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Fire behavior and smoke modeling: Model improvement and measurement needs for next-generation smoke research and forecasting systems

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Abstract

There is an urgent need for next-generation smoke research and forecasting (SRF) systems to meet the challenges of the growing air quality, health, and safety concerns associated with wildland fire emissions. This review paper presents simulations and experiments of hypothetical prescribed burns with a suite of selected fire behavior and smoke models and identifies major issues for model improvement and the most critical observational needs. The results are used to understand the new and improved capability required for the next-generation SRF systems and to support the design of the Fire and Smoke Model Evaluation Experiment (FASMEE) and other field campaigns. The next-generation SRF systems should have more coupling of fire, smoke, and atmospheric processes to better simulate and forecast vertical smoke distributions and multiple sub-plumes, dynamical and high-resolution fire processes, and local and regional smoke chemistry during day and night. The development of the coupling capability requires comprehensive and spatially and temporally integrated measurements across the various disciplines to characterize flame and energy structure (e.g., individual cells, vertical heat profile and the height of well

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mixing flaming gases), smoke structure (vertical distributions and multiple sub-plumes), ambient air processes (smoke eddy, entrainment and radiative effects of smoke aerosols), fire emissions (for different fuel types and combustion conditions from flaming to residual smoldering), as well as night-time processes (smoke drainage and super-fog formation).

Summary for the non-specialist reader

Fire behavior and smoke models provide smoke information for managers to assess fire impacts and develop mitigation plans. This review paper describes the modeling efforts performed to understand modeling issues and data needs. The results are used to support the design of field campaigns such as the Fire and Smoke Model Evaluation Experiment (FASMEE), which conduct comprehensive measurements of fuels, fire behavior, emission, smoke, and weather, and the development of the next-generation smoke research and forecasting systems.

Keywords

burn plan and measurement design; WRF-SFIRE-CHEM; FIRETEC; WFDS; Daysmoke; CMAQ

Introduction

Fire behavior and smoke models are numerical tools that provide smoke information on pollutant species and concentrations, spatial distributions, and temporal variations of smoke plume for land managers to assess the environmental, human health, ecological, economical and societal impacts of wildland fires and develop fire management plans and impact mitigation strategies (Sullivan 2009a; Goodrick *et al.* 2012; Strand *et al.* 2014; Mortiz *et al.* 2014). A range of fire behavior models exist, largely differing by the degree to which the methods of computational fluid dynamics (CFD) (see the Supplemental Materials for a list of acronyms) are used and the underlying physical processes are explicitly modeled. CFD based models that explicitly model the physical processes include the Wildland-urban interface Fire Dynamics Simulator (WFDS) (Mell *et al.* 2007, 2009; Mueller *et al.* 2014), FIRETEC (Linn *et al.* 2002, 2005; Pimont *et al.* 2011), WRF-SFIRE (Mandel *et al.* 2011, 2014), FIRELES (Tachajapong *et al.* 2008), and FIRESTAR (Morvan *et al.* 2009). Models that are empirically based on statistical analyses of experimental data and similarity theory include FARSITE (Finney 2004), Phoenix (Tolhurst *et al.* 2008), Prometheus (Tymstra *et al.* 2010), and BehavePlus (Andrews 2014).

Smoke models are developed based on atmospheric transport and dispersion theory and chemical mechanisms or statistical relationships. Various types of smoke models are available to simulate rise, dispersion, transport and deposition of smoke particle and gas and chemical reactions for generation of ozone and secondary organic carbon (Goodrick et al. 2012). Lagrangian models such as CALPUFF (Scire 2000), Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) (Draxler and Rolph 2003), FLEXPART (Stohl and Thomson 1999) and Daysmoke (Achtemeier *et al.* 2011) predict variations of individual moving smoke, which appears either as a collection of independent 'puffs' or as infinitesimal air 11s containing a fixed mass of pollutant particles. Eulerian models such as the Community Multiscale Air Quality (CMAQ) model (Appel *et al.* 2017), Comprehensive

Air Quality Model with Extensions (CAMx) (Ramboll Environ 2016), and the ECMWF Integrated Forecasting System (IFS) (Wedi *et al.* 2015) predict variations of smoke particle and gas concentrations at spatial grid points. Smoke models such as WFDS, FIRETEC, FIRELES, FIRESTAR, WRF-SFIRE, Daysmoke, CAWFE (Clark *et al.* 2004; Coen 2013), ARPS-DEVS (Dahl *et al.* 2015), and MesoNH-ForeFire (an atmospheric and fire spread model) (Filippi *et al.* 2011) and dynamic plume rise models (Freitas *et al.* 2010; Grell *et al.* 2011) explicitly resolve the plume rise.

As research tools, fire behavior and smoke models are used for simulating historical and current smoke conditions. They also can be used as operational forecast tools (i.e., providing future smoke information for planning or mitigation of air quality and visibility impacts of fires). The forecast applications require that the models execute fast enough to provide a usable forecast and that the data needed for their execution is readily available (Sullivan 2009b). For that reason, simpler systems such as VSMOKE-GIS (Harms and Lavdas 1997), Simple Smoke Screening Tool (Wade and Mobley 2007) and Prometheus are most often used operationally. Daily atmospheric chemistry models such as AIRPACT (Chen *et al.* 2008), GEOS-CHEM (Bey *et al.* 2001), and ECMWF IFS also includes smoke. Comprehensive operational smoke forecast systems such as BlueSky (Larkin *et al.* 2010) are developed based on smoke models linked with fuel, burn, and emission tools. Other smoke and chemistry models, in particular, Daysmoke, Planned Burn - Piedmont (PB-P) (Achtemeier 2005), and CMAQ model, are used both operationally and for research to inform a variety of management decisions on smoke dispersion, transport, and primary and secondary pollutant impacts.

The capability of current smoke research and forecasting (SRF) models has some limitations. For example, due to the lack of coupling between the local weather, fire behavior and emissions, emissions at an interval of an hour or a few hours are estimated based on climatological diurnal trends [as in Global Fire Emissions Database (GFED) (Randerson *et al.* 2015)]. Weather-driven fire behavior, which is accounted for in contemporary fire behavior models (Faggian *et al.* 2017), has high tempoeral varaibility, which is often not accounted for. Most SRF models are not able to produce high-resolution and fast varying spatial distribution of heat release across the landscape, which links the fire-source to the atmosphere. The smoke plume (sometimes also called smoke column or convection column) is composed of particles, gases and water vapor emitted into the atmosphere by the entire fire. Observations of large-perimeter prescribed fires often revealed that a smoke plume of the entire fire could include multiple sub-plumes (also called updrafts or cores) (Achtemier *et al.* 2012; Liu *et al.* 2010; Larkin *et al.* 2010). Most smoke models do not resolve individual sub-plumes as well as vertical plume concentration profiles (Raffuse *et al.* 2012).

Smoke research and management communities have an urgent need for next-generation SRF systems to address these issues as well as the growing air quality and safety concerns associated with wildland fire emissions. A key feature of such systems is accounting for complex interactions among the atmospheric processes, fire behavior, fire emissions, and smoke dynamics. Smoke dynamics describe all physical processes within the smoke plume, including plume rise and vertical distribution, transport and dispersion, multiple sub-plumes, eddies, turbulence and pyro-convection, entrainment of the ambient air, smoke-canopy interactions, and smoke radiative and cloud impacts. Recent advances have resulted in a number of coupled models that emphasize atmospheric physics and fire-atmosphere coupling at scales of hundreds of meters (e.g. WRF-SFIRE), or fire physics, combustion processes, and atmosphere coupling at scales of meters (e.g. WFDS and FIRETEC). The rapid increase in the resolution of numerical weather prediction and computational power over recent years opens new avenues for development of integrated systems (e.g. WRF-SFIRE-CHEM, Kochanski *et al.* 2015) that couple fire progression, plume rise, smoke dispersion and chemical transformations in a more coupled way.

To advance current modeling and forecast capability we need a better understanding of fire and smoke science, as well as rigorous testing, evaluation, and validation, to assess model performance under real-world application and the level and sources of model uncertainties. Efforts were made with the Smoke and Emissions Model Intercomparison Project (SEMIP) focused on model evaluation and comparison of fuels, emissions, plume rise, and smoke dispersion (Larkin *et al.* 2012). More efforts are needed, especially in model evaluation and comparison of fire behavior, smoke dynamics, and fire-smoke interactions. Currently available observational data do not easily facilitate model evaluation and comparison (Cruz and Alexander 2013; Alexander and Cruz, 2013), especially in the context of the coupled fire-atmosphere models, which require integrated datasets that comprehensively characterize the fuel, energy released, local micrometeorology, plume dynamics, and chemistry. To fill the data gaps, a number of field campaigns have been conducted or planned in the United States including Fire Influence on Regional and Global Environments Experiment (FIREX-AQ) (Warneke *et al.* 2014), Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen (WE-CAN) project (UCAR/NCAR EOL 2018), and the Fire and Smoke Model Evaluation Experiment (FASMEE) (Prichard et al. 2019), and in other countries such as the field-scale experimental testing of the role of fire-induced vorticity and heat-driven buoyancy in wildland fire spread (Pearce *et al.* 2018).

This review paper describes results from simulations of hypothetical burns conducted with a suite of selected fire and smoke models. This modeling effort was part of the FASMEE project (Phase I) which developed a study plan to help plan the FASMEE Phase II field campaign development (Ottmar *et al.* 2017), and was performed to identify major issues for fire behavior and smoke model improvement and the most critical observational needs, with a focus on fire, smoke, and atmospheric interactions. The findings from the modeling efforts are expected to provide guidance to plan and design burn and measurements of FASMEE as well as other field campaigns and to define the next-generation SRF systems.

Approach and Methods

FASMEE

FASMEE (Ottmar *et al.* 2017; Prichard et al. 2019), a continuation of the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) (Ottmar *et al.* 2016), focuses more than other field campaigns on measurement of interacting processes among the disciplines of fuels, fire behavior, smoke dynamics, meteorology, fire emissions and chemistry. FASMEE will be closely coordinated with the aircraft and satellite measurements from WE-CAN and FIREX-AQ.

