

# FINAL REPORT

Title: Application of Daysmoke and PB-P Models in Phase I  
of the Fire and Smoke Model Evaluation Experiment

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<https://sites.google.com/site/forestdisturbance>

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## TABLE OF CONTENTS

Abstract.....	5
1. Objectives .....	6
2. Background.....	6
3. Methods.....	9
4. Key findings from simulations and experiments.....	13
5. Participating in study plan development.....	22
6. Conclusions.....	22
7. Deliverables .....	24
8. Other products / activities.....	24
9. Cited literatures.....	24
Appendix A Tables and figures from Daysmoke and PB-P simulations and experiments. ....	26
Appendix B Model properties, modeling issues and gaps, and measurement needs.....	30
Appendix C The FASMEE measurement needs for Daysmoke and PB-P.....	32
Appendix D Desired burn and smoke conditions for Daysmoke.....	32
Appendix E Simple plume systems.....	33
Appendix F How to estimate the number of multiple updrafts.....	34
Appendix G How complex, explicit coupled fire models can inform operational simpler fire behavior and plume models.....	35
Appendix H How resolved fuels and fire dynamics must capture critical plume structure .....	35

## List of Figures

Figure 1 Connections of the Daysmoke and PB-P modeling efforts to FASMEE field campaign planning.

Figure 2 Procedure of Daysmoke and PB-P simulations and sensitivity experiments.

Figure 3 Plume heights of Rx burns during the RxCADRA campaign. The three panels are for Blocks 703C, 608A and 704A burned on February 6, 8, and 12, 2011, respectively. The left 9 bars are simulated using Daysmoke with varied plume core numbers. The last bar is ceilometer measurement.

Figure 4 Horizontal ( $x$ , km) and vertical ( $z$ , km) intersection of smoke plume from hypothetical burns at Ft Stewart during February 5-8, 2011 (unit: particle number per grid cell) simulated with Daysmoke.

Figure 5 The PB-P simulated smoke plume in Ft Stewart at midnight on February 6 (top) and 8 (bottom), 2011. The yellow and red dots are smoke particles and fog.

Figure 6 Plume heights of hypothetical Rx burns at Ft Stewart during February 5-8, 2011 simulated with Daysmoke. The bars are plume core numbers.

Figure 7 Vertical smoke plume profiles of hypothetical Rx burns at Ft Stewart during February 5-8, 2011 simulated with Daysmoke. The green, blue, red, and gray lines are for core numbers of 1, 2, 4, and 6. The values are normalized by dividing the total particle number of all vertical layers.

Figure 8 FAST sensitivity analysis of Daysmoke. The horizontal coordinate lists the model parameters (see Table A1 for their meanings). The vertical coordinate is the ratio (%) of partial variance of a parameter to total variance.

Figure 9 Horizontal ( $x$ , km) and vertical ( $z$ , km) section of smoke plume from idealized fire line burn (unit: particle number per grid cell) simulated with Daysmoke with different temperature ( $T$ ) and wind ( $U$ ) profiles.  $D$  is effective diameter.

Figure 10 The PB-P simulated smoke plume in Eglin for Block 703C (top), 608A (middle), and 704A (bottom) on February 6, 8, and 12, 2017, respectively. The yellow and red dots are smoke particles and fog.

Figure 11 PB-P simulated smoke from smoldering combustion at 0700 LST, October 19, 2016 near Grand Canyon, AZ. The yellow and red dots are smoke particles and fog.

## List of Figures and Tables in Appendixes

Figure A1 The development of more than 3 major sub-plumes from a Rx burn in Fishlake National Forest, UT during June, 2016 (Provided by Roger Ottmar).

Figure A2 Vertical profiles of meteorological conditions at Ft Stewart simulated with Weather Research and Forecasting (WRF) model. The four panels are temperature, specific humidity, westerly wind, and southerly wind. The green, red, blue, and gray lines are February 5-8, 2011.

Figure A3 Transport of smoke from hypothetical burn at Ft Stewart on February 6, 2011 (unit: particle number) simulated with Daysmoke. The four panels are different vertical layers. Horizontal and vertical are grids in x- and y-direction with grid size of 200 m.

