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Review

# Fire behaviour and smoke modelling: 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 behaviour 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. The development of the coupling capability requires comprehensive and spatially and temporally integrated measurements across the various disciplines to characterise flame and energy structure (e.g. individual cells, vertical heat profile and the height of well-mixing flaming gases), smoke structure (vertical distributions and multiple subplumes), ambient air processes (smoke eddy, entrainment and radiative effects of smoke aerosols) and fire emissions (for different fuel types and combustion conditions from flaming to residual smouldering), as well as night-time processes (smoke drainage and super-fog formation).

**Additional keywords:** burn plan and measurement design, CMAQ, Daysmoke, FIRETEC, WFDS, WRF-SFIRE-CHEM.

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## Introduction

Fire behaviour and smoke models are numerical tools that provide smoke information on pollutant species and concentrations, and spatial distributions and temporal variations of smoke plumes 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 2009*a*; Goodrick *et al.* 2013; Moritz *et al.* 2014; Strand *et al.* 2012). A range of fire behaviour models exist, largely differing by the degree to which the methods of computational fluid dynamics (CFD) (see the Supplementary material for a list of acronyms) are used and the underlying physical processes are explicitly modelled. 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), 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.* 2013). Lagrangian models such as CALPUFF (Scire *et al.* 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 parcel 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 European Centre for Medium-Range Weather Forecasts (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, Coupled Atmosphere-Wildland Fire-Environment (CAWFE) (Clark *et al.* 2004; Coen 2013), The Advanced Regional Prediction System – the Discrete EVent System (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 behaviour 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 be executed fast enough to provide a usable forecast and that the data needed for their execution are readily available (Sullivan 2009*b*). 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 Air Indicator Report for Public Awareness and Community Tracking (AIRPACT) (Chen *et al.* 2008), GEOS-CHEM (Bey *et al.* 2001) and ECMWF IFS also include smoke. Comprehensive operational smoke forecast systems such as BlueSky (Larkin *et al.* 2009) 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 models, 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, owing to the lack of coupling between the local weather, fire behaviour and emissions, emissions at an interval of 1 h 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 behaviour, which is accounted for in contemporary fire behaviour models (Faggian *et al.* 2017), has high temporal variability, 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 vapour emitted into the atmosphere by the entire fire. Observations of large-perimeter prescribed fires have often revealed that a smoke plume of the entire fire could include multiple subplumes (also called updrafts or cores) (Larkin *et al.* 2009; Liu *et al.* 2010; Achtemeier *et al.* 2012). Most smoke models do not resolve individual subplumes 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 behaviour, 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 subplumes, eddies, turbulence and pyroconvection, entrainment of ambient air, smoke–canopy interactions, and smoke radiative and cloud impacts. Recent advances have resulted in several coupled models that emphasise atmospheric physics and fire–atmosphere coupling at scales of hundreds of metres (e.g. WRF-SFIRE), or fire physics, combustion processes and atmosphere coupling at scales of metres (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 modelling 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 behaviour, smoke dynamics and fire–smoke interactions. Currently available observational data do not easily facilitate model evaluation and comparison (Alexander and Cruz 2013; Cruz and Alexander 2013), especially in the context of the coupled fire–atmosphere models, which require integrated datasets that comprehensively characterise the fuel, energy released, local micrometeorology, plume dynamics and chemistry. To fill the data gaps, several 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), the Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen (WE-CAN) project [University Corporation for Atmospheric Research (UCAR)/National Center for Atmospheric Center (NCAR) Earth Observatory Laboratory (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 modelling 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 behaviour and smoke model improvement and the most critical observational needs, with a focus on fire, smoke and atmospheric interactions. The findings from the modelling 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 behaviour, 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 behaviour, 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 (Fig. 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 modelling issues, gaps and field measurement needs. These were substantially derived from model simulations described in the present 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 USA to support the FIREX-AQ project during the summer of 2019; (2) USA south-west campaign with potential prescribed burns located in the Fishlake National Forest, UT, and North Kaibab Ranger District, AZ, which began with a comprehensive measurement of stand replacement prescribed fire in the Fishlake National Forest on June 20, 2019; and (3) USA south-east 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 subplumes 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 parameterisation schemes, which will be a new capacity of smoke models.

The fire behaviour and smoke modelling efforts conducted in Phase I of FASMEE and their connections to field measurements are illustrated in Fig. 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 has been learned from previous model applications, to identify major issues for fire behaviour 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 modelling.

### *Models utilised for fire behaviour 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 parameterise 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 daytime 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 parameterisations 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 summarised in Table 1.