The FASMEE collaborative effort will facilitate integration of data across the entire smoke science continuum from fuels, fire behavior, plume dynamics and meteorology to fire emissions, chemistry and transport, resulting in a large repository of information and scientific knowledge needed to advance the physically coupled fuels, fire, smoke, and chemistry systems (Figure 1). To accomplish its goals, FASMEE is portioned into three phases: analysis and planning (Phase I), implementation of field data collection (Phase II), and future improvements of research and operational models (Phase III). Phase I is completed with a study plan as the main deliverable that outlines critical modeling issues, gaps, and field measurement needs. These were substantially derived from model simulations described in this paper. Three observational field efforts were identified in Phase I to be carried out in Phase II: 1) the western wildfire campaign targeting wildfires in the western U.S. to support the FIREX-AQ project during the summer of 2019; 2) U.S. southwest campaign with potential prescribed burns located in the Fishlake National Forest, UT and North Kaibab Ranger District, AZ, beginning in spring 2019; and 3) U.S. southeast campaign focused on prescribed fires located in Fort Stewart, GA, beginning in the winter of 2020.

The observations and measurement data collected in Phase II will be used to understand fire and smoke processes and improve models during Phase III after completion of the field campaign. There are many pathways that the FASMEE field campaign could guide model improvement. For example, multiple smoke sub-plumes are not currently included in most models. They are closely related to fire-smoke interactions, which will be measured during Phase II of FASMEE. In addition, the data could be used to develop parameterization schemes, which will be a new capacity of smoke models.

The fire behavior and smoke modeling efforts conducted in Phase I of FASMEE and their connections to field measurements are illustrated in Figure 2. This review will be presented following the steps shown in the figure. We first describe simulations and experiments of hypothetical prescribed burns. We then use the results, together with analyses of model capability and what have been learned from previous model applications, to identify major issues for fire behavior and smoke model improvement and define next-generation SRF systems. We further discuss the priority measurement data needs to provide guidance for the measurement design and data collection plan. The data to be collected during a future field campaign would be used to evaluate and improve smoke modeling.

Models utilized for fire behavior and smoke simulations

SRF models were selected for simulation with the intention of representing a range of model classes, rather than specific models, to assess model limitations and measurement needs. WRF-SFIRE and WRF-SFIRE-CHEM were selected as examples of hybrid and integrated fire-atmosphere-chemistry models that parameterize fire spread but resolve emissions, plume rise, chemical smoke transformations and fire-atmosphere interactions. WFDS and FIRETEC served as examples of fire models resolving combustion and small-scale plume dynamics, but without atmospheric chemistry. Daysmoke and PB-P represented fast Lagrangian particle models computing day time plume rise and dispersion as well as smoke drainage during night time. CMAQ was chosen to represent chemical transport models that focus on chemical smoke transformations, rely on external parameterizations for plume height and emission computations, and do not resolve the fire-atmosphere interactions, plume dynamics or fire progression. The general capability of these models and their typical time and spatial scales are summarized in Table 1.

WRF-SFIRE-CHEM

WRF-SFIRE is a coupled fire-atmosphere model based on the Weather Research and Forecasting model (WRF) (Skamarock *et al.* 2008) and the Rothermel (1972) fire-spread model implemented using a level set method to evolve the fire front on a Eulerian grid in time (e.g., Mallet *et al.* 2009). The fuel and topographical data are defined on a separate fire grid (typically ~30 m resolution) which is used for fire spread, heat release and emission computations. This high-resolution grid is embedded within a coarser atmospheric grid (with typical resolution of hundreds of meters), which handles all weather-related computations. At each atmospheric time step (generally in the order of seconds) the fire-emitted heat and moisture fluxes computed at the fire grid are integrated into WRF's grid which handles pyro-convections and smoke dispersion. WRF-SFIRE is also coupled with a prognostic fuel moisture model, which assesses the moisture of 1h, 10h, 100h, and 1000h fuels (Mandel *et al.* 2012), and it assimilates fuel moisture observations from Remote Automated Weather Station (RAWS) (Vejmelka *et al.* 2016). WRF-SFIRE is designed to simulate the landscape-scale physics of the coupled fire-atmosphere phenomenon. WRF-SFIRE is capable of simulating large-scale, high-intensity fires under various topographical, meteorological, and vegetation conditions (Kochanski *et al.* 2013b). It has been evaluated in both research and forecasting modes (Kochanski *et al.* 2013a and b; Kochanski *et al.* 2015).

WRF-SFIRE was recently coupled (Kochanski *et al.* 2015) with WRF-CHEM (Grell *et al.* 2005) so that fire progression is simulated along with fire emissions and chemistry. Fire emissions are represented as a sum of fluxes of WRF-CHEM-compatible chemical species and ingested into the lowest WRF model layer at each WRF time step. Combustion rates are computed based on the mass of fuel consumed within each fire-grid cell. Emission fluxes are computed as the products of the combustion rates and fuel-specific emission factors. Fire emissions are transported and undergo chemical transformations in the atmosphere and interact with atmospheric radiation and microphysics, modeled by WRF-CHEM.

FIRETEC and WFDS

Both FIRETEC and the physics-based component of WFDS (WFDS-PB) use a finite-volume, large eddy simulation (LES) approach to model turbulence, where large-scale eddies are explicitly resolved in numerical grids and small eddies are simulated with sub-grid scale models. The vegetation-fuel complexes in both models are described as a highly porous medium within the 3D numerical grids and are characterized by mean or bulk quantities (e.g., surface area to volume ratio, moisture content, bulk density) of the thermally thin vegetation components of the overall fuel complex. Because FIRETEC and WFDS-PB were primarily developed to predict the evolution of the flaming front, they require the spatial and thermo-physical characteristics of the thermally thin component of the vegetative fuel; non-thermally thin fuels are assumed to not significantly contribute to the flaming front. Because both FIRETEC and the WFDS-PB explicitly model the aspects of the combustion processes, for a given fire, they utilize much finer computational grids (i.e., smaller grid cells on the order of 1 m) compared to WRF-SFIRE or Daysmoke. As a result, FIRETEC and WFDS-PB are more computationally expensive than other simpler models. FIRETEC and WFDS-PB differ from each other in their solution techniques and parameterizations (Hoffman *et al.* 2016; Morvan 2011).

The WFDS model can also be implemented using a level set method to propagate the fireline; this implementation is called WFDS-LS. The fire's rate of spread is obtained from the Rothermel model. In its simplest implementation, WFDS-LS is not coupled to a CFD solver (Bova *et al.* 2015). The implementation with the most physical fidelity couples the Rothermel fire spread model to a CFD solver and accounts for the coupling of the fire generated heat and the response of the atmosphere (Mell and Linn 2017). The method for handling the fireline propagation and heat input into the atmosphere is similar to what is done in WRF-SFIRE, although WFDS-LS lacks representation of many of the atmospheric processes (such as water condensation, atmospheric radiation), surface physics (capturing changes in surface temperature and moisture), and ability to provide integrated weather conditions offered by WRF-SFIRE.

Daysmoke and PB-P

Daysmoke is a local smoke plume dispersion and transport model for simulating 3D distributions and temporal variations of smoke particles. Daysmoke consists of four sub-models: an entraining turret model handling the convective lift phase of plume development and representing the sub-plumes within a buoyant plume, a detraining particle model, a large eddy parameterization for the mixed planetary boundary layer (PBL), and a relative emissions model that describes the emission history of the prescribed burn. Daysmoke was developed specifically for prescribed burning and has been extensively applied and evaluated in simulating smoke dispersion from prescribed fires in the U.S. Southeast (Liu *et al.* 2009). Daysmoke has relatively simple physics and no chemistry and thus needs much fewer computational resources than complex and interactive dynamical smoke models. Daysmoke includes algorithms to simulate the role of some special smoke properties such as multiple sub-plumes, which have smaller ascending velocities and are more affected by entrainment, and therefore are less efficient in the vertical transport of smoke in comparison with a single plume (Liu *et al.* 2010).

PB-P is a meteorological and smoke model designed for simulating near-ground smoke transport at night over complex terrain. PB-P runs at resolutions on the order of 30–90 meters to capture terrain features driving the development of local drainage flows. Similar to Daysmoke, PB-P is a Lagrangian particle model specifically designed for fire applications with a focus on operating in data-poor environments, using just a handful of weather stations and a single sounding location.

CMAQ

CMAQ is a Eulerian chemical transport model that contains a comprehensive state-of-the-science treatment of important gas (Yarwood *et al.* 2012), aqueous (Fahey *et al.* 2017), and aerosol phase chemistry (Carlton *et al.* 2010). This modeling system has been used to support operational forecasts of air quality and smoke (e.g., NOAA; http://airquality.weather.gov) and retrospective regulatory assessments. This modeling system has been used to assess near-field (1 to 4 km sized grid cells) and regional scale (12 km sized grid cells) reactive pollutant impacts from specific wildland fire events (Baker *et al.* 2016; Zhou *et al.* 2018; Baker *et al.* 2018) and wildland fire impacts in aggregate (Fann *et al.* 2013; Rappold *et al.* 2017).

Wildland fire emissions in CMAQ are usually based on fire location information from the SmartFire2 system (http://www.airfire.org/smartfire/), which relies on NOAA's Hazard Mapping System (HMS) satellite product and local activity data. The BlueSky fire emissions modeling framework typically applied for CMAQ includes multiple modules: the fuel loading model (Ottmar *et al.* 2007), the CONSUME fuel consumption model (Prichard *et al.* 2007), and the Fire Emission Production Simulator (FEPS) emission factors (Anderson *et al.* 2004). The Sparse Matrix Operator Kernel Emissions (SMOKE) model is used to convert daily non-fire emissions to hour of the day and provide more detailed VOC, NO_X, and primary $PM_{2.5}$ speciation. Smoke plume rise algorithms use estimates of heat flux to vertically allocate smoldering and flaming emissions into the 3D grid structure of CMAQ (Zhou *et al.* 2018). The key inputs for generating fire emissions are location of the fire (to determine biomass type), area burned, and wild/prescribed fire classification, which helps define the environmental conditions of burning.

Simulations and experiments

The simulations and experiments conducted with the above models are summarized in Table 2 with a very brief description provided below. Details on model configuration and application can be found in Supplement A.

We used WRF-SFIRE to simulate plume evolution for all three planned FASMEE burns. These simulations, performed for statistically typical days (defined as described in Kochanski *et al.* 2018), were used to identify expected plume top heights, levels of maximum vertical velocities and fire-induced winds. Time series of simulated plume top heights and vertical velocities were analyzed in order to define desired length of the burns that would assure full plume development. Various ignition procedures were tested to examine the impact of the fire initialization on plume evolution. Additionally, sensitivity analysis was conducted to identify the most critical parameters impacting plume vertical velocities, plume top height and smoke concentrations (Kochanski *et al.* 2018).