Figure A4 Transport of smoke from hypothetical burn at Ft Stewart on February 8, 2011 (unit: particle number per grid cell) simulated with Daysmoke. The four panels are different vertical layers. Horizontal and vertical are grids in x- and y-direction with grid size of 200 m.

Figure A5 Horizontal (x, km) and vertical (z, km) intersection of smoke plume from idealized fire line burn (unit: particle number per grid cell) simulated with Daysmoke with different effective diameters (D). T and U are temperature and wind.

Table A1 Parameters used in the FAST sensitivity analysis for Daysmoke.

Table B1: Major model properties.

Table B2: Modeling issues and gaps.

Table B3: Priority measurement needs.

## **Abstract**

This proposed study was in response to the Joint Fire Sciences FA-FON0016-0004 Fire and Smoke Model Evaluation Experiment (FASMEE) Task 5 - Modeling leads. The purpose was to evaluate Daysmoke and PB-Piedmont (PB-P) models to provide information for the FASMEE Phase 2 design. Daysmoke is a local smoke plume dispersion and transport model developed specially for prescribed burning (Rx). It is complementary to physically and chemically based regional smoke and air quality modeling tools and is able to provide some unique information such as the role of multiple updraft cores. PB-P is a very high resolution meteorological and smoke model designed for simulating near-ground smoke transport at night over complex terrain. The main objectives of this project were to conduct pre-burn simulations to provide information on model capacity, gaps and FASMEE measurement needs, and to conduct sensitivity experiment to understand the impacts of uncertainty in FASMEE experimental burns and measurements. The scientific issues for this project were the roles of multiple smoke sub-plumes in plume dynamics, smoke modeling sensitivity to uncertainty in burn conditions and model parameters, and the processes and mechanisms for formation of night smoke drainage and fog. Simulations have been conducted for historical Rx burns to evaluate Daysmoke and PB-P model performance, for hypothetical burns at FASMEE measurement sites to understand uncertainty of smoke plume development and modeling, and for idealized fire line burns to compare performance among fire and smoke models with varied physics and complexity.

The simulations and experiments indicate that Daysmoke is able to estimate plume rise of Rx burns with reasonable accuracy. Smoke behaviors dramatically change with weather patterns. Plume rise decreases remarkably with increasing number of smoke multiple cores. Plume rise simulation is very sensitive to setup of “burner” method. Night-time smoke drainage and super-fog occurred often with Rx burns. These findings suggest that the comprehensive FASMEE measurements of the related properties would be a key for improving Daysmoke and PB-P performance. The FASMEE burns should be conducted under such conditions so that the field measurements would collect simultaneous data of these properties for understanding the multiple sub-plume dynamics and evaluating and advancing the modeling tools. Weather conditions on the FASMEE experimental burn days are critical for obtaining anticipated smoke plumes for field measurements and could vary on daily basis at Ft Stewart. In addition, it is highly recommended to conduct night-time smoke measurements during FASMEE experiment in both the southeastern and the southwestern burn sites.

This project contributed to the development of the FASMEE Study Plan by providing information on model capacity, gaps, the data needs for model improvements, and desired burn and smoke conditions, and by drafting a few subsections in the Appendixes and main body. The major deliverables from this project include pre-burn modeling results, and presentation and manuscript on FASMEE modeling activity.

## 1. Objectives

The proposed objectives were:

- To conduct pre-burn simulations with Daysmoke and Planned Burn-Piedmont (PB-P) models to provide information on model capacity, gaps and FASMEE measurement needs for improving model performance.
- To understand the impacts of uncertainty in FASMEE experimental burns and measurements and modeling setting on smoke modeling through sensitivity experiments with Daysmoke and PB-P models.
- To work with the FASMEE program to vet the observational design, help develop 2017 FON, and assist in building the final Study Plan

The overall objective of the Fire and Smoke Model Evaluation Experiment (FASMEE) is to provide the observational data needed to evaluate operationally used fire and smoke modeling systems. The first phase of this project involved bringing together the scientific leadership required to develop the Study Plan for the observational campaign. Part of this scientific leadership involved modeling groups conducting pre-burn simulations to aid in developing the observational study design to ensure that the study design would capture critical data at the appropriate temporal and spatial resolution.