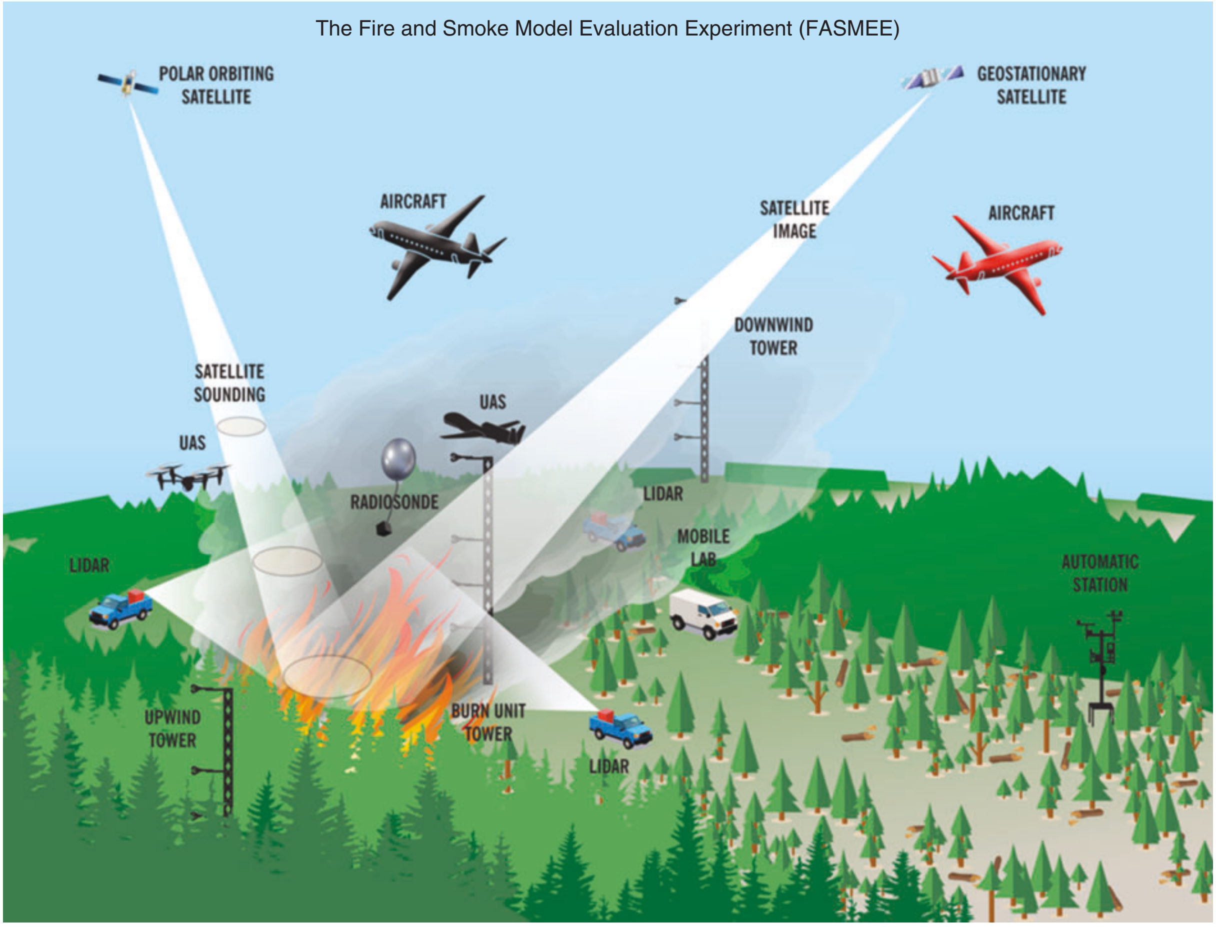


**Fig. 1.** Schematic representation of the Fire and Smoke Model Evaluation Experiment (FASMEE) project measurement platforms.

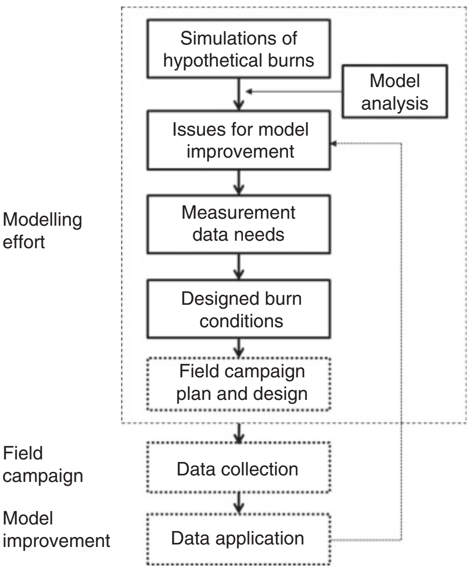


**Fig. 2.** Fire behaviour and smoke modelling efforts.

### *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) that 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 metres), 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 pyroconvections and smoke dispersion. WRF-SFIRE is also coupled with a prognostic fuel moisture model, which assesses the moisture of 1-, 10-, 100- and 1000-h 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

**Table 1. Major model properties**
WFDS, Wildland–urban interface Fire Dynamics Simulator

| 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 behaviour; relatively near-field smoke plume rise and downwind transport; simple atmospheric physics | Spatial scale: local; domain: ~1 km, larger for WFDS-LS; grid spacing: WFDS-PB: grid of cm to m (WFDS-PB), m (FIRETEC), m or larger (WFDS-LS). |
| Daysmoke and Planned Burn - Piedmont | 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 |
| Community Multiscale Air Quality-BlueSky | 3D Eulerian photochemical transport; gas, aerosol and aqueous-phase chemistry; air quality (especially particulate matter and ozone) | Spatial scale: regional; domain: up to 1000s of km; grid spacing: 4 to 12 km (1 km for fine-scale applications) |

conditions (Kochanski *et al.* 2013*b*). It has been evaluated in both research and forecasting modes (Kochanski *et al.* 2013*a*, 2013*b*, 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 incorporated 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, modelled 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 subgrid-scale models. The vegetation fuel complexes in both models are described as a highly porous medium within the 3D numerical grids and are characterised 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 thermophysical 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 utilise much finer computational grids (i.e. smaller grid cells on the order of 1 m) compared with 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 parameterisations (Morvan 2011; Hoffman *et al.* 2016).

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.* 2016). 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 submodels: an entraining turret model handling the convective lift phase of plume development and representing the subplumes within a buoyant plume; a detraining particle model; a large-eddy parameterisation 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 US south-east (Liu *et al.* 2009). Daysmoke has simple physics and no chemistry and thus needs far 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 subplumes, 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 m 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.

**Table 2. Simulations and experiments (presented in Supplementary material A)**
PB-P, Planned Burn - Piedmont; WFDS, Wildland–urban interface Fire Dynamics Simulator

| Model | Burn site and date | Domain | Issue |
|---|---|---|---|
| WRF-SFIRE v3.4.1 | Fort Stewart, UT, 14-Feb-2013 | Five nested, air resolutions between 0.15 and 36 km; fire mesh of 0.03 km | Plume evolution; ignition dependence; critical parameters |
| Daysmoke, MesoNH WFDS-PB, WFDS-LS WRF-SFIRE v3.4.1 | Not applicable | Line fire of 750 m long × 25 m deep; two ambient wind profiles and lapse rates | Model comparisons of smoke simulations under various air conditions |
| Daysmoke, PB-P | Stewart, GA, 5–8-May-2011; Kaibab NF, AZ, 19-Oct-2016 | Domain of 5 km, grid cell of 100 m (Daysmoke); 1 km, 20 m (PB-P) | Weather condition; multiple subplumes; night-time drainage |
| Community Multiscale Air Quality | Stewart, GA, daily 2013; Fishlake NF, UT, 06-Feb-2016 | South-east (Stewart); south-west (Fishlake) | Seasonal variability in $O_3$ production; impact of grid space |