WRF-SFIRE,WFDS, MesoNH (a non-hydrostatic mesoscale atmospheric model) (Filippi *et al.* 2009),and Daysmoke were implemented with "the burner method" (see Supplement B for details) to compare the impacts of wind and stability on smoke plume development. The outcomes provide an example of potential application of FASMEE data measurements to supporting smoke plume simulations from a range of model types using measured rather than simulated heat and mass generated by the fire. This facilitates the testing and comparison of different model approaches for smoke plume rise.

Daysmoke was used to simulate hypothetical burns at Fort Stewart, GA during February 5–8, 2011, the time period of the 2011 RxCADRE campaign (Ottmar *et al.* 2016), to identify weather systems (fronts, cyclones / anticyclones, low / high pressure systems, etc.) that would produce desired smoke plumes for the FASMEE field campaign. Known weather conditions in the Southeast U.S. simulated with WRF (Liu 2014) were investigated and used in these simulations. We employed sensitivity techniques to understand the dependence of smoke plume rise on sub-plume number. PB-P model was used to simulate the night-time smoke drainage and super-fog that could be related to a prescribed burn in the Kaibab National Forest, AZ.

CMAQ simulations used burn units at locations of previously-conducted prescribed burns in the southeastern US (Fort Stewart, GA) and the western US (Fishlake National Forest, UT). The results illustrate model capability to predict smoke at different grid scales and seasons relevant for field study measurements.

Simulation and experiment results

Coupled fire and smoke structure and evolutions

An example of the volume rendered smoke and the plume top height from a single WRF-SFIRE time frame is presented in Figure 3. An animation created from a series of such frames (available online at https://youtu.be/-dsbHFogIDw) has been generated in order to analyze general 3D fire and smoke evolutions, to be expected during the planned FASMEE burns at Fort Stewart, GA, North Kaibab, AZ, and Fishlake, UT. Time series of the maximum vertical velocities from these runs indicate 5 to 10 m/s updrafts located typically between 500 m and 2500 m above the ground (Figure 4a). The time series of the fire induced winds (computed as a difference between the wind from the coupled fire-atmosphere simulation and the simulation without fire) show that the fire-induced horizontal winds reach maximum values as high as 10 m/s, and for the Fort Stewart, GA burn are mostly confined within the first 50 m above the ground. However, in the complex terrain of Fishlake, UT and North Kaibab, AZ the simulated maximum horizontal wind disturbances occur at a much higher level (up to 1200 m for Fishlake, UT and 2700 m for North Kaibab, AZ above the ground). Based on these simulations, a combination of in-situ meteorological towers measuring near surface winds, and Light Detection and Ranging (LIDAR) scans characterizing flow at higher elevations is recommended to provide optimal wind measurement. Evolutions of simulated vertical velocities for analyzed burns take as long as 6 h from the ignition, confirming that the experimental plots should be large enough to accommodate burns lasting multiple hours.

Dependence on ignition procedure

Additional Fort Stewart, GA simulations with WRF-SFIRE performed with 5 different ignition procedures indicate that the ignition process plays an important role in the updraft evolution, especially during the first couple of burn hours. The ignition procedure should be precisely documented to enable realistic representation of the plume evolution in subsequent numerical simulations, or the burn should be long enough so that the impact of the ignition procedure on the plume evolution becomes negligible.

Critical parameters

The first-order variance decomposition of the vertical velocity at 1200 m, smoke concentration at 1400 m, and the plume top height indicate that the most important simulation parameters for WRF-SFIRE are the heat flux and the heat extinction depth (defining the depth over which the fire heat flux is distributed vertically in the model). They contribute to the variance of the vertical velocity, smoke concentration and the plume top height up to 50% and 40%, respectively, indicating the importance of comprehensive heat flux characterization including its vertical distribution (Kochanski *et al.* 2018).

Model inter-comparisons under various atmospheric conditions

By representing the heat and mass source of a fire with a burner (i.e. a stationary line fire) we were able to consistently compare different approaches to smoke plume rise modeling (see Supplement B for details of the burner method). The heat and mass generation properties of the burner can be based on measurements or be user prescribed for the purposes of model comparison. This approach removes the need to model fire spread thereby removing the confounding influence of the different fire spread approaches of the different models. Two different characteristic ambient wind speeds (u_o = 5 m/s and 1 m/s) are considered, each with two atmospheric lapse rates (LR = 0, −6 °C/km). Simulation results are shown in Figure 5 (u_o = 5 m/s) and Figure 6 (u_o = 1 m/s). The agreement between WFDS-PB and WFDS-LS implies that explicitly resolving gas-phase combustion is not necessary for smoke plume simulations of this scale if the heat release per unit area is known. The downwind distance at which plume stabilization occurs is very similar across most of the models. The one exception to this is MesoNH which has a higher plume height (approx. 500 m higher) than the other models with $\mathrm{u_o}$ = 1 m/s and lapse rate of −6 °C/km case (Figure 6). The plume-rise centerline predictions definitely differ most between the models. This highlights the need for measurements that will support the identification and improvement of the physics-based sub-models that simulate the interaction of the ambient and buoyancy generated wind fields during plume rise. For the higher wind speed cases, the vertical extent of the plume far downwind differs between the models (Figure 5). This has important implications to the predictions of smoke at ground level and highlights the need for measurements of ambient atmospheric turbulence, which drives dispersion of smoke particulates at these distances from the fire. Note that the generality of the findings is not known, because the simulations covered a very limited range of conditions, have an idealized heat source, and include no detailed investigation into the relevant difference between the models.

Smoke plume height simulated with Daysmoke is also affected by wind and stability (Figure 7), but the distance to plume stabilization is shorter and plume height is lower than those simulated with other models. The impact of ambient winds on the plume dispersion is evident for both vertical thermal profiles considered, while the effect of the atmospheric stability is evident only for the $\mathrm{u_o}$ = 1 m/s case. This suggests the importance of accurate measures of vertical temperature profiles in calm wind conditions. Plume rise will increase with effective diameter, which is determined by heat flux and exit vertical velocity. The calculation algorithms of exit velocity are not well evaluated and will benefit from measurements during the FASMEE field campaign.

Weather conditions

Liu et al. (2018) used Daysmoke to simulate hypothetical burns at Fort Stewart, GA for February 5–8, 2011. The results (not shown here) indicate that the smoke plume is not fully developed with a low plume height on February 5 under a shallow cyclonic system and a front that lead to warm, moist, and windy conditions during day time. However, smoke drainage and fog are formed during night time burning. Smoke plumes with clear boundaries appear on both February 6 and 7 with cool but dry and calm conditions during a transition between two low-pressure systems. The plume rises higher on the second day mainly due to lighter winds. Smoke on February 8 is in a loose structure of large horizontal dispersion and at a low height after passage of a deep low-pressure system with strong cool and dry winds. These results suggest that the ideal weather conditions for the desired smoke plumes for the FASMEE field campaign would be a period between two low-pressure systems.

Plume structure

Daysmoke simulations were conducted for a planned burn at Fort Stewart, GA with a fixed amount of total burned area but including varied number of sub-plumes. Note that the burned area of each updraft would decrease with increasing sub-plume number. The simulated vertical profiles (Figure 8) show large dependence on sub-plume number. Plume rise generally decreases with increasing sub-plume number for the first three days. The sensitivity analysis result (not shown) indicates the importance of the multiple sub-plume property, which is one of the two most important parameters together with thermal stability. Each parameter contributes to about one third of total variance. The third important parameter is entrainment coefficient which contributes about 16% of total variance.

Nighttime drainage and fog

The PB-P simulation of the prescribed burn conducted on October 18, 2016 in the Kaibab National Forest, AZ produces a super-fog event associated with smoke (the yellow dots) during the smoldering phase (Figure 9). The simulated drainage/slope flows become well-established after midnight. Smoke particles are oriented toward the south-southwest at 0300 LST, the hour when the accident along Highway I-40 (Gabbert 2016) (also see Supplement A) is first reported. This pattern continues through 0700 LST, when the simulation produces smoke and natural fog at a drainage near the lower left corner of the figure. The result suggests the need of night-time smoke measurement not only at the moist southeastern sites but also at the relatively dry western sites.

Seasonal variability in photochemical O_3 production

The CMAQ-BlueSky simulations of hypothetical burns at Fort Stewart, GA on March 18 and 22, 2013 are shown in Figure 10 (panels a and b). Southerly winds blow the smoke plume north with O_3 mixing ratio exceeding 10 ppb in the plume centerline 3 hours after ignition on the 18th and stagnant winds on the 22nd allow for precursor build-up and O_3 production in immediate proximity of the burn unit 6 hours after ignition. The annual 2013 modeling of this hypothetical fire indicates that O_3 can form year-round in that area but much less so in November and December which suggests those months would not be conducive for a field study focused on modeling photochemically produced pollutants like O_3.

Dependence on grid spacing

Figure 10 shows CMAQ-BlueSky modeled fire impacts at both 4 km (panels c and e) and 1 km (panels d and f) grid resolution to show smoke plume impacts on O_3 and $PM_{2.5}$ due to finer resolution model application at the actual (Monument Peak) and planned burn unit (Manning Creek) of Fishlake NF, UT 4 hours after ignition. Smoke plumes are similar for both with O_3 impacts greater than 5 ppb and $PM_{2.5}$ concentrations exceeding 20 µg/m^3. Further, O_3 inhibition is modeled at the location of each of these fires with a transition to O_3 production at both the Stewart, GA and Fishlake, UT prescribed burns when steady winds are present. Predicted $PM_{2.5}$ concentrations in the plume centerline are notably larger in the finer resolution simulation. Measurements are needed to understand whether this amount of O_3 formation is reasonable for a fire of this type and size and to confirm the timing of smoke plume transition from O_3 inhibition to production. Again, field study measurements are needed to constrain these results and understand whether they are realistic so that regulatory and health impact assessments can use this information with confidence.

Issues for model improvement

Major issues for model improvement are summarized in Table 3 and described below.

Fire behavior and energy

Heat release—Measurements of the fire-base depth, spread rate, and total mass consumption during flaming can be used to determine a first-order estimate of the 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 since fire lines 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-atmospheric coupled models such as 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 plume. The dynamical structure is an important factor for the formation of separate smoke sub-plumes. Measurements of the structures together with smoke dynamics are needed to understand the relations of smoke dynamics to horizontal and vertical fire heat fluxes (radiative and convective).