An additional application of models in the development of the FASMEE Study Plan was to assess potential impacts of uncertainty in prescription parameters on sampling design, particularly for downwind smoke measurements. Assessing such uncertainty would require an ensemble of model runs driven by perturbations in the prescription parameters. Such an ensemble could prove difficult for a number of models listed in the Funding Opportunity Notice (FON) due to data requirements and computational cost. In contrast, screening models such as Daysmoke and PB-P models have much lower data and computational requirements making ensemble applications much simpler.

The first two objectives have been achieved. This project also participated in the smoke model inter-comparison of idealized burn cases which was not a task of the original proposal. The scope and specific deliverables related to the third objective were modified during the project implementation in conjunction of and by direction of the Joint Fire Science Program. The modified major task was to participate in preparing appendixes on modeling in the Study Plan, which has been achieved. The original task to design, help develop 2017 FON was no longer required.

## 2. Background

Smoke models are numerical tools for simulating smoke dynamics and the air quality impacts of wildland fires. 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 the 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. 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 structures 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 issues on smoke plume structure and dynamics, 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, and providing observational 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.

This project was conducted to support planning and design of field campaign (FASMEE Phase I) by evaluating Daysmoke and PB-P models to understand their capacity, gaps and measurement needs and conducting pre-burn simulations to understand modeling uncertainty due to variability in the environmental conditions of experimental burns. The key smoke modeling questions with the models that the FASMEE measurements could provide necessary data for solutions include

**What are the roles of multiple fire cells / sub-plumes in smoke plume dynamics?**

Observations of plumes from large-perimeter prescribed (Rx) burning reveal the presence of sub-plumes (or multiple updraft cores) (Figure A1, Appendix A). These sub-plumes may vary in size depending on ignition patterns, the type, fuel type, loading and distribution, and weather conditions. Multiple sub-plumes, 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. Different approaches to implementing a burn will affect the development and structure of a smoke plume. This is an important aspect of Daysmoke's design as changes in heat flux, initial plume velocity, and number of updraft cores impacts entrainment, smoke plume vertical structure and ultimately plume rise. However, the uncertainty with this property limits the capacity and accuracy of Daysmoke simulation. The number of multiple updraft cores usually is not measured for Rx burns. In the past most Daysmoke simulations used a user specified number. Recent efforts linking Daysmoke to a simple rule driven fire spread model have yielded a consistent means of dynamically linking the number of cores to the spatial distribution of fire across the landscape (Achteimeier et al. 2012). Also, most smoke plume models, including Daysmoke, have focused on plume rise in recent years, which is one of the major smoke properties needed for regional air quality models such as CMAQ, but paid less attention to the question of what are typical patterns of smoke vertical profiles and the roles of ambient factors and mechanisms.

**What are smoke modeling sensitivity to uncertainty in determining burn conditions and model parameters?**

Accurately describing atmospheric conditions is critical for reliably predicting the transport of smoke. For example, smoke plume rise is strongly determined by transport wind, atmospheric stability, and the height of planetary boundary layer (PBL); however, these are also items that we rarely ever know accurately. There is always a level of uncertainty. Understanding how this uncertainty can propagate through the modeling process and potentially alter the study design is important.

**What are the processes and mechanisms for formation of smoke drainage and fog during night time?**



Burning processes and atmospheric conditions are different between day and night time. It is often that flaming lasts for a while after ignition during day time and then turns to smoldering into night time. The atmosphere is more likely convective and windy during day time, but inverse temperature layer develops with calm wind during night time. So topography becomes a major factor for smoke movement during night time. It is not very clear, especially under complex topography, about the processes and mechanisms during night time for the formation and distribution of smoke drainage and resultant fog, which can affect local visibility and traffic. PB-P model describes smoke movement under these conditions subject to the assumption of smoke being confined to a shallow layer with uniform meteorological conditions. While PB-P has been extensively evaluated for conditions in the Appalachian piedmont, it has not been as thoroughly tested for the terrain of the west.

The first phase of FASMEE would develop a study plan for an observational campaign focused on collecting the data needed to evaluate and improve fire and smoke models. Study design will be guided by modeling for defining data requirements and evaluating the spatial sampling plan. Developing the spatial sampling plan requires accounting for uncertainty. The spatial sampling plan needs to meet the spatial data requirements outlined by the modeling groups but must also be constrained by resource availability such that sampling resources are not wasted outside of the plume impact area.

