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Fire and Smoke Model Evaluation Experiment (FASMEE): Modeling Gaps and Data Needs

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Introduction

Fire and smoke models are numerical tools for simulating fire behavior, smoke dynamics, and air quality impacts of wildland fires. Fire models are developed based on the fundamental chemistry and physics of combustion and fire spread or statistical analysis of experimental data (Sullivan 2009). They provide information on fire spread and fuel consumption for safe and efficient prescribed (Rx) burning and wildfire suppression. They also provide inputs of heat release and emissions for smoke modeling. A large number of fire models such as BehavePlus, FIRETEC, NEXUS, FARSITE, and WFDS have been developed in the recent two decades.

Smoke models are based on atmospheric transport and dispersion theory and chemical mechanisms or statistical relationships. They provide concentrations of fire emitted gases and particles and their spatial patterns and temporal evolutions for fire management and impact assessment (air quality, human and ecosystem health, visibility and traffic, etc.). Various types (box, Gaussian, puff, particle, Eulerian, full physics) of smoke models are available, including VSMOKE, SASEM, CalPuff, HYSPLIT, Daysmoke, and CMAQ (Goodrick et al. 2012). Comprehensive operational smoke prediction systems such as BlueSky (Larkin et al. 2010) are developed based on smoke models together with fuel, burn and emission tools.

The capacity of current operational smoke prediction systems is limited due to complex plume structure. Plume rise is a key outcome that determines the relative impacts on local and regional air quality. Early smoke models estimated this property using the Briggs scheme (Briggs 1975) developed for power plant stacks. Recent smoke models modify this scheme or have developed new schemes for fire applications, but evaluations have been made mainly against wildfires. The vertical plume profiles are specified in most smoke modeling, or simulated often with large errors in determining overall plume structures and the level of highest species and particulate concentrations. The presence of multiple plume updrafts makes the horizontal plume structure inhomogeneous and more complex. There are no regular measurements, nor reliable methods for estimating the number of cores. In addition, models often have low skills in reproducing the features of tilting and eddy plume structure under strong background wind and turbulence.

There are also significant gaps in modeling smoke dynamics (Goodrick et al. 2012). While the fundamental science governing atmospheric transport and dispersion is fairly well-established, particularly for non-buoyant emissions, currently the evolution of strongly buoyant plumes is poorly described in most smoke models. Some dynamical fire behavior models are able to produce high-resolution and time varying spatial distribution of heat release across the landscape, which links the fire-source to the atmosphere and is an acknowledged integral component of modelling smoke dispersion and transport, but they are largely decoupled with advanced smoke models for predicting the dynamical effect on plume development. Also, forest vegetation can have significant effects on boundary- and surface-layer structure by altering the distribution of turbulent kinetic energy and turbulent heat and momentum fluxes that, in turn, affect the local and within-canopy transport and diffusion of smoke from wildland fires, particularly low-intensity surface fires. These interactions are yet to be included in most smoke models.

There is an urgent need for developing the next-generation of operational smoke prediction systems for fire and smoke management. Such systems would address the above described smoke plume structure and dynamics issues, especially the coupling among dynamical fire behavior and smoke plume, as well as interactions with atmospheric and canopy processes. Efforts have been made in developing coupled fire and smoke models such as WRF-SFIRE-Chem and WFDS. Another essential effort involves conducting comprehensive field measurements of individual fields of fuels, fire and emission, smoke, meteorology, and atmospheric chemistry for evaluating the existing fire and smoke models, providing observational evidence and data for developing new capacity in modeling interactions and feedbacks of the coupled systems.

The Fire and Smoke Model Evaluation Experiment (FASMEE) (Ottmar et al. 2016) is a comprehensive and coordinated field campaign to create a dataset that will result in an improved understanding and prediction of wildland fire generated smoke to support better land and fire management. FASMEE is aimed specifically at both modeling systems in use today as well as the next generation of modeling systems expected to become operationally useful in the next 5 to 10 years. Modeling has been done to support planning and design of field campaign (FASMEE Phase I). This paper describes the FASMEE modeling efforts.