Fire spread—Fire spread is an important process determining fuel consumption, spatial patterns and temporal variations of heat release rate, burned area and burn duration. The lateral fire progression is particularly impacted by atmospheric turbulence. In the models such as WRF-SFIRE the flank rate of spread is parameterized using local wind perturbations normal to the flank and the Rothermel formula (Rothermel 1972) for head-fire rate of spread. Characterization of the lateral fire spread and atmospheric turbulence is needed to validate and improve this approach.

Smoke and meteorology

Vertical smoke distribution—Plume rise and vertical smoke distribution are important factors for partition of smoke particles between their local and regional air quality impacts. Smoke particles and other pollutants such as ozone generated from photochemical reactions would mostly affect air quality and human health near the burn site if they are trapped in the PBL, but can affect long range in downwind through transport by wind if they penetrate into the free atmosphere. Smoke plume models such as Daysmoke have focused on improving simulation of plume rise but not vertical smoke profiles.

Sub-plumes—Individual sub-plumes within a smoke plume would be highly dynamic, often forming as a result of localized fuel accumulations and ignition process. Once formed, they would instantly affect heat fluxes, exit velocity and temperature, which are important for smoke plume rise and vertical profile simulation. Individual sub-plumes need to be precisely defined operationally but would be extremely difficult to detect and count in reality. The number of multiple sub-plumes usually is not measured for prescribed burns. Therefore, observational and modeling evidence is needed to understand the roles of sub-plumes.

Smoldering combustion and night-time smoke—Fire emission factors strongly depend on combustion mode (Surawski *et al.* 2015). The smoldering stage of a prescribed burn could produce additional VOC, $PM_{2.5}$ and CO emissions after the flaming front passage. Currently, many smoke models use bulk emission factors independent on the burning stage. During night with smoke coming mainly from smoldering combustion under stable thermal stratification and calm winds, topography becomes a major factor for smoke dispersion. Some smoke models describe smoke movement under these conditions subject to the assumption of smoke being confined to a shallow layer with uniform meteorological conditions. Model performance in simulating smoke drainage and fog formation has been extensively evaluated for conditions in the U.S. Southeast (Achtemeier 2009) but not for the complex terrain of the U.S. west.

Fire-atmosphere interactions—Atmospheric and fuel conditions are one of the drivers for fire ignition and spread, while heat and water released from burning change air temperature, humidity, and turbulence. Better coupling approaches need to be developed to feed high-resolution heat release from fire models to smoke models. Accounting for the feedbacks of fire-induced atmospheric disturbances on fire and plume behavior are also needed. The impacts of vegetation and wind changes on fire behavior along the fire perimeter for an established, well behaved, freely evolving fire have been investigated (Cruz *et al.* 2015; FCFDG 1992), but need to be documented for more fuel types through targeted experiments and confronted with simulations. It is important to assess how well the model is able to resolve pyro-convection changes when the burning area becomes small relative to the size of the atmospheric grid cell, and the fire surface heat fluxes may become poorly resolved.

Smoke-atmosphere interactions—The entrainment rate of the ambient air into smoke plume depends on plume and atmospheric conditions and varies in space and time. Due to the lack of measurements, understanding, and the numerical schemes of the complex thermal and dynamical processes on smoke plume boundaries, some smoke models use constant empirical values. A model's ability to resolve turbulent mixing near the plume edge as it rises is crucial for realistic rendering of plume evolution and should be assessed. Currently, smoke optical properties are not well characterized in photochemical models. Smoke can reduce radiation and temperature below the smoke layer due to scattering and absorption of smoke particles. This feedback is not included in most modeling studies. Therefore, photochemistry is likely overstated near large events consequently impacting the modeling of O_3 and secondary PM formation processes. Dynamics of pyro convections and their impacts on plume rise need to be better simulated.

Emissions and chemistry

Distributions of air pollutants with distance and time—Smoke properties change during transport and dispersion due to various complex physical and chemical processes inside smoke plume such as photochemical reactions. Measurements of O_3, $PM_{2.5}$, their precursors, and important chemical intermediate species are needed near the burn site and along with distance downwind and time from the fire event. These data provide critical understanding of near-fire chemistry and downwind chemical evolution of pollutants during both day and night hours.

PM and gas speciation—Speciation is a necessary process to provide initial chemical conditions for air quality modeling based on fire emissions. Measurements are needed for improving PM, VOC, and NO_x speciation of fire emissions and a better understanding of appropriate speciation for modeling fires at different scales. Currently speciation of VOC and nitrogen gases of fire emissions for different fuel types and combustion conditions is not very well understood, which affects significantly both primary emissions and subsequent downwind secondary chemical pollutant production.

Measurement needs

The priority measurements needed for fire behavior and smoke modeling are summarized in Table 4. Observations of fuels and fire behavior are needed to drive, evaluate, and improve the models. The ambient and local meteorology is needed to initialize and provide forcing for the atmospheric component of the models and parameterize fire progression, assess fire emissions and fire heat release, and resolve plume rise, dispersion and chemical transformation. Chemical measurements are needed to evaluate and improve fire emissions and chemical smoke transformations in the atmosphere and evaluate the air quality impacts. The measurements of the plume optical properties are needed for better representation of climate impacts and also in-plume chemistry that is dependent on accurate representation of photolysis rates such as O_3 formation.

Fuel and combustion

Basic fuel properties—Fuel parameters, such as fuel type, fuel load, fuel depth, and fuel moisture are needed to accurately implement fire behavior models and evaluate fire spread components of coupled fire-atmosphere models. Char fraction and moisture fraction need to be known for implementing the burner method, and these depend on fuel type and condition.

Fuel consumption—The actual fuel consumption derived from pre- and post- fire fuel load is needed to evaluate whether the emissions factors used in the model adequately represent fluxes of pollutants and to validate the combustion rate and heat release over time against the total heat release. The rates at which fuel mass is consumed are a critical measurement for implementing the burner method. The rate of fuel consumption will need to be correlated with overhead imagery of the fireline and matched to fuel type. The forecasting applications that introduced fire generated heat into the atmosphere all implement the burner method. However, in these models the characteristics of the "burner" are based on an assumed burn time and spread rate. Usually the Rothermel model is used for the spread rate. This use of the Rothermel is inconsistent with its derivation because the local wind speed, which is affected by the fire, is used as input. The Rothermel model is based on a wind speed unaffected by the fire. The use of the burner method, based directly on measurements or prescribed, can help to characterize the errors from inconsistent use of the Rothermel model and also supports model comparison.

Spatial fuel heterogeneity—Measures of spatial heterogeneity in the vegetation may be required to develop the relationship between overhead imagery and rate of fuel-mass consumption. Estimates are probably also necessary for the three-dimensional fuel structure and nominal heterogeneity of the pre-fire stand. Some estimate is also needed of the stand structure that remains after the fireline passes, because this estimate determines the drag and thus could affect the indrafts and plume velocities near the ground, especially for lower-intensity fires

Fire behavior and energy

Ignition Procedure—Where prescribed fire is to be modeled, as in the FASMEE burns, the ignition procedure has to be carefully characterized due to its strong impact on the initial fire behavior and plume rise. Required measurements are the location on the ground of ignition sources, the time these sources are placed on the ground, and the time needed for an ignition to grow to a fire of the same size and intensity as the measurement resolution (e.g., thermal energy).

Fire spread—High-resolution observations of fireline progression are needed. Both a steady fire progression from a simple ignition procedure and frequent measurements of the fire location, rates of spread, and heat fluxes are needed to gain information on the lateral fire rate of spread.

Radiation and heat—High-resolution observations of fire heat fluxes are needed to assess how well coupled fire-atmosphere models resolve propagating fire as a heat source for driving pyro-convection. The fundamental quantity needed to implement the burner method is the time-dependent and spatially-explicit heat release rate per unit area along the fireline(s). Measurements of the heat transport are needed to assess whether this parameterization can realistically render the actual vertical heat transfer and how the vertical decay scale depends on type of the fire and its intensity.

Smoke and meteorology

Atmospheric conditions—Fire spread is computed based on coupled atmosphere-fire winds interacting directly with the fire front. Therefore, the model's ability to resolve the near-fire flow is crucial from the standpoint of fire progression, heat release, and plume development. Atmospheric conditions are essential for smoke dispersion and transport. In situ observations of near-fire wind, temperature, and heat and moisture fluxes at multiple levels are needed to assess the model's capability to realistically represent the fire-atmosphere coupling.

Fluxes, turbulence, and convection—Plume dynamics are affected by heat fluxes, and entrainment of colder, drier ambient air into the convective column. Therefore, the model's ability to resolve turbulent mixing, simulate formation of pyro-cumulus, and couple smoke aerosols and microphysics is crucial to realistically represent plume evolution, and it should be assessed based on measurements of turbulent fluxes of heat and momentum, as well as ambient meteorological conditions which define properties of the air being entrained into the smoke column.

Plume structure—Multiple sub-plumes are an important smoke feature that affects fire heat transfer and smoke plume rise. Measurements of the number, location, and size of multiple sub-plumes and their variations with time are needed to run smoke models and to develop parameterization schemes to estimate the sub-plume parameters.

Nighttime smoke movement—The measurements of emissions from the smoldering stage, smoke drainage, and fog formation, together with local wind, temperature, humidity, and air pressure, are needed to run and evaluate nighttime smoke drainage and super-fog modeling.

Emissions and chemistry

Fire emissions and representation—Fire plume rise and vertical allocation of emissions into the atmosphere need more evaluation in photochemical grid models for different fire types and sizes. Warm- and cold-season field measurements of heat flux, meteorology, and chemistry will allow the development of better approaches for vertical allocation of emissions during flaming and residual smoldering stages. Because of the lack of in situ measurements, simulated vertical emission profiles have not been validated.

Smoke chemistry—Fire emissions of speciated $PM_{2.5}$, precursors to secondarily formed $PM_{2.5}$, and precursors to O_3 formation are needed by fuel type and combustion component (flaming to smoldering) classified by MCE or combustion temperature. Speciation of VOC and nitrogen gases for different combustion conditions are poorly characterized, yet they have significant impacts on both primary emissions and secondary pollutant production. Speciated $PM_{2.5}$ organic aerosol measurements are needed near the fire and at multiple distances downwind to better understand dilution and chemistry impacts on $PM_{2.5}$ organic carbon evolution.

