIRETEC show that the model outputs agree well. QUIC-Fire is the first tool intended to provide an opportunity for prescribed fire planners to compare, evaluate, and design burn plans, including complex ignition patterns and coupled fire-atmospheric feedback. Additional work to incorporate process-based emissions production into QUIC-Fire has also shown promise (Josephson et al. 2020).

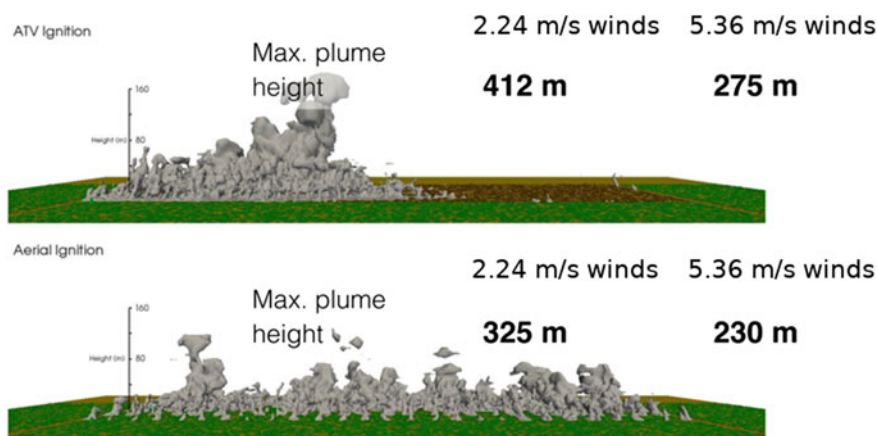


Fig. 3.11 View from upwind of burn unit illustrating differences in modeled maximum plume heights between 5-line, 16-ha ATV, and aerial ignitions for two surface wind speeds. From Furman et al. (2019)

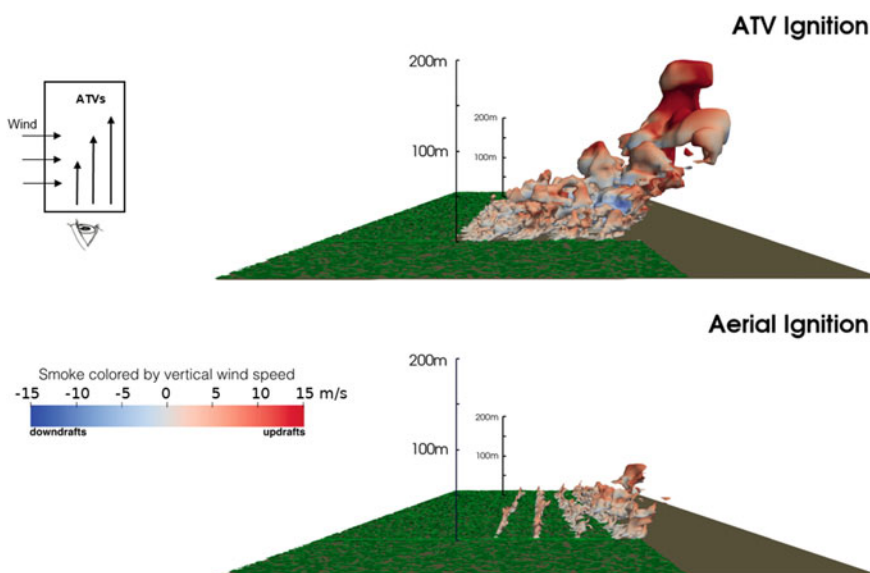


Fig. 3.12 Crosswind view indicating plume height 3 min after ignition begins with 5.36 m s⁻¹ wind. “Trees” were removed for visual clarity. Plume color denotes vertical wind speed of heated gasses. From Furman et al. (2019)

3.3 Gaps in Understanding the Link Between Fire Behavior and Plume Dynamics

Many current smoke modeling tools have a number of limitations that are largely linked to the fire event not being an explicit part of the simulation (Liu et al. 2019). By excluding the fire event from the simulation, these tools are unable to incorporate detailed and rapidly varying spatial distributions of heat release across the landscape, which links the fire source to the atmosphere, often leading to the development of multiple plume cores. In addition, emissions must be estimated with a method such as climatological diurnal trends as in the Global Fire Emissions Database (Randerson et al. 2017) or the Smoke Emissions Reference Application database (Prichard et al. 2020).