### *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 modelling system has been used to support operational forecasts of air quality and smoke (e.g. NOAA; http://airquality.weather.gov, accessed 3 June 2019) and retrospective regulatory assessments. This modelling 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; Baker *et al.* 2018; Zhou *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/, accessed 3 June 2019), which relies on NOAA's Hazard Mapping System (HMS) satellite product and local activity data. The BlueSky fire emissions modelling framework typically applied for CMAQ includes multiple modules: the fuel loading model (Ottmar *et al.* 2007), the CONSUME fuel consumption model (Prichard *et al.* 2009), 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 volatile organic compound (VOC), $NO_x$ and primary particulate matter that have a diameter of less than 2.5 micrometers ($PM_{2.5}$) speciation. Smoke plume rise algorithms use estimates of heat flux to vertically allocate smouldering 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 wildfire and prescribed fire classification, which helps define the environmental conditions of burning.

### *Simulations and experiments*

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

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 analysed 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 initialisation 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 for 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 5–8 February 2011, the time period of the 2011 RxCADRE campaign (Ottmar *et al.* 2016), to identify weather systems (fronts, cyclones, anticyclones, low and high pressure systems, etc.) that would produce desired smoke plumes for the FASMEE field campaign. Known weather conditions in the south-east USA 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 subplume 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 south-eastern 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 Fig. 3. An animation created from a series of such frames (available online at https://youtu.be/-dsbHFogIDw, accessed 3 June 2019) has been generated in order to analyse general 3D

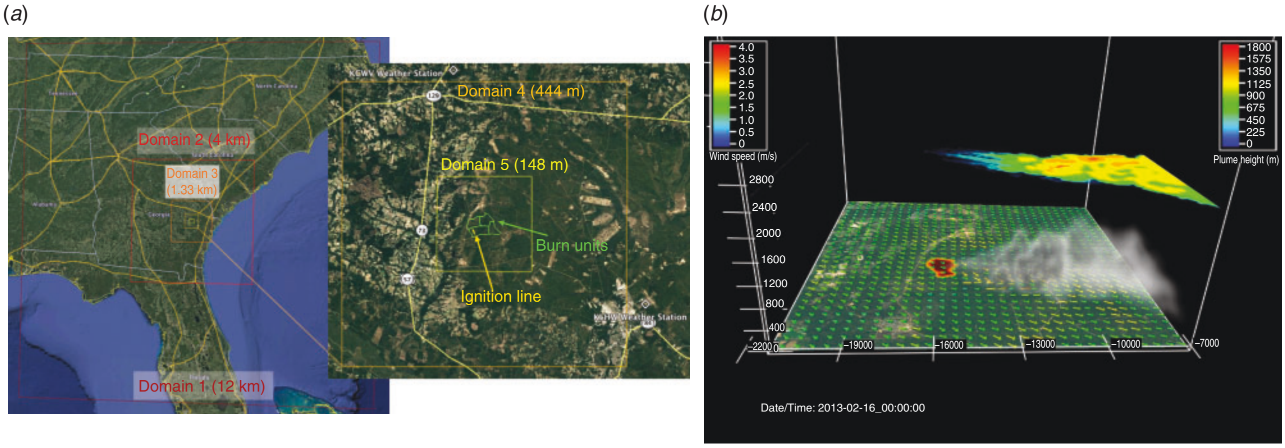


**Fig. 3.** WRF-SFIRE simulation of a prescribed burn at Fort Stewart, GA, on 15 February 2013. (*a*) Simulation domains and burn units. (*b*) Simulated smoke plume. The colour arrows represent wind speed (see left-hand colour bar) and direction. The upper level plane shows local plume heights (see right-hand colour bar).

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 $s^{-1}$ updrafts located typically between 500 and 2500 m above the ground (Fig. 4*a*). 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 $s^{-1}$, 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 characterising flow at higher elevations is recommended to provide optimal wind measurement. Evolutions of simulated vertical velocities for analysed 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 five 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 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, the 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, the smoke concentration and the plume top height up to 50 and 40% respectively, indicating the importance of comprehensive heat flux characterisation including its vertical distribution (Kochanski *et al.* 2018).

### *Model intercomparisons 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 modelling (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 ($u_0 = 5$ and 1 m $s^{-1}$) are considered, each with two atmospheric lapse rates (LR = 0, $-6$°C $km^{-1}$). Simulation results are shown in Fig. 5 ($u_0 = 5$ m $s^{-1}$) and Fig. 6 ($u_0 = 1$ m $s^{-1}$). 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 stabilisation 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 $u_0 = 1$ m $s^{-1}$ and lapse rate of $-6$°C $km^{-1}$ case (Fig. 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 submodels 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 (Fig. 5). This has important implications for the predictions of smoke at ground level and highlights the need for measurements of ambient atmospheric turbulence, which drives dispersion of