Near-fire site and downwind measurements—Measurements of near-fire and downwind chemical evolution of O_3, $PM_{2.5}$, and their precursors during both day and night hours are needed. A better understanding of the interplay among fire emissions, plume transport, dispersion, and chemistry in the context of simulating air quality impacts of wildland fires is needed.

Plume optical properties—Models such as WRF-SFIRE-CHEM have the required modeling capability of the radiative effects of smoke aerosols in principle, but they need an integrated dataset for evaluation. Currently, smoke optical properties are poorly characterized for some pollutants in these models, which may result in potentially overstated photochemistry near large events which impacts O_3 and secondary PM formation processes.

Desired burn conditions

Some fundamental conditions for the planned experimental burns (Table 5) were defined through analyses of the simulation and experiment results (Figures 3–10) and measurement needs (Table 4). Note that the different models have quite different desired burn conditions for model testing. In general, fuel distribution and ignition procedure are particularly important to WRF-CHEM-SFIRE, WFDS, and Daysmoke. Burn season and fire size are important to CMAQ.

Fuel types

A range of fuel types and burn areas typical for the U.S. southeast and west is desirable to provide a robust range of typical conditions to understand how best to represent both small and large-scale wildland fire in smoke modeling systems. The typical fuels that can be found at the FASMEE sites are mixed conifer and aspen at Fishlake and the higher-elevation sites of North Kaibab, ponderosa forests at the lower-elevation sites of North Kaibab, plantation-established longleaf/slash pine forests at the Fort Stewart sites, and plantation-established longleaf/loblolly at the Savannah sites.

Distribution of fuels

For models based on simplified fuel descriptions such as WRF-SFIRE, the ideal site would be covered with uniform fuel close to one of the standard fuel behavior models. For evaluation of model capability in terms of plume rise and dispersion, preferred fuel properties would be those that ensure a moderate to high-intensity burn.

Spatial scale

For models with high spatial resolution such as WFDS-PB, vegetation type and spatial variability should be characterized at spatial scales that are on the order of the expected fire depth and height.

Burn season

For the development of models such as CMAQ, prescribed burns of medium intensity during non-growing season (winter and early spring) in the southeastern US and medium to high intensity during growing season (e.g., summer) in the western US are desired.

Fire size and duration

To observe fire behavior of value for model improvement, the experimental fires should burn long enough to fully evolve to semi-steady state. The size of the fire plot should be big enough to enable such evolution. The test simulations performed for Fort Stewart indicate that to allow for the fire progression and plume evolution over a period of 6h, the experimental burn plots should be at least 250 acres in size. To capture the diurnal cycle of plume evolution, the burn should be extended to at least 12h, which would imply the desired size of burn plots of 500 acres or more.

Ignition procedure

Aerial ignition by a helicopter is planned. In the southwestern sites the ignition will produce a simplified ignition to obtain as close as possible a free-running uphill fire. Many models such as WRF-SFIRE are capable of simulating complex ignition patterns, but cases with complicated ignition are not as useful for model validation because they make validation studies on the effect of individual factors on fire behavior difficult or impossible.

Fire intensity

Experimental burns should be intense enough to ensure a clear fire signature in the measurement data. For the smoke plume measurements to be able to measure exit temperature and vertical velocity, at least moderately intensive burning to generate heat flux of at least 500k W/m in the Southeast and highly intensive burning to generate heat flux of over 1000k W/m in the Southwest are desired.

Night-time and smoldering combustion

Nighttime smoke drainage and the formation of super-fog are typically a result of smoldering. The burns should include a smoldering stage.

In summary, the fuel, fire, and meteorological conditions suggested for a burn manger to identify suitable days for burning with a burn prescription that would meet all the criteria in this section and generate a desired smoke plume for the FASMEE field measurement would be like this: a plot of at least 250 acres in the Southeast and 500 acres in the Southwest; spatially uniform fuels with large fuel loading and low moisture content enough to generate heat flux of at least 500k W/m for moderate intensity fire in the Southeast and over 1000k W/m for high intensity fire in the Southwest; aerial ignition to produce a simple fireline with burning for longer than 6 hours to generate a stable plume; and wind speed at 1 m/s or only slightly higher for a full developed plume.

Conclusions

Simulations and experiments of hypothetical prescribed burns with a suite of fire behavior and smoke models have identified some major modeling issues that should be understood for model improvement: 1) Current smoke models are unlikely to receive the needed dynamical and high-resolution fire behavior information for smoke modeling and forecast of large burns. 2) Improved capability in modeling high-resolution and dynamical fire energy and smoke plume is needed. 3) Multiple sub-plumes are not well described without understanding the mechanisms and concurrent measurements of the coupled fire and smoke processes. 4) The feedbacks of atmospheric disturbances induced by fire and smoke processes are not well represented in current fire and smoke models. 5) Speciation of fire emissions for different fuel types and combustion conditions and the impacts on atmospheric chemical pollutant production during both day- and night-time need to be better characterized.

Next-generation SRF systems with improved capability in fire behavior and smoke modeling to address these issues are needed to meet the challenges of the growing air quality, health, and safety concerns associated with wildland fire emissions. The next-generation SRF systems should be extensively coupled among fire, smoke and atmosphere. They should be equipped with the new capability in simulating and predicting vertical smoke distributions and multiple sub-plumes, dynamical and high-resolution fire processes, and smoke chemistry at local and regional scales during day and night.

The development of the next-generation SRF systems requires comprehensive and coordinated measurements across the fields of fuels, fire behavior and energy, smoke and meteorology, and emission and chemistry. The modeling efforts reviewed in this paper support plan and design of field campaigns by identifying the critical measurement data needs and desired burn conditions as summarized in Tables 4 and 5.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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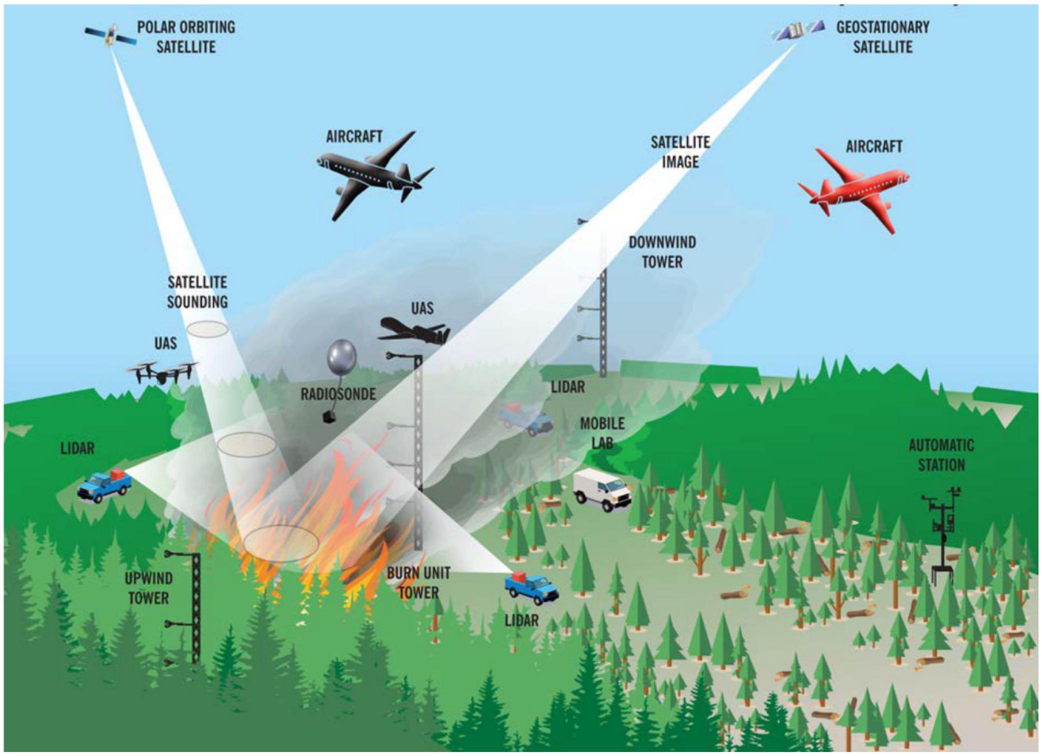

Figure 1.

Schematic representation of the FASMEE project measurement platforms.

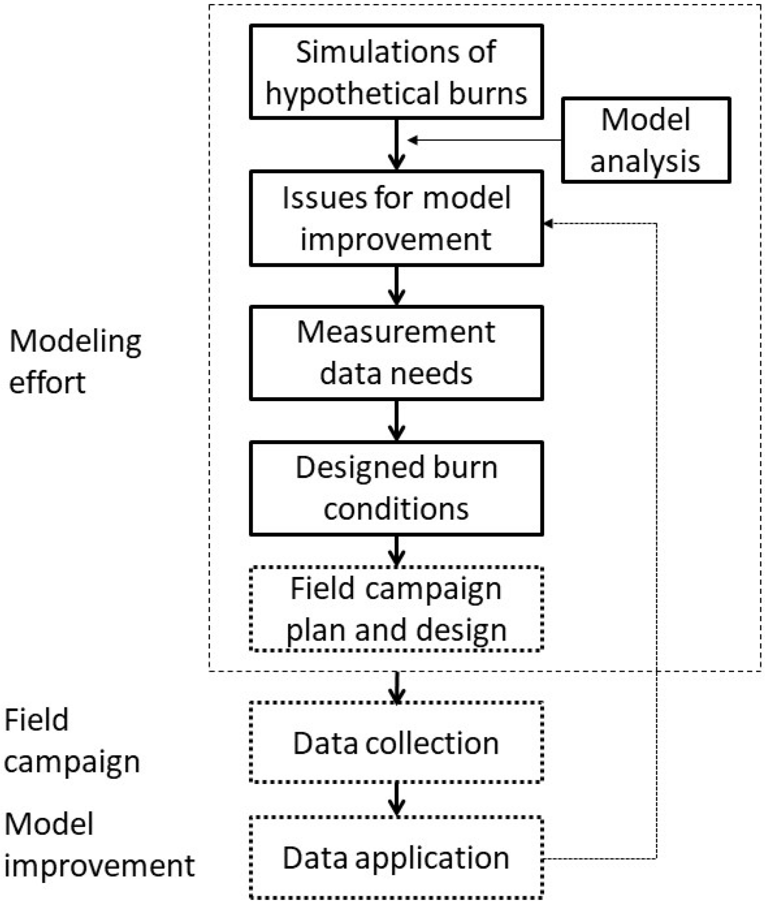

Figure 2.