Advancing our modeling capability beyond these empirically derived methods and toward more process-based methods is critical for predicting emissions in the no-analog climate expected in future decades. Making this shift to process-based models requires an improved understanding of fire and smoke processes, as well as collecting data tailored to rigorous testing, evaluation, and validation of model performance under real-world conditions (Liu et al. 2019).

Many currently available observational datasets are not suitable for evaluating coupled fire–atmosphere models, because these tools require integrated datasets that comprehensively characterize fuels, energy released, local micrometeorology, plume dynamics, and smoke chemistry (Alexander and Cruz 2013; Cruz and Alexander 2013). To fill such data gaps, several field campaigns have been conducted or are planned in the USA. In 2012, the RxCADRE field campaign collected integrated data on fuels, fire behavior, fire effects, and smoke on large prescribed fires at Eglin Air Force Base (Florida) for the specific purpose of evaluating fire and smoke models (Ottmar et al. 2016). The RxCADRE data are currently being used to evaluate coupled fire–atmosphere modeling systems.

Moisseeva and Stull (2020) examined plume rise from an experimental burn of the RxCADRE campaign, using WRF-SFIRE by taking advantage of the combined fire behavior and plume measurements collected by the project. Their model results capture the timing, rise, and dispersion of the fire plume reasonably well compared with observations of emissions and dispersion data collected from an airborne platform during the experiment. Although the plume observations available in RxCADRE were limited, other efforts are working to increase the amount and quality of plume observations, including the Fire Influence on Regional and Global Environments Experiment (FIREX-AQ) (Warneke et al. 2018), Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN) project (https://www.eol.ucar.edu/field_projects/we-can), and Fire and Smoke Model Evaluation Experiment (FASMEE) (Prichard et al. 2019). Liu et al (2019) has outlined specific information needed to advance our knowledge of fire–atmosphere coupling and its ties to plume dynamics (Chap. 4) (Fig. 3.13).

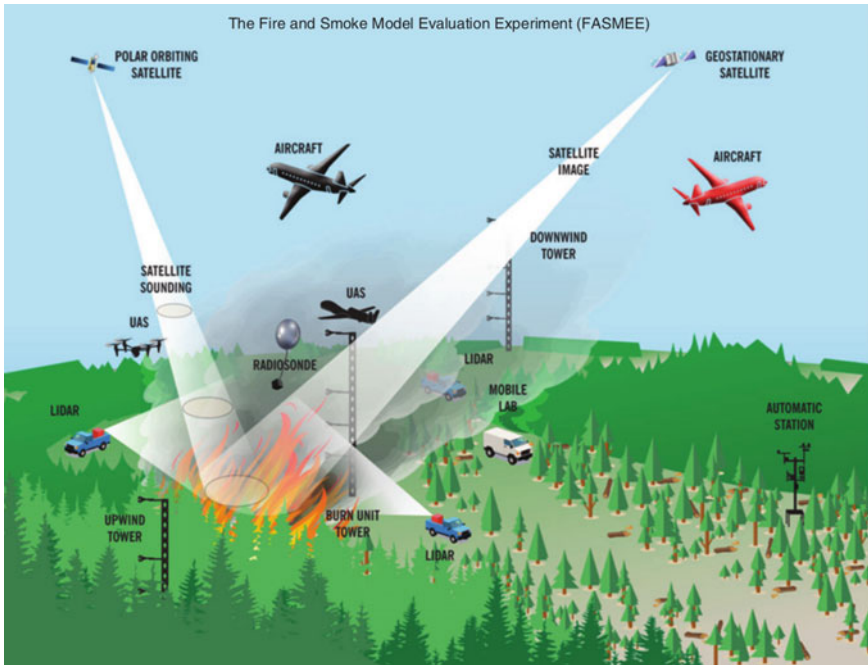


Fig. 3.13 Schematic representation of the Fire and Smoke Model Evaluation Experiment (FASMEE) project measurement platforms. From Liu et al. (2019)