Methodology

The modeling efforts were implemented through (Figure 1): identifying issues and gaps with some specific fire and smoke models, identifying data needs for filling the gaps, conducting pre-burn simulations to illustrate the anticipated smoke plumes from the field campaigns and examine the sensitivity to varied burning circumstance, and proposing approaches to apply the collected data to evaluate and improve fire and smoke modeling which is expected to lead to the development of the next-generation of operational smoke prediction systems.

Several fire and smoke models, including WRF-SFIRE (Mandel et al. 2011, 2014), WFDS (Mell et al. 2007, 2009, Mueller et al. 2014), FIRETEC (Linn et al. 2002, 2005; Pimont et al. 2011), Daysmoke (Achtemeier, 1998; Achtemeier et al., 2011), PB-Piedmont (PB-P; Achtemeier, 2005), and CMAQ (Byun and Schere 2006), were involved in these efforts. General capability and often used space and time scales with these models are summarized in Table 1.

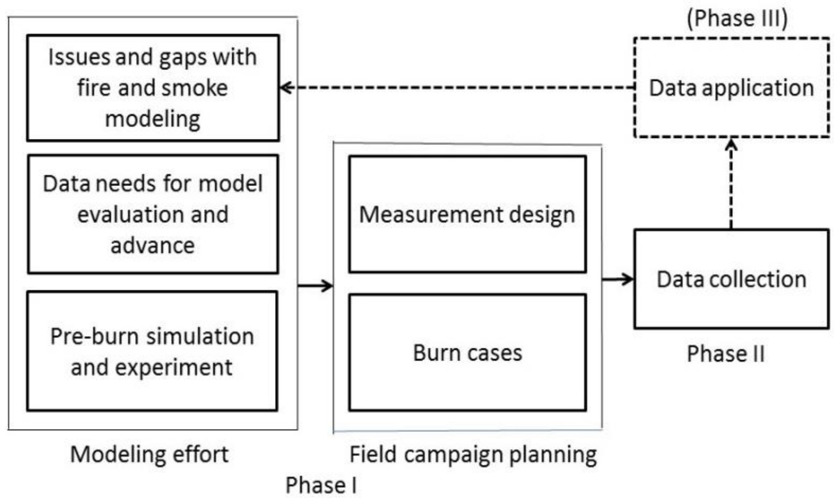

Figure 1 The modeling efforts with FASMEE.

WRF-SFIRE is a coupled fire-atmosphere model for fire and smoke modeling at varied scales from landscape to regional. It is developed based on Weather Research and Forecasting model (WRF; Skamarock et al. 2008) and the Rothermel (1972) fire-spread model implemented using a level set method (that is, specifying the fire spread rate based on known topography, vegetation, and meteorology properties) to evolve the fire front on an Eulerian grid in time (e.g., Mallet et al. 2009). WRF-SFIRE is designed to simulate the landscape-scale physics of the coupled fire-atmosphere phenomenon, and focuses on the importance of rapidly changing meteorological conditions at the fire line, taking into account local feedbacks between the fire, fuel, terrain and the evolving atmospheric boundary layer. WRF-SFIRE is capable of simulating large-scale high-intensity fires, under various topographical, meteorological, and vegetation conditions (Kochanski et al. 2013a and b, Kochanski et al. 2015). WRF-SFIRE resolves basic fire-atmosphere feedbacks, pyro-convection, and plume rise without relying on an external plume parameterization. WRF-SFIRE was recently coupled (Kochanski et al. 2015) with WRF-CHEM (Grell et al. 2011) so that fire progression is simulated along with fire emissions and chemistry.

WFDS-PB and FIRETEC are physics-based fire models for landscape-scale high-resolution modeling. They use a finite-volume, large eddy simulation approach to model turbulence, where the 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 of these 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, and bulk density) of the thermally-thin vegetation components of the overall fuel complex. There are differences in solution techniques and parameterizations between FIRETEC and WFDS (Morvan 2011, Hoffman et al. 2016). WFDS-LS (Bova et al. 2016) is implemented using a level set method to propagate the fire line and simulate smoke dynamics. Because both FIRETEC and the WFDS-PB explicitly model the aspects of the combustion processes they need, for a given fire, they utilize much fine computational grids (i.e., small grid cells) and therefore are computationally expensive.