Fire behavior and smoke modeling efforts and their connections to field measurements.

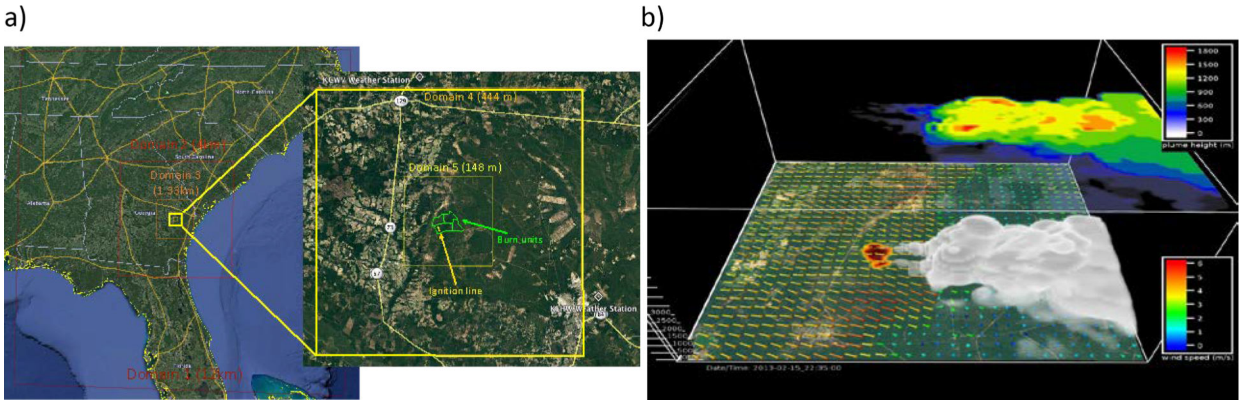

Figure 3.

WRF-SFIRE simulation of a prescribed burn at Ft. Stewart, GA on February 15 2013. The color arrows represent wind speed (see bottom color bar) and direction. The upper level plane shows local plume heights (see upper color bar).

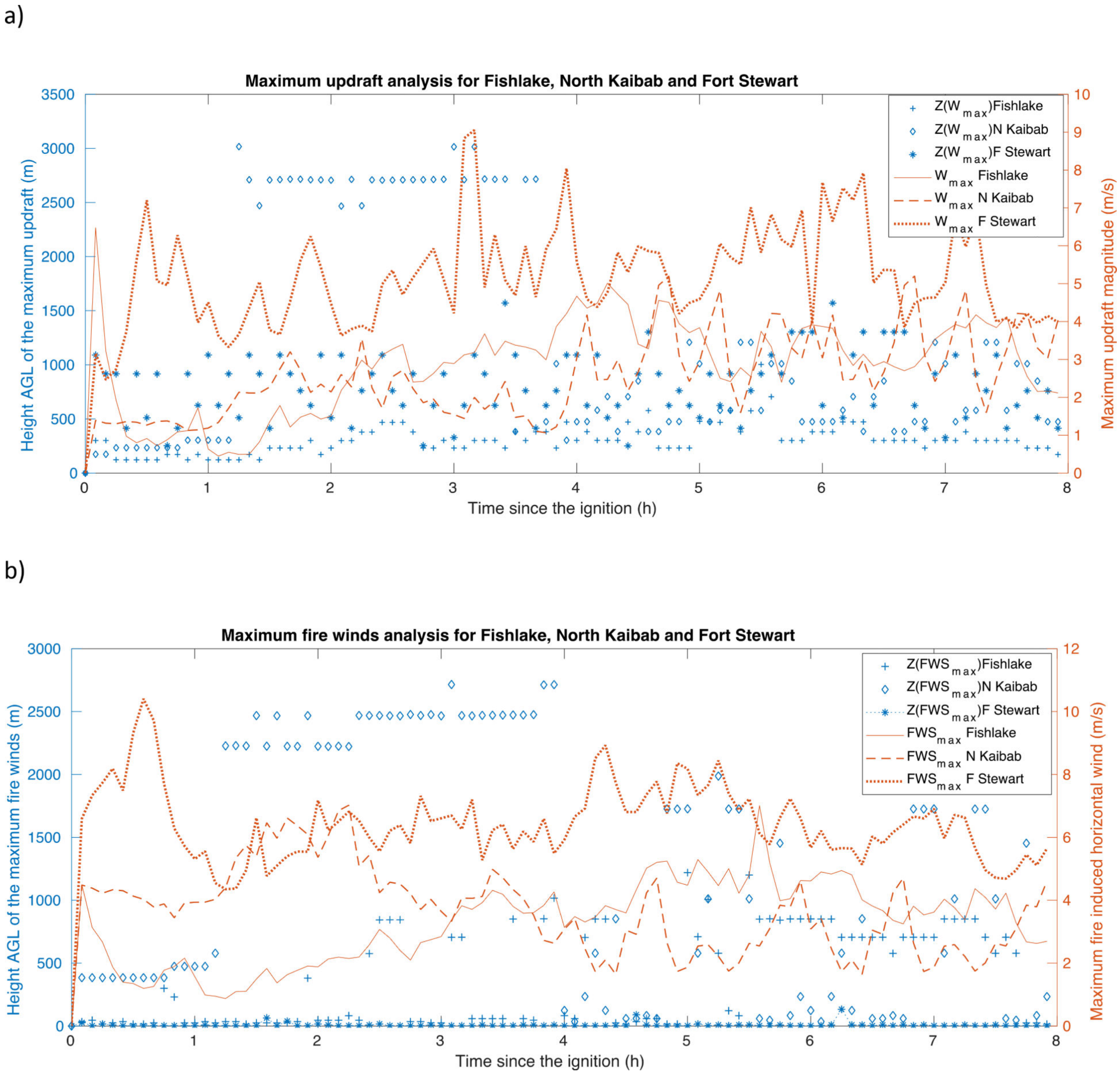

Figure 4.

a) Time series of the heights (blue points) and magnitudes (red lines) of the maximum updrafts. b) Time series of the heights (blue points) and magnitudes (red lines) of the maximum fire-induced horizontal winds from simulations of Fishlake, UT, North Kaibab, AZ and Fort Stewart, GA burns, performed for: 09.03.2014, 09.05.2008 and 04.22.2014, respectively.

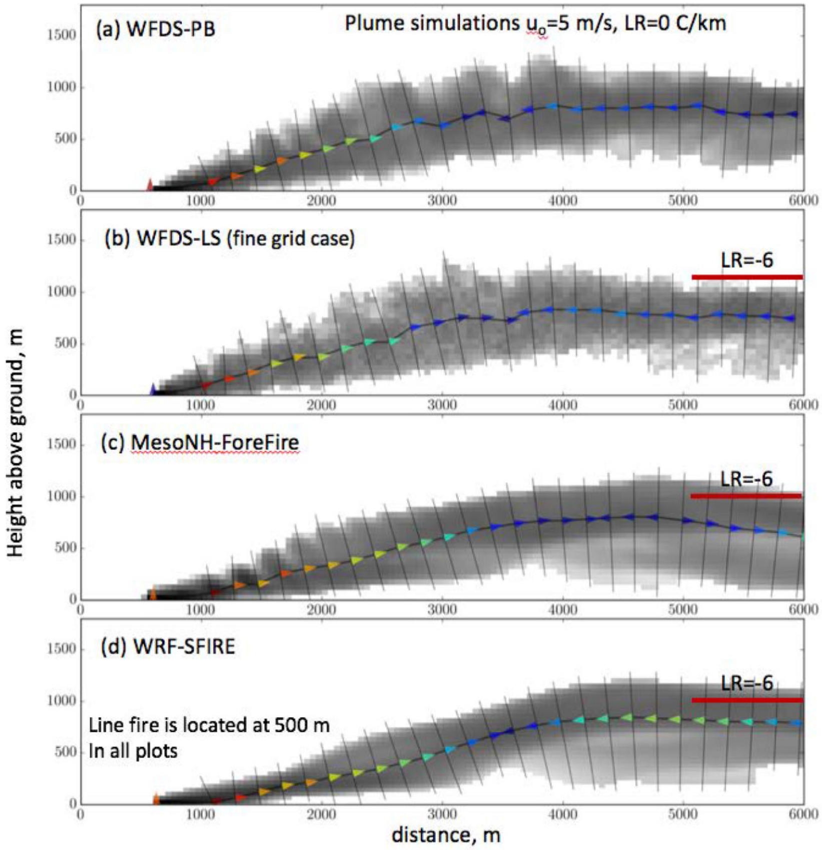

Figure 5.

Simulated smoke plumes at time *t* = 1000 s after ignition of the stationary line fire. u_0 (m/s) and LR (°C/km) are the wind speed constant and lapse rate, respectively (see Supplement A). (a) WFDS-PB with the combustion processes directly modeled. (b-d) Three other models without explicitly model combustion. LR = 0 C/km for the shaded plumes; the thick magenta line on the right-hand-side shows the plume center height at distance 6000 m for the case of LR = −6 °C/km. Shading shows the smoke plume with the degree of darkness increasing with smoke concentration.

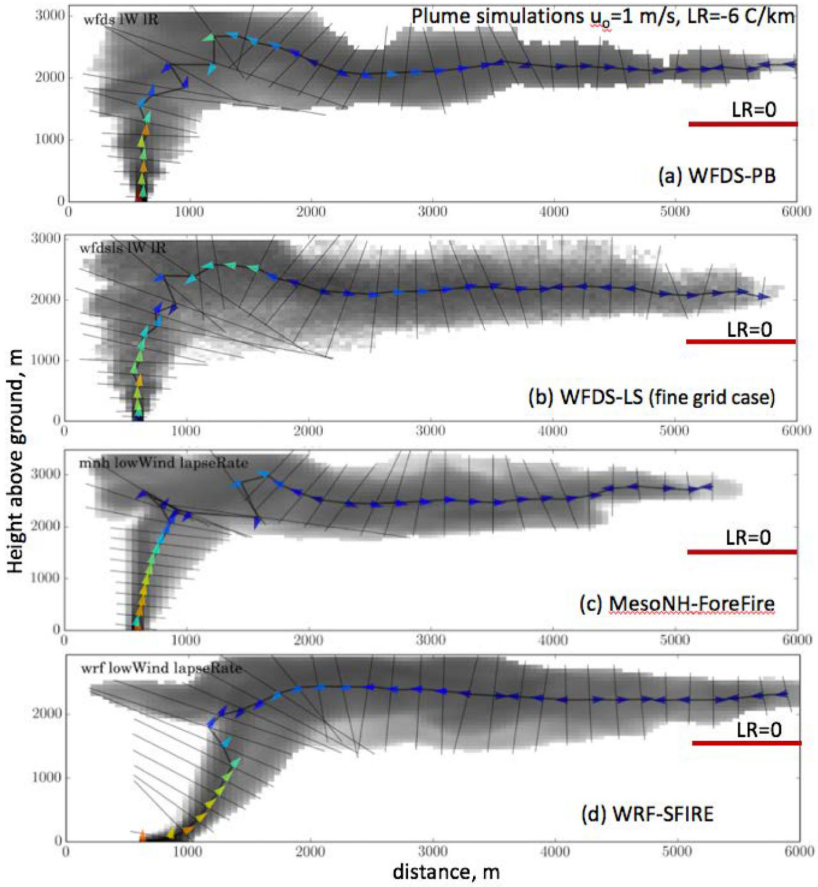

Figure 6.