3.3.1 Heat Release

Measurements of fire-base depth, spread rate, and total mass consumption during flaming can be used to calculate a first-order estimate of heat release per unit area for fire behavior model validation and as inputs for smoke models. Note that a single-point measurement can be misleading, because firelines are not uniform. For this reason, a more complete set of measurements to support model testing would provide the fire-base depth, spread rate, and total mass consumption along the fire perimeter. Furthermore, surface heat is vertically distributed over the first few grid-cell layers in some fire–atmosphere coupled models (e.g., WRF-SFIRE), which means the appropriate vertical decay scale (extinction depth) needs to be assessed. Also, fire heat varies in both space and time, leading to complex dynamical structures of smoke plumes. Dynamical structure is an important factor for the formation of separate smoke plume cores. Measurements of the structures together with smoke dynamics are needed to understand the relations of smoke dynamics to horizontal and vertical heat fluxes (radiative and convective) during fires.

3.3.2 *Fire Spread*

Fire spread is important for determining fuel consumption and spatial and temporal variation of heat release, burned area, and burn duration. Lateral fire progression, spread perpendicular to the predominant wind direction, is particularly affected by atmospheric turbulence. In models such as WRF-SFIRE, the lateral rate of spread is parameterized using (1) local wind perturbations normal to the flank, and (2) the Rothermel formula (Rothermel 1972) for head-fire rate of spread. Some of these normal wind perturbations can be created by fine-scale differences in topography, fuels, and pressure gradients that are dampened or smoothed; these differences are not neglected in the WRF scheme and are partially preserved in the CAWFE modeling scheme. Characterization of lateral fire spread and atmospheric turbulence, in concert with variation in fuel and topography, is needed to validate and improve this approach (Bebieva et al. 2020). We must better understand where WRF-SFIRE type simplifications are “good enough,” or when fine-scale modeling of fuels and topography to produce wind perturbations are necessary (Coen 2018).

3.3.3 *Plume Cores*

Individual plume cores within a smoke plume are highly dynamic, often forming as a result of local fuel accumulations and ignition processes. Once formed, they can instantly affect heat fluxes, exit velocity, and temperature, which are important for smoke plume rise and vertical profile simulation. Despite their importance, the number of plume cores is rarely noted for prescribed burns. Because the dynamic nature of plume cores makes them difficult to define and track, observational and modeling evidence is needed to understand the roles of sub-plumes.

3.4 Vision for Improving Smoke Science

A scale-appropriate abstraction of fire is needed to supply heat and emissions to smoke models. The typical current level of abstraction—representing a fire as a simple point-source with either a constant emission rate or diurnal emissions profile—may be appropriate for coarse-scale continental assessments. However, smoke models are often used to address a range of scales for local visibility and air quality concerns where a more detailed description of a fire in space and time may be required for accurate results. At the local scale, the modeling approach of Kochanski et al (2019) captures the coupling between fire and atmosphere to provide a detailed abstraction of the smoke source. This coupled approach is also ideal for prescribed fire applications, because it allows for complex ignition patterns common in prescribed fire operations.

Between these two extremes in scale lies the regional scale where the simple point-source is inadequate; as at finer scales, we must begin to account for variations in fuels and fire geometry that influence plume organization and lead to near-field underestimation and far-field overestimation of surface smoke concentrations (Riebau et al. 2006). The fully coupled approach of the local scale may become too computationally intensive at the regional scale to be useful for forecasting as the number of fires in a region increases. At regional scales, a more flexible abstraction of the fire event is required that differs in level of detail between the two extremes.