Daysmoke and PB-Piedmont are local-scale models for day-time smoke dynamics and night-time smoke drainage, respectively. Daysmoke consists of four sub-models: an entraining turret model, a detraining particle model, a large eddy parameterization for the mixed boundary layer, and a relative emissions model that describes the emission history of the prescribed burn. Daysmoke was developed specially for prescribed burning and has been extensively applied and evaluated in simulating smoke dispersion from Rx fires in the Southeast (Liu et al., 2009). Daysmoke includes algorithms to simulate the role of multiple updraft cores, an important smoke property for plume rise and air quality impact simulation (Liu et al., 2010). PB-P is a very high-resolution meteorological and smoke model designed for simulating near-ground smoke transport at night over complex terrain. PB-Piedmont runs at resolutions on the order of 30-90 meters to capture terrain features driving the development of local drainage flows.

CMAQ is an Eulerian model that contains a comprehensive and state-of-the-science treatment of important gas (Sarwar et al. 2011), aqueous (Sarwar et al. 2013), and aerosol phase chemistry (Fountoukis and Nenes 2007, Carlton et al. 2010, Koo et al. 2014). WRF is applied to generate the necessary meteorology that is used as input to the Sparse Matrix Operator Kernel Emissions (SMOKE) model (https://www.cmascenter.org/smoke/) and CMAQ-SMOKE processes wildland fire emissions generated using the BlueSky framework (Larkin et al. 2010) which integrates fuels and consumption based on the CONSUME model to generate emissions, and then converts daily fire emissions to hour of the day to provide more detailed VOC, NO_X, and primary $PM_{2.5}$ speciation. Smoke plume rise algorithms use heat flux estimates to vertically allocate smoldering and flaming emissions into the 3D grid structure. CMAQ has been applied at local (~1 to 4 km sized grid cells) to continental (12 km sized grid cells) scale and evaluated extensively against measurements (Baker et al. 2016, Baker et al. 2015, Baker et al. 2013, Kelly et al. 2014). It is extensively used for retrospective modeling assessments, operational forecasting, and assessing near-field and regional scale reactive pollutant impacts from specific wildland fire events (Baker et al. 2016) and wildland fire impacts in aggregate (Fann et al. 2013).

Table 1 Major model properties

Model	Capacity	Scale
WRF-SFIRE	Level set fireline; Atmospheric physics and chemistry, smoke transport and gaseous products; WRF's nesting.	Regional and local; Domain of km or larger; Fire mesh of tens of m.
WFDS and FIRETEC	Emphasis on capturing the fire behavior; Relatively near-field smoke plume rise and downwind transport; Simple atmospheric physics included.	Local; Domain of about 1 km; larger for WFDS-LS; Grid of m, FIRETEC; cm ~m, WFDS-PB; m or larger WFDS-LS
Daysmoke and PB-P	Developed specially for Rx burning smoke; Computationally fast with simple physics; Topography-air interaction for night smoke (PB-P).	Local; Domain of 5 km (Daysmoke) and 1 km (PB-P); Grid cell of 100 m and 20 m.
CMAQ-BlueSky	3D Eulerian photochemical transport; Gas, aerosol, and aqueous phase chemistry; Focus on air quality (especially particulates and ozone).	Regional; Domain up to 1000s of km; Grid cell of 4~12 km (1 km for some fine scale applications).

Results

Modeling issues and gaps

Major modeling issues and gaps are summarized in Table 2 with details provided below.

Heat release — Heat released from fires is a fundamental mechanism for fire-smoke-atmosphere interactions. The heat release per unit area (HRRPUA) along the fire perimeter and location of the fire perimeter is a measure of how quickly heat is introduced into the atmosphere and requires sufficiently accurate predictions of the spatial distribution and time history of mass loss rates and subsequent turbulent mixing and combustion. Measurements of fire depth, spread rate, and total mass consumption during flaming along the fire line can be used to determine a first-order measure of HRRPUA, while a single point measurement can be very misleading since fire lines are generally not uniform. Furthermore, surface heat is vertically distributed over the first few layers in some fire-atmospheric coupled models such as WRF-SFIRE, but the parameterization needs to be assessed. Also, fire heat varies in both space and time. The dynamical structure is an important factor for the formation of separate smoke updrafts. Measurements of this structure together with smoke dynamics are needed to understand the relations between fire energy and smoke plume.