Simulated smoke plumes at time $t = 1000$ s after ignition of the stationary line fire. u_0 (m/s) and LR (°C/km) are wind speed constant and lapse rate. Note that unlike Figure 5, in this figure the shading, centerline, and convective flux are for a lapse rate of −6 °C/km, not 0 °C/km; the thick magenta line shows the height of the plume centerline for LR = 0 °C/km. The shading is smoke plume with darkness degree increasing with smoke concentration.

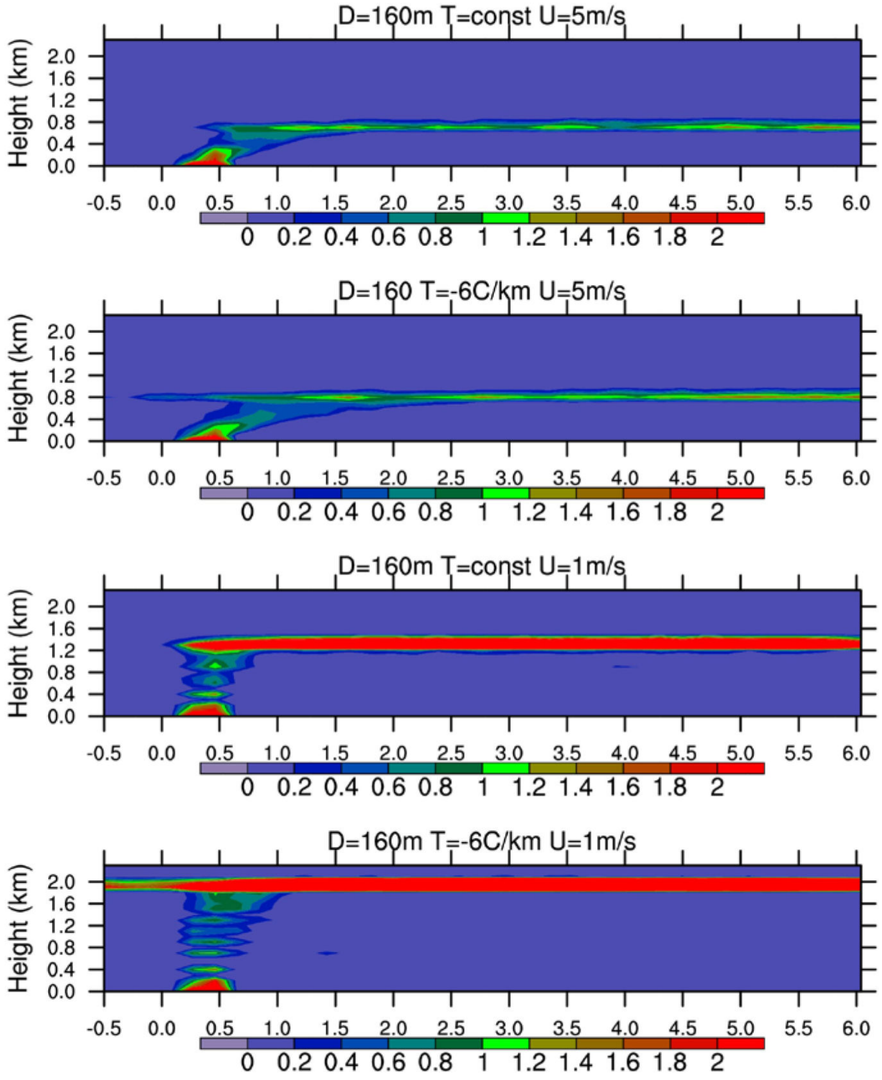

Figure 7.

Smoke plume (unit: particle number per grid cell) at time $t = 1000$ s after ignition of the stationary line fire simulated with Daysmoke. D, T, and U are effective diameter (m), wind speed (m/s), and lapse rate (°C/km). The horizontal is distance from fire (km).

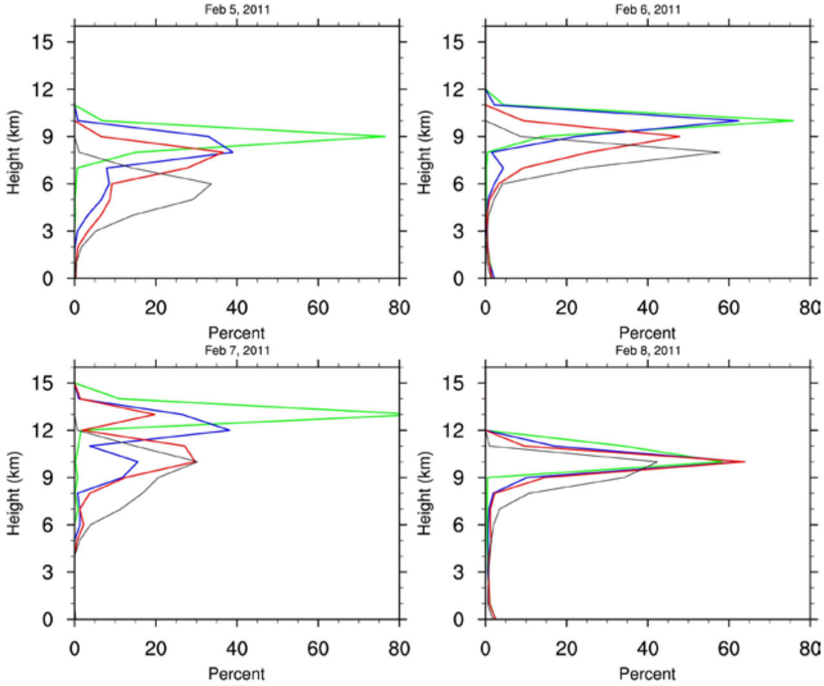

Figure 8.

Vertical smoke plume profiles of hypothetical prescribed burns at Ft Stewart, GA during February 5–8, 2011 simulated with Daysmoke. The green, blue, red, and gray lines are for sub-plume numbers of 1, 2, 4, and 6. The values are normalized by dividing the total particle number of all vertical layers.

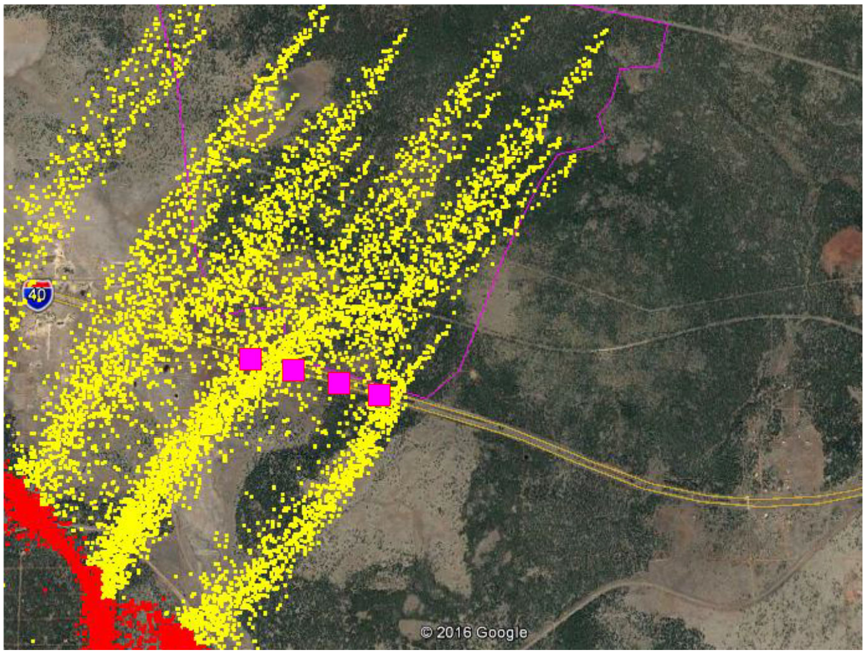

Figure 9.

PB-P simulated smoke from smoldering combustion at 0700 LST, October 19, 2016 near the Grand Canyon, AZ. The yellow and red dots are smoke particles and fog. The parallel double lines are I-40.