Coupled models such as FIRETEC, WFDS, CAWFE, QUIC-Fire, and WRF-SFIRE could be the central tools in developing such an abstraction. Running a series of simulations with these models with known fire behavior and plume behavior at a range of spatial scales would allow for calculating plume rise and fine-scale wind perturbations along ignition perimeters. This would include common ignition methods for prescribed fire, such as aerial ignitions, strip-head fires, and spot ignitions. These relationships would connect some basic information about the ignition (e.g., line spacing) and return appropriate inputs of heat and emissions through time, scaled to the spatial and temporal elements of the burn unit. For coupled models in these scenarios, developing multiple-core updrafts would be explicitly simulated as the atmosphere responds to the distribution of heat across the landscape, effectively building this fine-scale process into quantitative relationships. An important outcome would be improved estimates of plume rise for use in dispersion models (Chap. 4).

Advances in modeling heat release from wildland fires must be accompanied by advances in our ability to observe fires. Technological advances and improved affordability of both sensors and sensor platforms are revolutionizing our ability to collect information on wildland fires. Sensor systems which were previously cost prohibitive for widespread use in fire research, such as hyperspectral cameras, image intensifiers, and thermal cameras, are now less expensive and are being more commonly used. Allison et al. (2016) provide a review of the application of a number of these technologies to wildfire detection and monitoring. The technology is advancing toward an integrated hierarchical system of sensors that combine continuous monitoring for early detection with field-deployable small sensing platforms to provide detailed data for specific fire incidents.

Challenges identified by Allison et al. (2016) include developing robust automatic detection algorithms, integrating sensors of varying capabilities and modalities, and developing best practices for introducing new sensor platforms (e.g., small UASs) in a safe and effective manner within a fire perimeter. Image processing techniques are advancing rapidly due to increased computing power and the emergence of machine learning tools. Moran et al. (2019) describe a hybrid threshold gradient method for detecting areas of flaming combustion that combines the use of a temperature threshold value such as the Draper point (525 °C) with a gradient-based edge detection algorithm. This combined approach yields solutions that maintain observed variability while maximizing indifference to sensor resolution and spectral band differences.

Zhao et al. (2018) demonstrated the effectiveness of using saliency detection combined with a deep convolutional neural network to segment wildfire images

into regions of smoke, flaming combustion, and burned areas. Deep convolutional neural networks are a state-of-the-art machine learning method for image recognition (Lecun et al. 2015), and saliency detection extracts core objects from a complicated scene (Itti et al. 1998). Combining these techniques provides a more robust solution, as individual images are broken down into a set of core objects which are then compared by the neural network.

Adding to the value of new imaging techniques and platforms is the ability to integrate information across sensors and platforms to provide an enhanced view of the environment. Jimenez et al. (2018) describe an experimental design and preliminary results for linking highly resolved ground-based fire measurements collocated with in situ and thermography remotely sensed by UASs. Linkage of the in situ and UAS thermography offers an opportunity to link the combustion environment with post-fire processes and wildland fire modeling efforts across a broader spatial scale.

Fassnacht et al. (2021) combined satellite-based differenced Normalized Burn Ratio (dNBR) information with high-resolution orthoimages from a UAS to identify sources of variability in satellite data related to pre- and post-fire vegetation structure. Their results suggest that the fraction of consumed canopy cover, along with shadows of snags and standing dead trees with remaining crown structure, influenced what the satellite detects, providing an underestimate of dNBR. Improving our ability to examine the fire environment across scales will improve our understanding of variability in the data and inform modeling of fire processes.