The unique features of Daysmoke and PB-P make sensitivity analyses feasible and relatively easy, allowing for the simulation of a wide range of scenarios for FASMEE's planned burns. An additional advantage of Daysmoke/PB-P for evaluating potential burn scenarios is that they are run at higher resolutions than most other smoke dispersion models providing a more detailed description of the plume during the plume rise process. While Daysmoke/PB-P are not as physically detailed as say WRF-SFire/Chem, the ability to produce ensemble predictions for various scenarios provides value over a smaller collection of deterministic runs.

### **3. Methods**

#### **3.1 Modeling efforts and FASMEE**

The modeling efforts of Daysmoke and PB-P simulations and experiments are connected to the FASMEE measurements through the following steps (Figure 1):

- Simulations and experiments were first conducted with selected fire and smoke models for hypothetical burns at the future FASMEE burn sites.
- The findings from the simulations and experiments, combined with what have been learned from applications of these models in the past, were used to understand modeling issues and gaps.

- The measurement data needs for model improvement and the desired burn conditions that would create the smoke plumes to be simulated were then provided. This would help design and plan of data measurements and burn implementation.
- The approaches were proposed to apply the collected data to evaluate and improve smoke modeling which is expected to contribute to the development of the next-generation of operational smoke prediction systems.

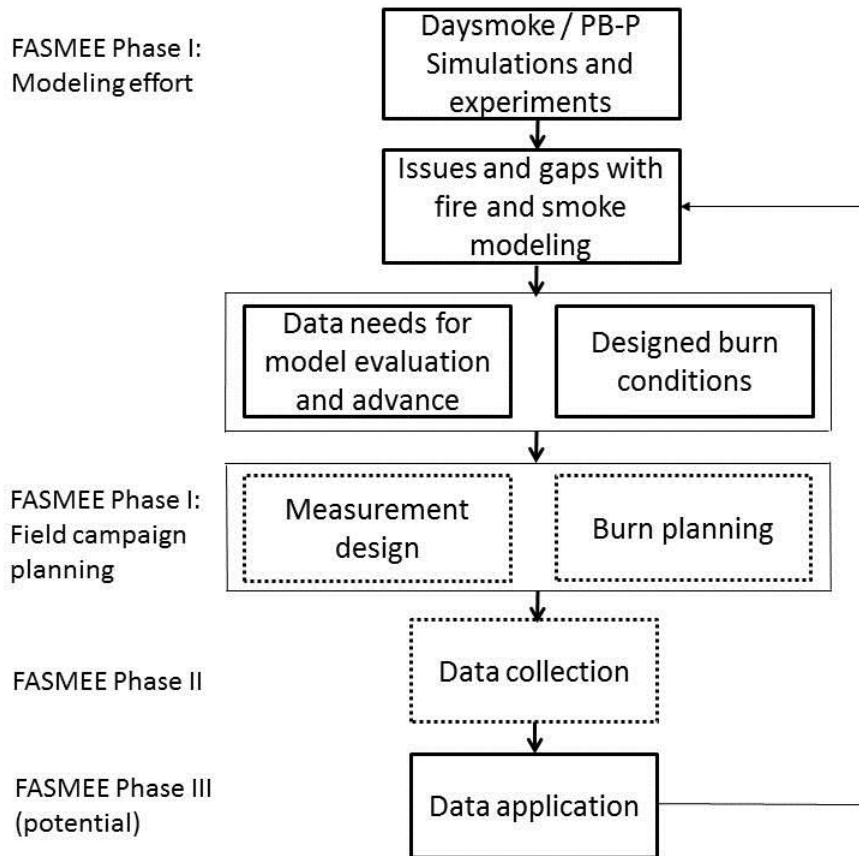


Figure 1 Connections of the Daysmoke and PB-P modeling efforts to FASMEE field campaign planning.

### 3.2 Models

Daysmoke (Achtemeier 1998, Achtemeier et al. 2011) is a local smoke plume dispersion and transport model for simulating three-dimensional distributions and temporal variations of smoke particles with some unique features. First, Daysmoke was developed specially for Rx burning and has been extensively applied and evaluated in simulating smoke dispersion from Rx in the Southeast (Liu et al., 2009). Secondly, Daysmoke has relatively simple physics and no chemistry and thus needs much less computation resources in comparison with complex and interactive dynamical smoke models. Thirdly, Daysmoke includes algorithms to simulate the role of some special smoke properties and processes such as multiple plumes.