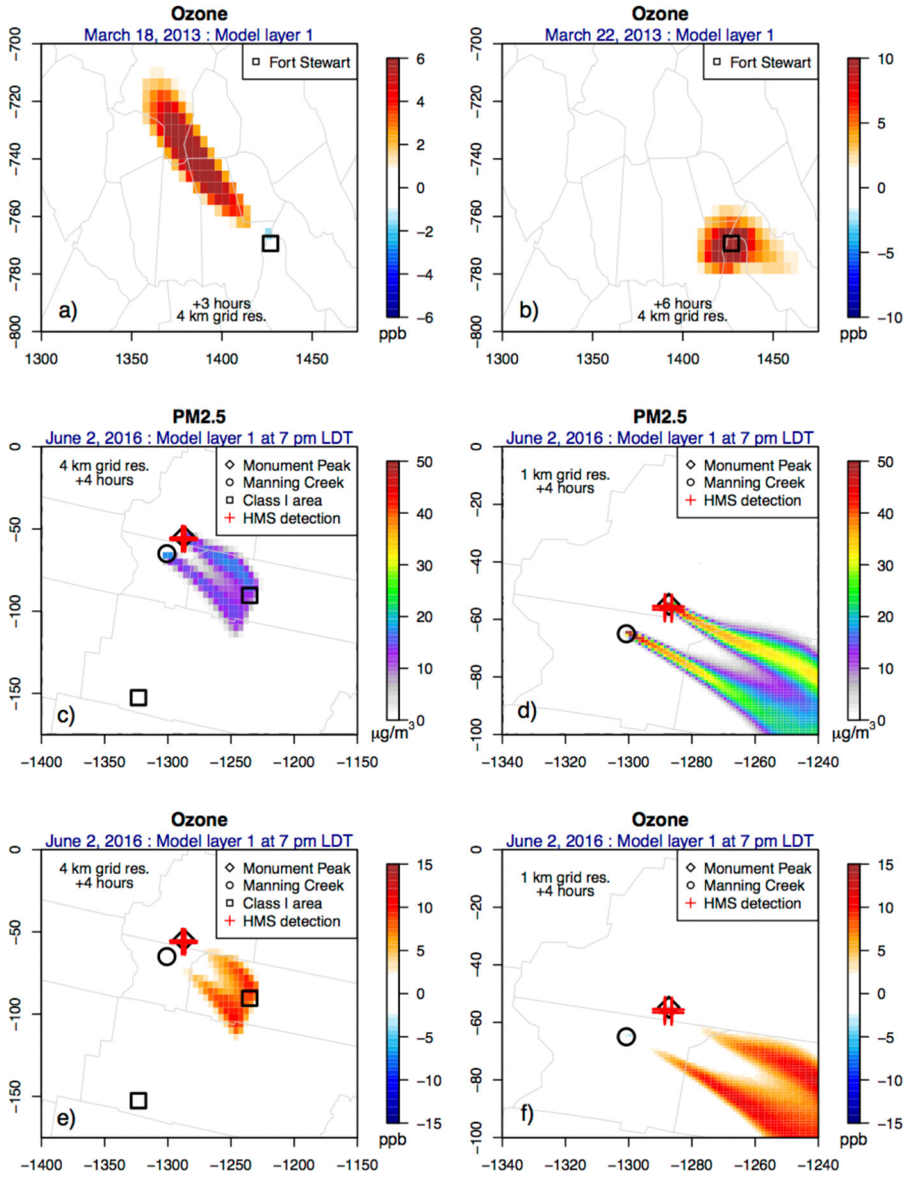

Figure 10.

CMAQ-BlueSky estimated O_3 (ppb) on (a) March 18 and (b) March 22, 2013 for a hypothetical 868 acre prescribed fire at Fort Stewart, GA. Model predicted $PM_{2.5}$ (c and d, μg m^{-3}) and O_3 (e and f, ppb) are shown for an actual and planned burn unit at Fishlake NF, UT on June 2, 2016 at 4 hours after ignition at both 4 km and 1 km grid resolutions. NOAA Hazard Mapping System (HMS) satellite-based fire detections for the fire detections for the Monument Peak burn are also shown.

Table 1

Major model properties.

Model	capability	Scale
WRF-SFIRE-CHEM	Level set fireline; Atmospheric physics and chemistry, smoke transport and gaseous products; WRF's nesting.	Spatial scale: regional and local; Domain: km or larger; Fire grid spacing: tens of m.
WFDS and FIRETEC	Emphasis on capturing the fire behavior; Relatively near-field smoke plume rise and downwind transport; Simple atmospheric physics.	Spatial scale: local; Domain: about 1 km, larger for WFDS-LS. Grid spacing: WFDS-PB: Grid of cm ~ m (WFDS-PB), m (FIRETEC), m or larger (WFDS-LS).
Daysmoke and PB-P	Computationally fast with simple physics; Topography-air interaction for night smoke.	Spatial scale: local; Domain: ~ 5 km (Daysmoke), 1 km (PB-P); Grid spacing: ~ 100 m.
CMAQ-BlueSky	3D Eulerian photochemical transport; Gas, aerosol, and aqueous phase chemistry; Air quality (especially PM and ozone).	Spatial scale: regional; Domain: up to 1000s of km; Grid spacing: 4~12 km (1 km for fine scale applications).

Table 2

Simulations and experiments (presented in Supplement A).

Model	Burn site & date	domain	Issue
WRF-SFIRE v3.4.1	Fort Stewart, UT, 02/14/2013	5 nested, air resolutions between 0.15 and 36km; fire mesh of 0.03km.	Plume evolution; Ignition dependence; Critical parameters.
Daysmoke MesoNH WFDS-PB, WFDS-LS WRF-SFIRE v3.4.1	N/A	Line fire of 750 m long × 25 m depth; two ambient wind profiles and lapse rates.	Model comparisons of smoke simulations under various air conditions.
Daysmoke, PB-P	Stewart, GA, 02/5-8, 2011; Kaibab NF, AZ, 10/19, 2016	Domain of 5km, grid cell of 100m (Daysmoke); 1km, 20m (PB-P).	Weather condition; Multiple sub-plumes; Nighttime drainage.
CMAQ	Stewart, GA, daily 2013; Fishlake NF, UT, 06/02/2016	Southeast (Stewart); Southwest (Fishlake).	Seasonal variability in O_3 production; Impact of grid space.

Table 3

Issues and gaps for fire and smoke model improvement.

Field	Process	Issues and gaps
Fire behavior and energy	Heat release	Need measurements of unit heat release per unit area along the fire perimeter; Improve vertical distribution of radiative and convective heat flux generated by the fire; Understand the relations between heat structure and multiple sub-plumes.
	Fire spread	Parameterization of lateral fire progression may underestimate the lateral fire spread, burnt area and the total buoyancy of the fie plume
Smoke and meteorology	Plume distribution	Plume top heights are often provided with large uncertainty, and without the vertical concentration profiles which are generally specified not resolved based on fire dynamics and local weather conditions
	Multiple sub-plumes	No routine measurements are available; Some modeling tools are in early development stage; Parameterization schemes are needed.
	Smoldering combustion and night smoke	Bulk emission factors not dependent on the burning stage; Night-time smoke drainage modeling has many assumptions; Not evaluated for burned sites with complex topography.
	Fire-atmosphere interactions	Need measurements of all at commensurate spatial and temporal scales to predict and validate interactions between vegetation, wind fire behavior and plume dynamics; Coupled fire-atmosphere models and air quality models.
	Smoke-air interactions	Improve entrainment estimates; Better characterize smoke optical properties; Understand the impacts of pyro cumulus on vertical smoke distribution and fire behavior.
Emissions and chemistry	Pollutants with distance and time	Lack in near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species.
	PM and gas speciation	PM, VOC, and nitrogen gas speciation not very well understood for different fuel types and combustion conditions.

Table 4

Priority measurement needs.

Field	Property	Parameter	Purpose
Fuels and consumption	Fuel conditions	Type, load, bulk density, spatial distribution above and on ground; Dead and live fuel moistures; latitude / longitude, elevation, slope.	Inputs of fire behavior and smoke modeling.
	Consumption	Rate, amount, smoldering/flaming stage.	Estimate fire emissions.
	Spatial heterogeneity	Pre- and post-fuel stands.	Fire behavior and consumption.
Fire behavior and energy	Ignition	Pattern, start time, duration, time and space dependence; Burned area.	Inputs of fire behavior and smoke modeling.
	Fire spread	Fireline location, shape, depth, time and space evolution; Lateral fire progression.	Evaluation of fire behavior modeling; Improving fire-vegetation-air interaction.
	Radiation and heat	Spatial distribution and temporal variation; Time dependent location of plume envelope to the downwind distance of neutral buoyancy.	Fire model evaluation; smoke model inputs; Improve / develop parameterizations of the fire-induced heat flux and multiple sub-plume number.
Smoke and meteorology	Atmospheric conditions	3D temperature, winds, moisture, pressure, precipitation	Inputs of fire and smoke modeling, model evaluation.
	Fluxes, turbulence, and convection	Fire exit vertical velocity and temperature; Sensible, latent and radiative fluxes; Atmospheric turbulence; PBL height; Entrainment rate; Pyro-cumulus (height, cloud condensation nuclei).	Evaluate fire models; Inputs and evaluation of smoke modeling; Assess and improve fire-air interaction modeling.
	Plume structure	Vertical profile and rise; Multiple sub-plume number, location, time change, merging process.	Model validation and improvement of fire gas and aerosol chemical evolution in local and remote areas
	Nighttime smoke	Smoldering stage emissions; Local wind, temperature, humidity, and air pressure.	Inputs of smoke drainage and fog formation modeling
Emissions and chemistry	Fire emissions	PM, O_3, CO, CO_2, CH_4, VOC speciation (incl. carbonyls); CH_3CN, nitrogen gases.	Validate and improve fire emissions estimates; O_3 and $PM_{2.5}$ chemistry
	Smoke chemistry	Speciated and size resolved PM, particle number and diameter; SO_2, NH_3, CH_4, VOC speciation; Oxidized nitrogen gases, photolysis rates.	Smoke modeling evaluation; Understand factors and dynamics of multiple sub-plumes and develop model parameterization
	Near-event and downwind measurements	PM, CO, CO_2, and VOC near-fire and downwind.	Inputs and evaluation of smoke modeling
	Plume optical properties	Light scattering/absorption of plume constituents; Cloud and ice condensation nuclei; Solar radiation, jNO_2 photolysis.	Better representation of the radiative impacts of smoke on cloud microphysics, radiation and photochemistry

Table 5

Desired burn conditions.

Field	Property	Condition	Benefit
Fuels	Distribution	Uniform fuel close to one of the standard fuel behavior models.	Simplified fuel descriptions with Rothermel fire spread model.
	Scales	At spatial scales on the order of the expected fire depth.	To run dynamical fire models such as WFDS.
	Types	A range of fuel types and burn areas typical for the FASMEE sites.	To represent both small and large scale wildland fire in smoke modeling systems.
Fire	Size and duration	Long enough to evolve to semi- steady state; The size of the fire plot should be big enough to enable such evolution.	Fully developed plume.
	Ignition	As simple as possible in spatial location and timing; Multiple ignitions.	Easy to validate the effect of on fire behavior; Formation of sub-plumes.
	Intensity	Intense enough to ensure a clear fire signature in the measurement data	Evaluation of fire behavior modeling; Improving fire-vegetation-air interaction.
	Season	Non-growing season (low to medium intensity in SE), summer (medium to high intensity in the west).	Estimates of PM and O_3 impacts can be evaluated.
	Stage	Include a smoldering stage with measurements fire emissions and weather.	Nighttime smoke drainage and possible formation of super-fog.