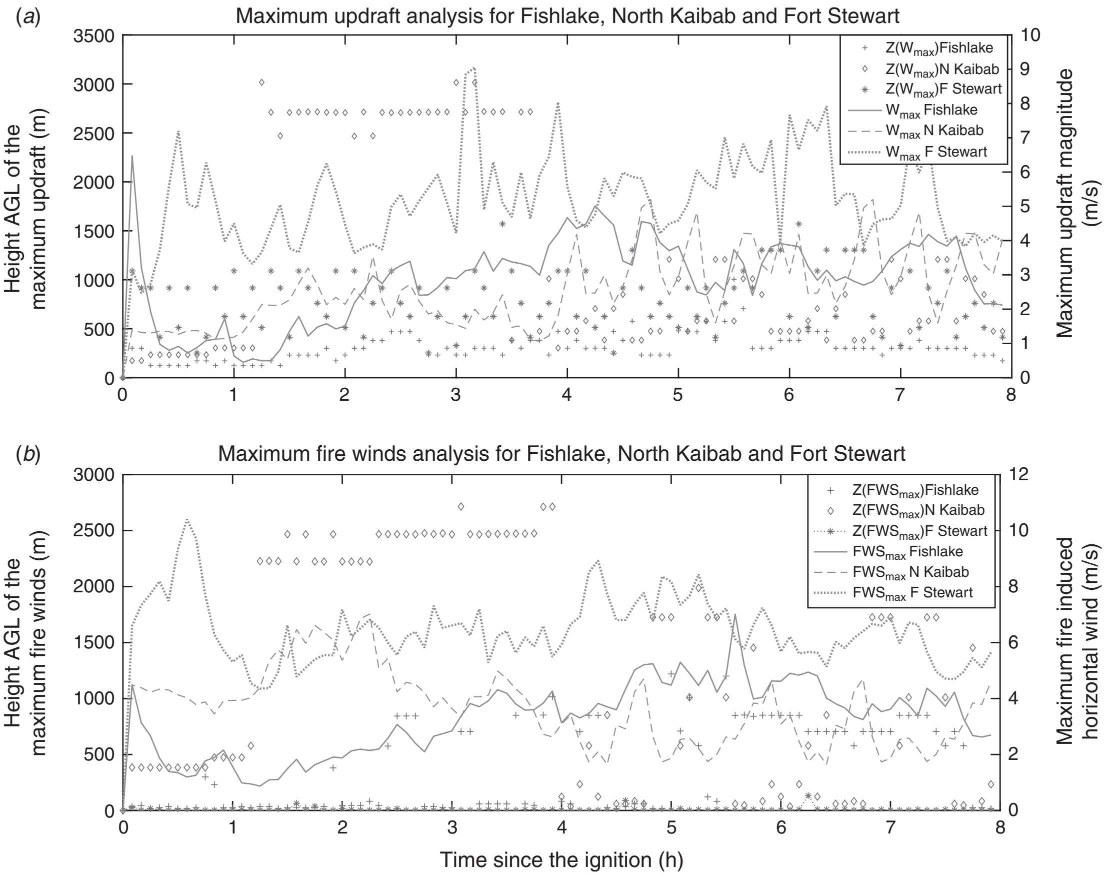


**Fig. 4.** (*a*) Time series of the heights (points) and magnitudes (lines) of the maximum updrafts. (*b*) Time series of the heights (points) and magnitudes (lines) of the maximum fire-induced horizontal winds from simulations of Fishlake, UT, North Kaibab, AZ, and Fort Stewart, GA, burns, performed for 3 September 2014, 5 September 2014 and 22 April 2014, respectively. $W_{max}$ and $FWS_{max}$ are maximum vertical velocity and maximum fire induced horizontal wind, respectively. Z is the height where $W_{max}$ or $FWS_{max}$ occurs.

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 idealised 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 (Fig. 7), but the distance to plume stabilisation 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, whereas the effect of the atmospheric stability is evident only for the $u_0 = 1$ m s$^{-1}$ 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 5–8 February 2011. The results (not shown here) indicate that the smoke plume is not fully developed, with a low plume height on 5 February under a shallow cyclonic system and a front that lead to warm, moist and windy conditions during daytime. However, smoke drainage and fog are formed during night-time burning. Smoke plumes with clear boundaries appear on both 6 and 7 February with cool but dry and calm conditions during a transition between two low-pressure systems. The plume rises higher on the second day mainly owing to lighter winds. Smoke on 8 February 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 subplumes. Note that the burned area of each updraft decreases with increasing subplume number. The simulated vertical profiles (Fig. 8) show large dependence on subplume number. Plume rise generally decreases with

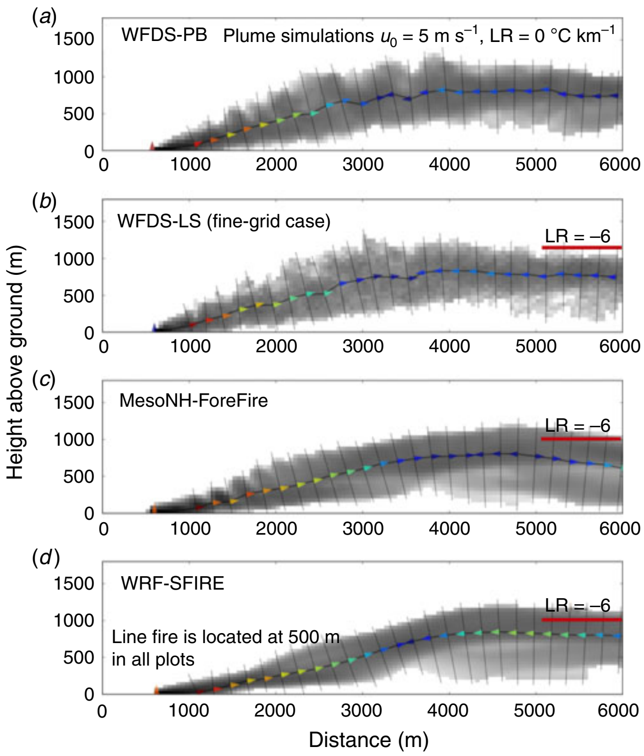


**Fig. 5.** Simulated smoke plumes at time $t = 1000$ s after ignition of the stationary line fire. $u_0$ (m s$^{-1}$) and LR (°C km$^{-1}$) are the wind speed constant and lapse rate respectively (see Supplement A). (*a*) WFDS-PB with the combustion processes directly modelled. (*b–d*) Three other models without explicitly model combustion. LR = 0°C km$^{-1}$ for the shaded plumes; the thick magenta line on the right-hand-side shows the plume centre height at distance of 6000 m for the case of LR = –6°C km$^{-1}$. Shading shows the smoke plume with the degree of darkness increasing with smoke concentration.