Fire spread — Fire spread is an important process determining fuel consumption, spatial patterns and temporal variations of heat release, and burned area and duration. One of the fire spread properties, lateral fire progression, impacts atmospheric turbulence on the lateral fire movement, which advance the fire even under conditions of zero mean wind speed in direction normal to the fire. Fire progression in some models such as WRF-SFIRE with simple fire component is a sub-grid scale process, parameterized using the Rothermel formula for head-fire rate of spread. For winds at an angle to the fire flanks, propagation is computed using the wind speed component normal to the fireline, which may underestimate the lateral fire spread and burnt area.

Smoke vertical profile — Plume rise and smoke vertical distribution are important factors for partitioning between local and regional air quality impacts of smoke. More smoke particles in the lower levels mean more severe local impact, while more smoke particles in the upper levels mean a larger chance to affect clouds. Smoke plume models have focused on refining mechanisms of plume rise in recent years, but paid less attention to characterizing smoke vertical profiles.

Multiple updrafts — Observations of plumes from large-perimeter prescribed fires reveal the presence of sub-plumes (or multiple updraft cores). Multiple updrafts, being smaller in diameter than a single core updraft plume, would be more impacted by entrainment and thus would be expected to grow to lower altitudes. Smoke profile is very sensitive to updraft core number. The number of multiple updraft cores usually is not measured for Rx burns. Observational and modeling evidence is needed to understand the roles of sub-plumes.

Smoldering and night-time smoke — The smoldering stage of a Rx burn could produce extra $PM_{2.5}$ and CO. Currently, many smoke models use bulk emission factors not dependent on the burning stage. Furthermore, burning processes and the atmospheric conditions are different during night with smoke coming mainly from smoldering combustion under stable thermal stratification and calm winds. Under such conditions 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 Southeast but not for the terrain of the west.

Table 2 Modeling issues and gaps

Issue	Gap
Heat release	Need measurements of unit heat release 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 plume updrafts.
Fire spread	Parameterization of lateral fire progression may underestimate the lateral fire spread and burnt area.
Plume distribution	Plume rise is provided with large uncertainty; Vertical profiles are mostly specified.
Multiple plume updrafts	No routine measurements are available; Some modeling tools are in early development stage; Parameterization schemes are needed.
Smoldering 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.
Pollutants with space 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.
Fire-atmosphere interactions	Need measurements of all at commensurate spatial and temporal scales to predict and validate the impacts of vegetation and wind on fire behavior; Effectively represent plume across the scales and fire behavior between fire and atmospheric 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.

Air pollutants with distance and time — Near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species are needed along with distance and time from the fire event, which will provide critical understanding of near-fire chemistry and downwind chemical evolution of these pollutants during both day and night-time hours.

PM and gas speciation — Measurements are needed for improved 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 are not very well understood, which affects significantly both primary emissions and subsequent downwind secondary chemical pollutant production.

Fire-atmosphere interactions — Better coupling approaches need to be developed to feed high-resolution heat release from fire models to smoke modeling. The feedbacks of fire-induced atmospheric disturbances to fire modeling 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 need to be understood and the related data are needed. It is important to assess how the model ability 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-air interactions — The entrainment of the ambient air into smoke plume is a major mechanism to depress smoke plume development. The entrainment rate depends on both plume and atmospheric conditions and varies in space and time. 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. Due to the lack of measurements and theoretical descriptions, some smoke models use constant empirical values. Optical properties of smoke are critically important for appropriately characterizing near-fire and downwind photochemistry so that photolysis can be correctly attenuated in the photochemical model. Currently, smoke optical properties are not well characterized in these models meaning photochemistry is likely overstated near large events, consequently impacting O_3 and secondary PM formation processes. Formation of pyrocumulus clouds has important implications for high-altitude smoke injection. Dynamics of pyro convections and their impacts on smoke plume need to be better understood and simulated.