3.5 Emerging Issues and Challenges

3.5.1 *Magnitude of Fire and Smoke Impacts*

In recent years, prominent smoke impacts have been observed in many locations in the USA. In California, long-duration smoke events—termed “smoke waves” by Liu et al. (2016)—are now emitting enough $\text{PM}_{2.5}$ to become the primary source in the annual emissions inventory. The modeling work of Koman et al. (2019) found that 97.4% of California residents lived in a county with at least one smoke wave during the 2007–2013 study period, and 24.7% of the population lived in a county averaging at least one smoke wave per year. Based on data from the California Air Resources Board (CARB 2020), for the period 2014–2019, the average annual area burned was 34% higher and the $\text{PM}_{2.5}$ emissions from wildfires 43% higher than during the study period of Koman et al. (2019), indicating that smoke-wave events were more common in recent years.

3.5.2 Managing Fuels to Minimize Air Quality Impacts

At the root of increasing impacts on regional air quality is accumulation of fuels on the landscape, exacerbated by a warming climate that is creating increased likelihood and opportunities for fuels to drive extreme fire behavior, thus leading to an extended duration of smoke waves (Chap. 2). These impacts are not necessarily uniform, predictable, or even consistent from one year to the next, one fire to the next, or one day to the next for a given fire. Fuel continuity as affected by fire exclusion, previous wildfire and other disturbance footprints, and previous fuel treatments interact with weather (and climate) to create the conditions for large-fire growth and smoke waves.

Koontz et al. (2020) showed that fire severity (damage to natural resources, typically mortality in overstory trees) in dry forests of the Sierra Nevada (California) was higher in forests with higher homogeneity of fuels at all scales above 90 m (the smallest scale tested). The resilience of these forests, which may have been reduced by structural homogenization caused by several decades of fire exclusion, could be restored with management that targets increased forest structural variability (Chap. 8). A smoke modeling framework that links changes in forest structure and associated changes in fire behavior at fine scale (<90 m, and probably <30 m) with plume development and smoke dispersion could evaluate the potential for fuel reduction treatments to limit smoke-wave impacts. From the perspective of operations, planning, and State Implementation Plans this modeling ability could provide a foundation for strategic application of fuel reductions, thus informing prioritization of treatments that would minimize smoke impacts.

3.5.3 Need for Dispersion Climatologies

Simultaneous, Monte Carlo modeling of fuels, fire, smoke emissions, and meteorology from micro- to mesoscales is beyond current computational capabilities, thus complicating assessment of model sensitivities (Bakhshaii and Johnson 2019). Kochanski et al. (2019) provided an example of potential sensitivity, showing that spatial resolutions of 1.3 km or finer were required to resolve canyon winds and smoke-enhanced inversions in the complex terrain of the Klamath Mountains (California), an area characterized by steep elevations and relatively fine-scale “corrugation” of the landscape.

Integrating smoke climatologies (Kaulfus et al. 2017), high-resolution modeling (Kochanski et al. 2019; Kiefer et al. 2019), and reanalysis climatologies may provide a tool for linking regional weather patterns with dispersion and spread parameter sensitivities, as the plume climatologies provide constraints against which to test models. Such climatologies would allow us to develop scenario-based, high-resolution, and atmospherically coupled modeling exercises on these “modes” of transport; developing a library of likely dispersion scenarios that could be used operationally for wildfires and planning prescribed fires across large landscapes.

Table 3.1 Atmosphere-fire models cited in the text, including appropriate spatial and temporal scales for their use

Model	Coupling method	Spatial scale	Domain area	Temporal scale	CPU usage
FIRETEC	One way	1–5 m	1–5 km ²	1 s–2 h	No real time
WFDS-PB	One way	1 mm–10 m	1–5 km ²	1 s–4 h	No real time
CAWFE	Two way	10 m–30 m	1–10 km ²	1 s–h	No real time
WRF-SFIRE	Two way	10 m–10 km	1–km ²	1 s–days	Real time
MesoNH-ForeFire	Two way	10 m–1 km	1–100 km ²	1 s–h	Approx. real time
ARPS/DEVS-FIRE	Two way	10 m–1 km	1–100 km ²	1 s–h	No real time