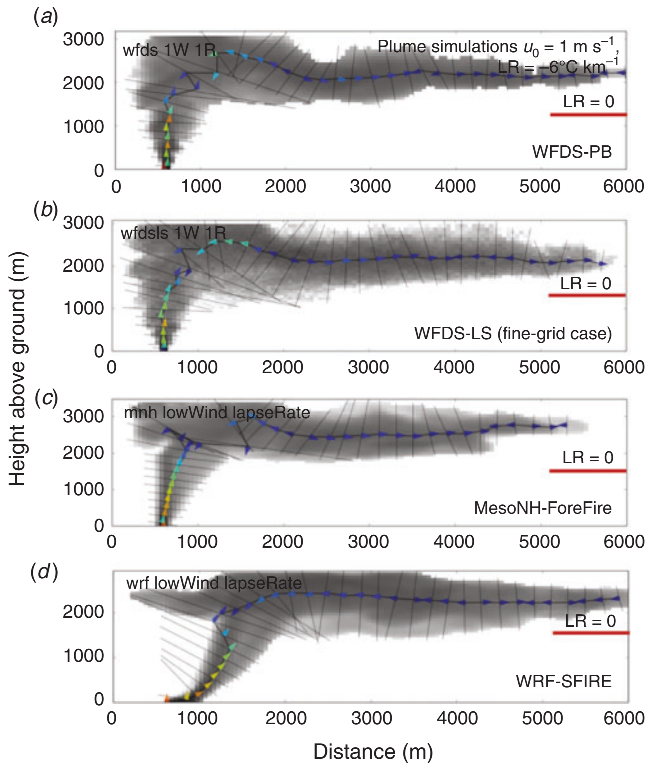


**Fig. 6.** Simulated smoke plumes at time $t = 1000$ s after ignition of the stationary line fire. $u_0$ (m s$^{-1}$) and LR (°C km$^{-1}$) are wind speed constant and lapse rate. Note that unlike Fig. 5, in this figure the shading, centerline and convective flux are for an LR of –6°C km$^{-1}$, not 0°C km$^{-1}$; the thick magenta line shows the height of the plume centerline for LR = 0°C km$^{-1}$. The shading is smoke plume with darkness degree increasing with smoke concentration.

increasing subplume number for the first 3 days. The sensitivity analysis result (not shown) indicates the importance of the multiple subplume property, which is one of the two most important parameters with thermal stability. Each parameter contributes to approximately one-third of total variance. The third important parameter is entrainment coefficient, which contributes ~16% of total variance.

## *Night-time drainage and fog*

The PB-P simulation of the prescribed burn conducted on 18 October 2016 in the Kaibab National Forest, AZ, produces a super-fog event associated with smoke (the yellow dots) during the smouldering phase (Fig. 9). The simulated drainage or slope flows become well established after midnight. Smoke particles are oriented towards the south–south-west at 0300 local standard time (LST), the hour when an 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 south-eastern sites but also at the dry western sites.

## *Seasonal variability in photochemical $O_3$ production*

The CMAQ-BlueSky simulations of hypothetical burns at Fort Stewart, GA, on 18 and 22 March 2013 are shown in Fig. 10*a* and *b*. Southerly winds blow the smoke plume north with an $O_3$ mixing ratio exceeding 10 ppb in the plume centerline 3 h after ignition on 18th, and stagnant winds on 22nd allow precursor build-up and $O_3$ production in immediate proximity of the burn unit 6 h after ignition. The annual 2013 modelling 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 modelling photochemically produced pollutants like $O_3$.

## *Dependence on grid spacing*

Fig. 10 shows CMAQ-BlueSky modelled 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 (Manning Creek) burn unit of Fishlake National Forest, UT, 4 h after ignition. Smoke plumes are similar for both, with $O_3$ concentration changes greater than 5 ppb and $PM_{2.5}$ concentrations exceeding 20 μg m$^{-3}$. Further, $O_3$ inhibition is modelled at the location of each of these fires with a transition to

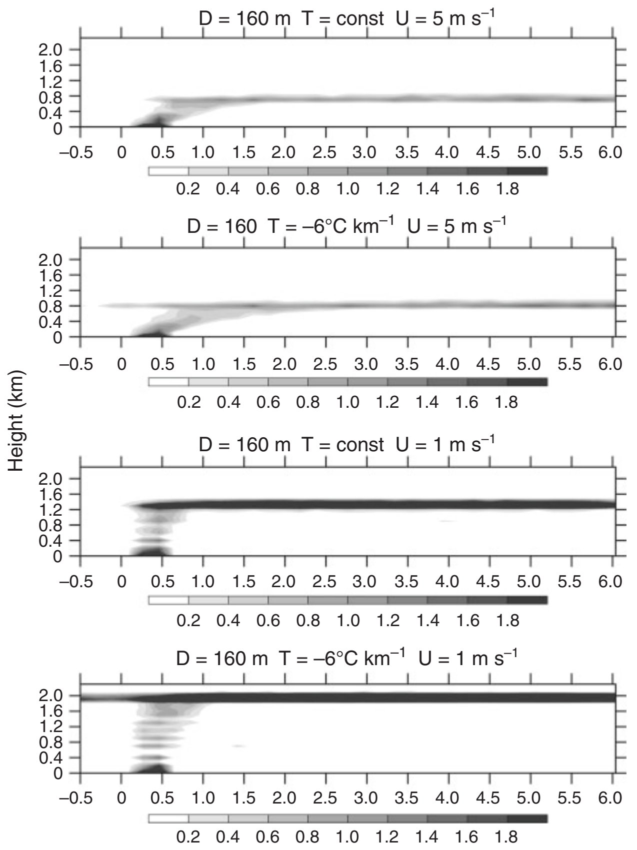


**Fig. 7.** Smoke plume (unit: particle number per grid cell) at time $t = 1000$ s after ignition of the stationary line fire simulated with Daysmoke. D, T, and U are effective diameter (m), wind speed (m s$^{-1}$) and lapse rate (°C km$^{-1}$). The horizontal is distance from fire (km).

$O_3$ production at both the Stewart, GA, and Fishlake, UT, prescribed burns when steady winds are present. Predicted $PM_{2.5}$ concentrations in the plume centreline 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 make use of this information with confidence.

## Issues for model improvement

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

### *Fire behaviour 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 behaviour 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–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 plumes. The dynamical structure is an important factor for the formation of separate smoke subplumes. 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, and spatial patterns and temporal variations of heat release rate, burned area and burn duration. The lateral fire progression is particularly affected by atmospheric turbulence. In the models such as WRF-SFIRE, the flank rate of spread is parameterised using local wind perturbations normal to the flank and the Rothermel formula (Rothermel 1972) for head-fire rate of spread. Characterisation 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 trapped in the PBL, but can have long-range effects 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.