Table 3 Priority measurement needs

Field	Property	Parameter	Purpose
Fuels and consumption	Fuel conditions	Type, load, density, 3-D structure, above and under ground	Inputs of fire behavior modeling
	Fuel moisture	1, 10, 100, 1000 hr; Live fuel moisture.	Inputs of fire and smoke modeling
	Consumption	Rate, amount, smoldering/flaming stage,	Estimate fire emissions
	Burn block	latitude/longitude, elevation, slope	Model inputs
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 core number
Meteorology and smoke	Fluxes and turbulence	Fire exit vertical velocity and temperature; Sensible, latent and radiative heat fluxes; Atmospheric turbulence; PBL height	Evaluate fire models; Inputs and evaluation of smoke modeling; Assess and improve fire-air interaction modeling
	Weather	3D temperature, winds, moisture, pressure	Inputs of fire and smoke modeling
	Plume structure	Vertical profile and rise; Multiple updraft plume number, location, time change, merging process	Model validation and improvement of fire gas and aerosol chemical evolution in local and remote areas
	Smoke-air interactions	Entrainment rate; Pyro-cumulus	Inputs of smoke modeling; Improve smoke-air interaction modeling
Emissions and chemistry	Plume O_3 and PM chemical evolution	Speciated and size resolved PM, particle number and diameter and polarity; SO_2, NH_3, CH_4, VOC speciation; Oxidized nitrogen gases, photolysis rates	Smoke modeling evaluation; Understand factors and dynamics of multiple smoke plumes and develop model parameterization
	Lofted smoke 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
	Smoldering emissions	PM, CO, CO_2, and VOC near-fire and downwind; Smoke drainage; super-fog	Inputs and evaluation of smoke modeling; Night 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

Measurement needs for model improvements

The priority measurements needed by fire and smoke modeling are summarized in Table 3. For each of the measurement fields (fuels and combustion, fire behavior and energy, meteorology and smoke, and emissions and chemistry), several properties and related parameters as well as their roles in fire and smoke modeling are identified. In general, 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, 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. Of most importance for plume chemistry are gas and aerosol species relevant for O_3 or $PM_{2.5}$ formation. 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.

Pre-burn simulations

Pre-burn simulations are ongoing (some examples are given below) to illustrate anticipated fire smoke plumes behavior of the planned FASMEE Rx burns, the ways to apply the data from previous field campaign and future FASMEE measurements, and model conduct comparisons.

Simulations with WRF-SFIRE for the Fort Stewart and Fishlake burn sites have 5 nested domains with the atmospheric resolutions of 36km, 12km, 4km, 1.33km, 444m, and 148m, 41 vertical levels, fire mesh ~30m, LANFIRE fuel data at 30m resolution, and 30m elevation data. The simulations at Ft. Stewart (Figure 2) display the high-resolution 3D fire and smoke structures and dynamical evolutions, which show what smoke plumes could be expected for the planned FASMEE burns at this site. Other potential simulations include running a larger ensemble of simulations for varied moisture, fuel load, ignition pattern and atmospheric conditions to assess expected variance in temperature, wind speed, moisture and smoke concentration at potential tower locations to estimate the part of the variance due to the individual factors and the resulting reduction of uncertainty of the model.

The simulations with WFDS are performed in a single-domain idealized mode with a stationary heat source and simplified meteorological forcing (single profile). This scenario would allow for an inter comparison between all the fire/smoke models, as well as a basic assessment of model uncertainties. Also, the burner method, that is, the fire heat and mass fluxes are prescribed based on the field measurements (to be described in more details below), is used to provide smoke models with sufficient information to simulate plume without having to simulate fire behavior.

Besides the FASMEE sites, Daysmoke and PB-P models also simulate the burn cases at Eglin, FL during the RxCADRE field campaign, an effort to bridge between historical and future field measurement data. In addition, sensitivity simulations are conducted with varied parameter values to understand the impacts of model and measurement uncertainty on smoke simulations. Figure 4 shows a PB-P simulation of smoke from an Rx burn in the Kaibab NF of northern Arizona on October 19, 2016. It was reported that the smoke, reduced visibility down to about 20 feet and closed part of I-40, which might be related to numerous accidents. The simulated smoke passes across I-40. The air was cool and unusually humid resulting in a superfog potential index (SPI) of 8 of 10 meaning a high risk for superfog the night after the burn.