Adapted from Bakhshaii and Johnson (2019)

3.5.4 When and Where is Coupled Fire–Atmosphere Modeling Needed?

The coupled fire–atmosphere models discussed in this chapter would seem ideal for providing time-varying inputs of emissions and heat release for use with smoke dispersion tools, but these models should not be viewed as a universal solution, because each model has characteristics best suited to different spatial and temporal scales (Table 3.1). Among the coupled models using numerical weather prediction models, differences in semiempirical assumptions inherent in model formulation affect model performance, depending on the degree of topographic complexity and synoptic conditions (Coen 2018).

When large-scale synoptic conditions are the dominant driver of fire spread, the simplifying assumptions used by WRF-SFIRE (Kochanski et al. 2013) show promise and allow for real-time forecasting with modern 100-plus processor computing clusters (Kochanski et al. 2019). As topographic slopes exceed 40°, and fine-scale fuel consumption and fire-induced winds start driving fire behavior, the WRF-SFIRE approach may be limited due to the aggressive dissipation of fine-scale motions and gradients that occur under these conditions (Coen 2018).

Finer-scale models such as CAWFE may improve the resolution of fire-induced flows but lack the ability to do so operationally until faster computers or more computationally efficient approaches are available. However, these retrospective approaches have the potential to help in planning and prioritizing areas of the landscape where fuels, weather, and topography might create fire–atmosphere coupling characteristic of some large wildfires [e.g., the previously mentioned Rim fire (Peterson et al. 2015) and King fire (Coen et al. 2018)].

3.6 Conclusions

This chapter focuses on how fire events are described in the smoke modeling process and how these descriptions can reduce the error associated with forcing a fire to conform to an idealized anthropogenic emissions source, such as a point source (e.g., industrial stack emissions). Liu et al. (2019) highlighted several needs for next-generation smoke research and forecasting systems:

- Acquire dynamic and high-resolution fire energy and emissions information for smoke modeling of large burns.
- Improve the capability to describe multiple sub-plumes and understand mechanisms governing their evolution.
- Understand feedbacks between atmospheric disturbances induced by fire and smoke processes.
- Link combustion processes to speciation of fire emissions across fuel types and combustion conditions.

Achieving such model improvements requires extensive and detailed observations of the spatial and temporal evolution of heat released by wildland fires, as heat release connects the fire to the overlying smoke plume. Remote sensing provides a safe and reliable means of collecting such observations. The emergence of new observing platforms such as small UASs and thermal sensors, combined with new processing techniques allowing integration of multiple data streams, will help improve the temporal and spatial resolution of heat release measurements at scales appropriate for model development. Integrated field campaigns such as FASMEE (Prichard et al. 2019) that seek to measure the fire environment as thoroughly as possible will help facilitate the transition of new modeling tools from research to operations by providing a testbed for developing the data necessary for model advancements.

3.7 Key Findings

- Wildland fires are poorly described as emission sources in current operational smoke modeling tools. Fires are complex emission sources that evolve through time and are not well represented as traditional point, line, or area sources used in air quality models.
- A number of newer research tools have improved descriptions of wildland fires as heat and emission sources. Transitioning such tools to operations will require further data collection for understanding model performance and uncertainty but will enhance our ability to cope with evolving environmental conditions during wildland fires.
- Remote sensing provides a robust platform for a wide range of fire measurements such as energy release and fire area. Technological advances are expected to improve sensor abilities in the future.

3.8 Key Information Needs

In addition to the fuel information described in Chap. 2, key fire behavior and energy release measurements include:

- Quantitative fire radiation from satellite, airborne, and tower-based platforms.
- Flame front dimensions and spread rates that include forward, lateral, and backing spread.
- Combustion efficiency, and emissions partitioning between flaming and smoldering combustion.
- Convective fluxes are needed in space and through time as inputs to plume models.

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