#### *Subplumes*

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

#### *Smouldering combustion and night-time smoke*

Fire emission factors strongly depend on combustion mode (Surawski *et al.* 2015). The smouldering 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 of the burning stage.

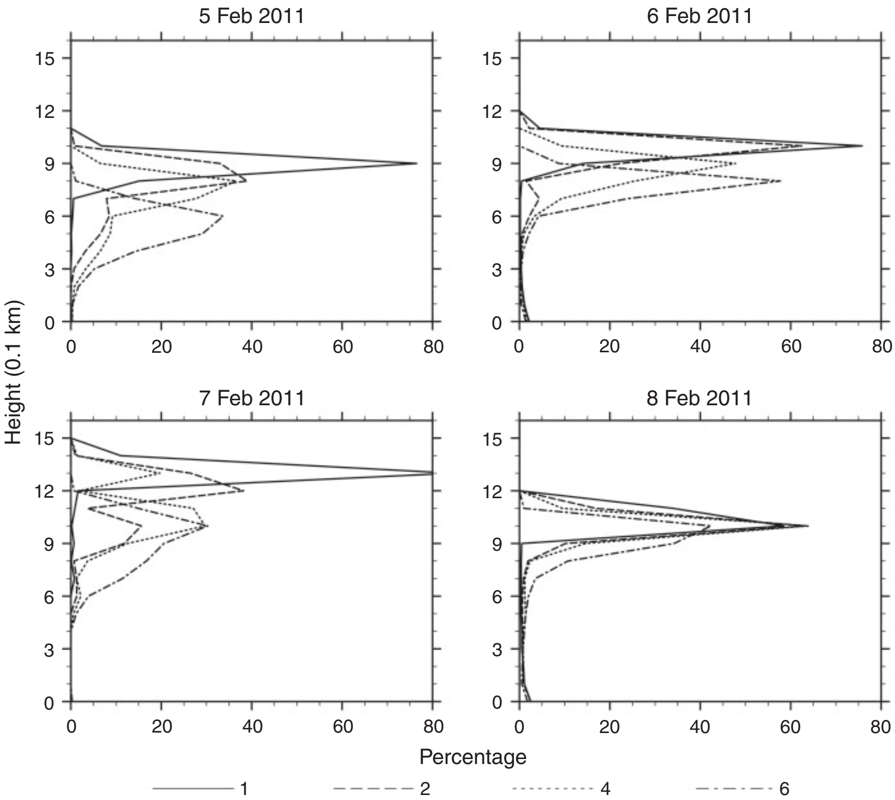


**Fig. 8.** Vertical smoke plume profiles of hypothetical prescribed burns at Fort Stewart, GA, during 5–8 February 2011 simulated with Daysmoke. The values are normalised by dividing the total particle number of all vertical layers.

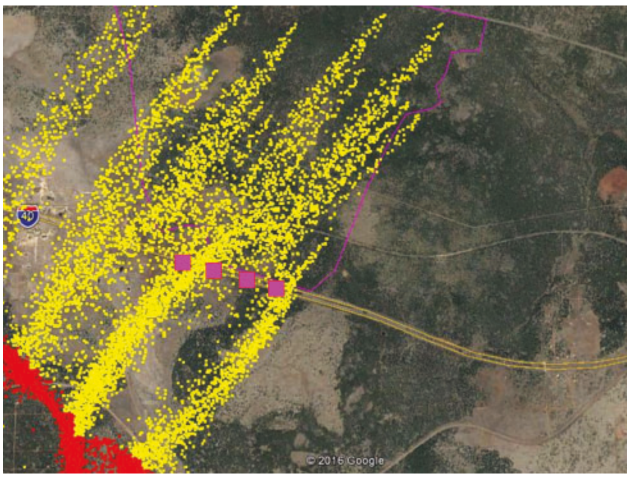


**Fig. 9.** PB-P simulated smoke from smouldering combustion at 0700 LST, 19 October 2016, near the Grand Canyon, AZ. The yellow and red dots are smoke particles and fog. The parallel double lines and purple squares are I-40.

During night, with smoke coming mainly from smouldering 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 US southeast (Achtemeier 2009) but not for the complex terrain of the US 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 behaviour is also needed. The impacts of vegetation and wind changes on fire behaviour along the fire perimeter for an established, well-behaved, freely evolving fire have been investigated (Forestry Canada Fire Danger Group (FCFDG) 1992; Cruz *et al.* 2015), 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 pyroconvection 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.