One of the purposes of the CMAQ pre-burn simulations is to evaluate the impacts of Rx burns on tropospheric O_3, an important contributor to smog, which is one of the major concerns for Rx burning during Southeast growth season. CMAQ - BlueSky simulated $PM_{2.5}$ and O_3 from a recent historical Rx fire at Fishlake NF using multiple grid resolution configurations and the burn unit being held for FASMEE at Fishlake NF using the June 2-3, 2016 conditions. Simulations conducted for Fort Stewart, GA for each day of a previous year (2013) to understand season variability in photochemical production (Figure 5) show the spatial distribution of the ground O_3 concentration on an early spring day. That modeling 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 smoke impacts. In addition, it is planned to replicate all of the prescribed burns done as part of FASMEE phase 2.

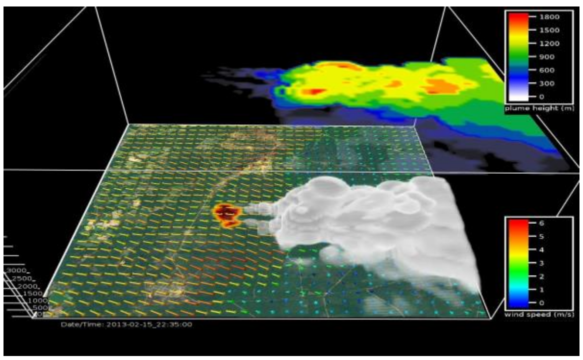

Figure 2 WRF-SFIRE simulation of a prescribed burn at Ft. Stewart on February 15 2013. The color arrows represent wind speed (see bottom color bar) and direction. The upper level plane shows local plume heights (see upper color bar).

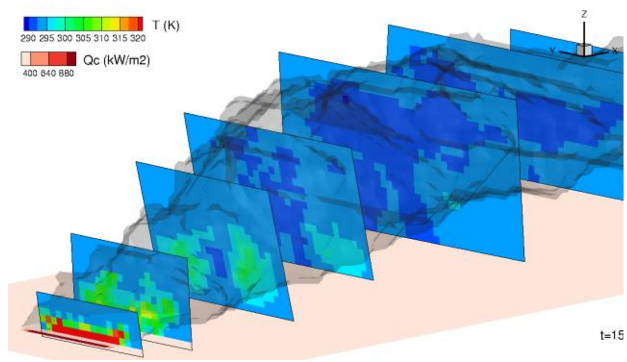

Figure 3 Simulations with WFDS of an idealized stationary test burn (burner). A line source is used and cross sectional planes are shown; the planes are orthogonal to the centerline plume motion at each point downwind. The domain is 6 km x 4 km x 2 km.

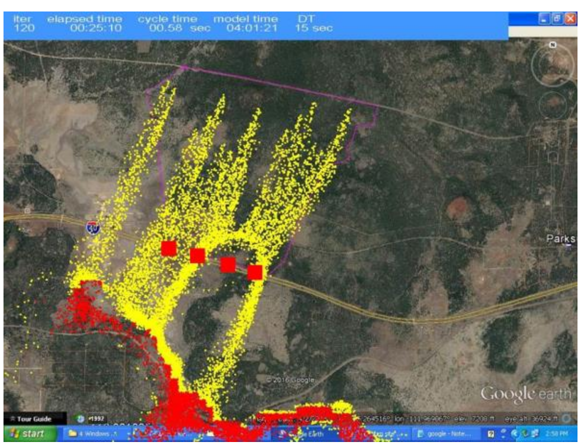

Figure 4 PB-P simulation of night-time smoke particle (yellow) and fog formation (red) for the prescribed burn in the Kaibab National Forest on October 19, 2016.