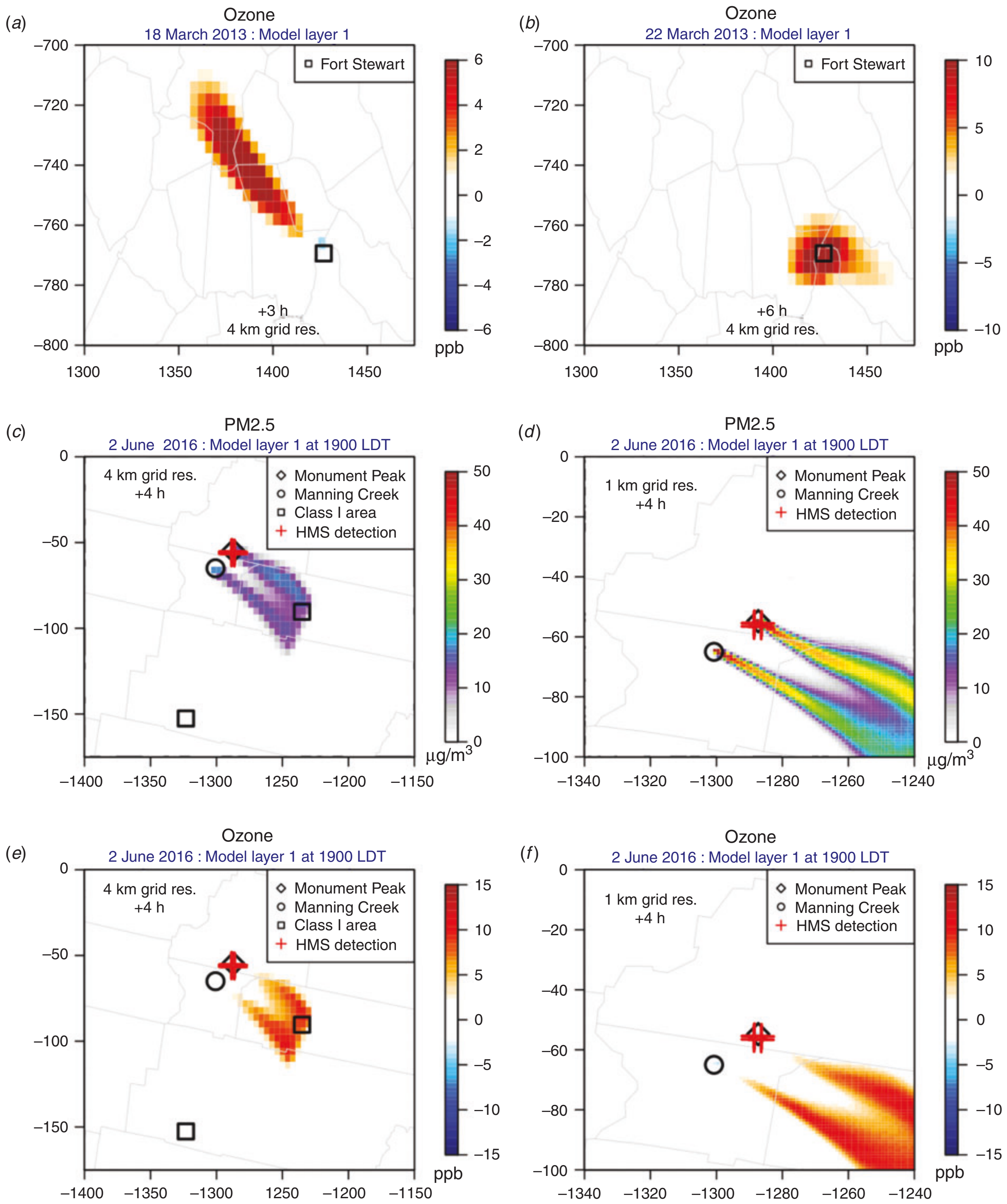


**Fig. 10.** CMAQ-BlueSky estimated $O_3$ (ppb) on (*a*) 18 March and (*b*) 22 March 2013 for a hypothetical 868 acre (approximately 350 ha) prescribed fire at Fort Stewart, GA. Model predicted $PM_{2.5}$ (*c*, *d*, $\mu g\ m^{-3}$) and $O_3$ (*e*, *f*, ppb) are shown for an actual and planned burn unit at Fishlake NF, UT, on 2 June 2016, 4 h after ignition at both 4- 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. LDT is local daylight time.

### *Smoke–atmosphere interactions*

The entrainment rate of the ambient air into the smoke plume depends on plume and atmospheric conditions and varies in space and time. Owing to the lack of measurements, understanding and the numerical schemes of the complex thermal and dynamical processes on smoke plume boundaries, some smoke

**Table 3. Issues and gaps for fire and smoke model improvement**

| Field | Process | Issues and gaps |
|---|---|---|
| Fire behaviour and energy | Heat release | Need to measure 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 subplumes |
| | Fire spread | Parameterisation of lateral fire progression may underestimate the lateral fire spread, burnt area and total buoyancy of the fire plume |
| Smoke and meteorology | Plume distribution | Plume top heights are often provided with large uncertainty, and without the vertical concentration profiles that are generally specified rather than being resolved based on fire dynamics and local weather conditions |
| | Multiple subplumes | No routine measurements are available; some modelling tools are in early development stage; parameterisation schemes are needed |
| | Smouldering combustion and night smoke | Bulk emission factors not dependent on the burning stage; night-time smoke drainage modelling has many assumptions; not evaluated for burned sites with complex topography |
| | Fire–atmosphere interactions | Need measurements at commensurate spatial and temporal scales to predict and validate interactions between vegetation, wind fire behaviour and plume dynamics; coupled fire–atmosphere models and air quality models |
| | Smoke–air interactions | Improve entrainment estimates; better characterise smoke optical properties; understand the impacts of pyrocumulus on vertical smoke distribution and fire behaviour |
| Emissions and chemistry | Pollutants with distance and time | Lack of near-event and downwind measurements of $O_3$, $PM_{2.5}$, their precursors and important chemical intermediate species |
| | PM and gas speciation | Particulate matter, volatile organic carbon and nitrogen gas speciation not very well understood for different fuel types and combustion conditions |

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 characterised in photochemical models. Smoke can reduce radiation and temperature below the smoke layer owing to scattering and absorption of solar radiation by smoke particles. This feedback is not included in most modelling studies. Therefore, photochemistry is likely overstated near large events, consequently affecting the modelling of $O_3$ and secondary PM formation processes. Dynamics of pyroconvections 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 owing to various complex physical and chemical processes inside smoke plumes such as photochemical reactions. Measurements of $O_3$, $PM_{2.5}$, their precursors and important chemical intermediate species are needed near the burn site 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 modelling based on fire emissions. Measurements are needed for improving PM, VOC and $NO_x$ speciation of fire emissions and for a better understanding of appropriate speciation for modelling fires at different scales. Currently, speciation of VOC and nitrogen oxide 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 behaviour and smoke modelling are summarised in Table 4. Observations of fuels and fire behaviour are needed to drive, evaluate and improve the models. The ambient and local meteorology is needed to initialise and provide forcing for the atmospheric component of the models and parameterise 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. 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 behaviour models and evaluate fire spread components of coupled fire–atmosphere models. Char fraction and moisture fraction need to be known to implement the burner method, and these depend on fuel type and condition.

**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 and longitude, elevation, slope | Inputs of fire behaviour and smoke modelling |
| | Consumption | Rate, amount, smouldering or flaming stage | Estimate fire emissions |
| | Spatial heterogeneity | Pre- and post-fuel stands | Fire behaviour and consumption |
| Fire behaviour and energy | Ignition | Pattern, start time, duration, time and space dependence; burned area | Inputs of fire behaviour and smoke modelling |
| | Fire spread | Fireline location, shape, depth, time and space evolution; lateral fire progression | Evaluation of fire behaviour modelling; 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 and develop parameterisations of the fire-induced heat flux and multiple subplume number |
| Smoke and meteorology | Atmospheric conditions | 3D temperature, winds, moisture, pressure, precipitation | Inputs of fire and smoke modelling, model evaluation |
| | Fluxes, turbulence and convection | Fire exit vertical velocity and temperature; sensible, latent and radiative fluxes; atmospheric turbulence; planetary boundary layer height; Entrainment rate; pyrocumulus (height, cloud condensation nuclei) | Evaluate fire models; inputs and evaluation of smoke modelling; assess and improve fire–air interaction modelling |
| | Plume structure | Vertical profile and rise; multiple subplume number, location, time change, merging process | Model validation and improvement of fire gas and aerosol chemical evolution in local and remote areas |
| | Night-time smoke | Smouldering stage emissions; local wind, temperature, humidity, and air pressure. | Inputs of smoke drainage and fog formation modelling |
| Emissions and chemistry | Fire emissions | Particulate matter, $O_3$, CO, $CO_2$, $CH_4$, volatile organic carbon 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; oxidised nitrogen gases, photolysis rates | Smoke modelling evaluation; understand factors and dynamics of multiple subplumes and develop model parameterisation |
| | Near-event and down-wind measurements | Particulate matter, CO, $CO_2$ and VOC near fire and downwind | Inputs and evaluation of smoke modelling |
| | Plume optical properties | Light scattering and 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 |

#### *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 introduce 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 model 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 values, can help to characterise 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 prefire 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 behaviour and energy*

#### *Ignition procedure*

Where prescribed fire is to be modelled, as in the FASMEE burns, the ignition procedure has to be carefully characterised owing to its strong impact on the initial fire behaviour 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 pyroconvection. 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 parameterisation 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 pyrocumulus, and coupled 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 subplumes are an important smoke feature that affects fire heat transfer and smoke plume rise. Measurements of the number, location and size of multiple subplumes and their variations with time are needed to run smoke models and to develop schemes to estimate the subplume parameters.

#### *Night-time smoke movement*

The measurements of emissions from the smouldering stage, smoke drainage and fog formation, together with local wind, temperature, humidity and air pressure, are needed to run and evaluate night-time smoke drainage and super-fog modelling.

### *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 smouldering 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 smouldering) classified by modified combustion efficiency or combustion temperature. Speciation of VOC and nitrogen oxide gases for different combustion conditions is poorly characterised, 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 modelling capability for the radiative effects of smoke aerosols in principle, but they need an integrated dataset for evaluation. Currently, smoke optical properties are poorly characterised for some pollutants in these models, which may result in potentially overstated photochemistry near large events that affects $O_3$ 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 (Figs 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 for WRF-CHEM-SFIRE, WFDS and Daysmoke. Burn season and fire size are important for CMAQ.

### *Fuel types*

A range of fuel types and burn areas typical for the US south-east 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 modelling 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, and plantation-established longleaf and slash pine forests at the Fort Stewart sites.

**Table 5. Desired burn conditions**

| Field | Property | Condition | Benefit |
|---|---|---|---|
| Fuels | Distribution | Uniform fuel close to one of the standard fuel behaviour models | Simplified fuel descriptions with Rothermel fire spread model |
| | Scales | Spatial scales on the order of the expected fire depth | To run dynamical fire models such as Fire Dynamics Simulator (WFDS) |
| | Types | A range of fuel types and burn areas typical for the Fire and Smoke Model Evaluation Experiment (FASMEE) sites | To represent both small- and large-scale wildland fire in smoke modelling 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 on fire behaviour; formation of subplumes |
| | Intensity | Intense enough to ensure a clear fire signature in the measurement data | Evaluation of fire behaviour modelling; improving fire–vegetation–air interaction |
| | Season | Non-growing season (low to medium intensity in SE), summer (medium to high intensity in W) | Estimates of PM and $O_3$ impacts can be evaluated |
| | Stage | Include a smouldering stage with measurements of fire emissions and weather | Night-time smoke drainage and possible formation of super-fog |

### 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 behaviour 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 characterised 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 south-eastern 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 behaviour 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 the fire progression and plume evolution over a period of 6 h, the experimental burn plots should be at least 250 acres (approximately 100 ha) in size. To capture the diurnal cycle of plume evolution, the burn should be extended to at least 12 h, which would imply desired size of burn plots of 500 acres (approximately 200 ha) or more.

### Ignition procedure

Aerial ignition by a helicopter is planned. In the south-western sites, a simplified ignition is planned 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 behaviour 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 $m^{-1}$ in the south-east and highly intensive burning to generate heat flux of over 1000k W $m^{-1}$ in the south-west are desired.

### Night-time and smouldering combustion

Night-time smoke drainage and the formation of super-fog are typically a result of smouldering. The burns should include a smouldering stage.

In summary, the fuel, fire and meteorological conditions suggested for a manager to identify suitable days for prescribed burning and to prepare 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 as follows: a plot of at least 250 acres (approximately 100 ha) in the south-east and 500 acres (approximately 200 ha) in the south-west; spatially uniform fuels with high fuel loading and moisture content low enough to generate heat flux of at least 500k W $m^{-1}$ for moderate-intensity fire in the south-east and over 1000k W $m^{-1}$ for high-intensity fire in the south-west; aerial ignition to produce a simple fireline burning for longer than 6 h to generate a stable plume; and wind speed of 1 m $s^{-1}$ or only slightly higher for a fully developed plume.

## Conclusions

Simulations and experiments of hypothetical prescribed burns with a suite of fire behaviour and smoke models have identified some major modelling issues that need to be understood for model improvement: (1) current smoke models are unlikely to receive the needed dynamical and high-resolution fire behaviour information for smoke modelling and forecast of large burns. (2) Improved capability in modelling high-resolution and dynamical fire energy and smoke plumes is needed. (3) Multiple subplumes 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 characterised.

Next-generation SRF systems with improved capability in fire behaviour and smoke modelling 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 subplumes, 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 behaviour and energy, smoke and meteorology, and emission and chemistry. The modelling efforts reviewed in this paper support the planning and design of field campaigns by identifying the critical measurement data needs and desired burn conditions as summarised in Tables 4 and 5.

## Conflict of interest

All authors do not have conflicts of interest.

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