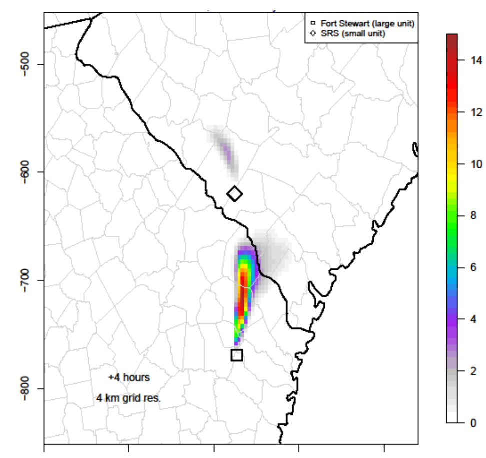

Figure 5 CMAQ-Bluesky estimated O3 (ppb) on March 18, 2013 for a hypothetical 868 acre prescribed fire at Fort Stewart.

Approaches of post-burn data applications

Some specific approaches are proposed to apply the FASMEE measurements to improve smoke modeling. Below are two examples.

Smoke plume model development using burner method — Given the challenges in both measurement and modeling, it will be advantageous to identify the measurements that will support first order smoke plume simulations. The plume rise portion of models does not necessarily require combustion to be directly modeled. Instead, the estimated heat release rate per unit area of the pool fire (i.e., a burner) is prescribed based on measurements. The major benefit of the burner method for modeling is that it provides the models that explicitly resolve plume dynamics with sufficient information to model plume rise without having to model wildland fire behavior. It also simplifies and focuses the measurements. The key FASMEE measurements for this purpose are the minimum set that allows you to infer, at all locations in the fire perimeter relevant to smoke plume formation, the time course of fire heat generation.

Multiple updraft simulation — The FASMEE data will be used to validate the assumption about the formation and development of sub-plumes. For the high resolution of fire energy measurement, its structure and dynamic variation are used to display clearly separate patterns related to ignition patterns and fuel structure. Some spatial tools such as wavelet transform are used to identify the major separate spatial systems. Thresholds of a minimum size of the separate systems at which the systems could be found to link them to individual smoke plume updrafts. This information together with measured smoke properties will be used to develop a parameterization scheme to estimate the number of multiple updraft cores using techniques such as similarity theory. Furthermore, the Rabbit Rules Model (RRM) (Achtemeier et al. 2012) is a "rules" based fire spread model to estimate multiple updraft core number. One problem with RRM is that it may produce too many small air pressure cells sometimes during the burning period, which unlikely represent actual smoke plumes. FASMEE measurements provide high-resolution fire radiative power and energy, air pressure, and smoke plumes, which will be used to obtain a cut-off scale to exclude some air pressure cells from being used to account for the number of multiple smoke updrafts.

Conclusion

Modeling efforts to support the FASMEE field campaign indicate a number of critical modeling issues and data needs to develop the next-generation of operational smoke prediction systems. This information is necessary for the design of FASMEE measurements (elements, spatial resolution, time frequency, precision, etc.), and ensures the maximum value of the measurements for smoke modeling evaluation, improvement, and new capacity development.

Current smoke models need better methods for simulating the coupling between fire behavior and smoke plume rise. This requires the coordinated measurements of high-resolution and dynamical evolution of fuel properties, fire heat release, fire spread, plume dynamics, and meteorology. Smoke plume structure in current smoke models is highly simplified, with vertical profiles specified in most models and no explicit treatment of multiple updrafts. Measurements of flame and related energy structure such as individual cells, vertical heat profile and the height of well mixing flaming gases and ambient air, smoke eddy and entrainment, and emerging of multiple updrafts are needed to improve smoke structure modeling and develop new parameterization schemes. Current speciation of fire emissions for different fuel types and combustion conditions (e.g., flaming to smoldering components of the fires) and the impacts on atmospheric chemical pollutant production during both day- and night-time are not very well understood. This requires better emissions estimates and near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species along with distance and time. The smoke-atmospheric interactions including the radiative, thermodynamic, and cloud effects of smoke particles and feedbacks to smoke and fire developments are either not or poorly described in smoke models. Measurements of characterization of smoke optical and cloud microphysical properties are needed to fill this gap.

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