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 Rx burn. The entraining turret model handles the convective lift phase of plume development and represents the updraft within a buoyant plume. This updraft is not constrained to remain within the mixed layer. A burn in Daysmoke may have multiple, simultaneous updrafts cores. In comparison with single-core updrafts, multiple-core updrafts are smaller in updraft velocities and diameter, more affected by entrainment, and therefore less efficient in the vertical transport of smoke.

PB-P (Achteemeier 2005) 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. As with 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.

### 3.3 Simulations

The Daysmoke and PB-P simulation and experiments were performed following the procedure displayed in Figure 2. Three types of simulations were conducted:

a. **Bridging with previous datasets** Daysmoke and PB-P models simulated the historical burn cases at Eglin, FL during the RxCADRE field campaign in early February, 2017. The Blocks were 703C, 608A and 704A burned on 6<sup>th</sup>, 8<sup>th</sup>, and 12<sup>th</sup>, respectively. This effort was to bridge between historical and future field measurement data. PB-P also simulated an actual Rx burn near the Kaibab National Forest and the Great Canyon, Arizona. The simulations were used to evaluate model performance and uncertainty.

b. **Simulating ground burn cases** Daysmoke and PB-P models simulated hypothetical burns during the same period of early February 2011 at Ft Stewart, GA (Block 3), one of the future FASMEE burn sites.

c. **Comparing with other models using “Burner” method** “Burner” approach was proposed by JFSP project 16-4-05-1 (FIRETEC and WFDS Modeling of Fire Behavior and Smoke in Support of FASMEE) to apply the field measurements for smoke modeling. Fire behavior and smoke dynamics (heat release, exit velocity and temperature, etc.) are specified as model inputs. Daysmoke simulations were conducted for idealized fire line burn cases using this approach. The effective plume diameter in Daysmoke, the diameter a plume would have if emissions from an irregular-shaped burning area were spread over a circular area, was specified with a base value of 160 m converted from the “burning” block of 750m × 25m (18750 m<sup>2</sup>).

Fuel conditions were specified based on field measurements. Meteorological conditions were from WRF, RAWS, and / or weather Metadata.

### 3.4 Sensitivity experiments

Sensitivity experiments were conducted with Daysmoke and PB-P models to understand the impacts of field measurement uncertainty on smoke plume rise simulation. Two types of sensitivity technique were applied. One technique called “change and response” method obtains different model outputs in response to changes in a single parameter or a certain type of parameters. This gives a quantitative estimate to the dependence of the simulated property on the parameter(s). Daysmoke and PB-P simulations were conducted for four hypothetical burns Ft Stewart. A cold front system moved through the burn site during the simulation period, bringing different weather conditions. Thus, the results could be used to evaluate smoke plume dependence on weather conditions. Furthermore, various core numbers of smoke plumes were used to understand the uncertainty of smoke plume modeling to the sub-plume property.

The other technique called Fourier Amplitude Sensitivity Test (FAST) (Liu et al. 2010) obtains different model outputs in response to changes in a group of parameters. This technique is often used to identify the most important parameters for the model. Fifteen parameters in Daysmoke were selected for the FAST analysis (Table A1).  $C_e$ , which is used in ETM as entrainment coefficient, measures how intense the ambient air interacts with the plume. Seven parameters in DPM,  $C_p$ ,  $C_u$ ,  $C_w$ ,  $K_x$ ,  $K_z$ ,  $W_c$  and  $w^*$ , determine the fallout processes of smoke particles from the plume. One parameter in LED,  $W_r$ , measures the impact of large eddies on smoke plumes. Three out of four parameters in REM,  $W_0$ ,  $dT$ , and  $D_f$ , were computed based on burning information. Initial plume vertical velocity and temperature anomaly measure the intensity of a burn. Diameter of flaming area measures total released energy. Another one, number of updraft cores,  $N_c$ , was specified. Two ambient parameters are thermal lapse rate  $T_z$  and background wind speed  $V$ .

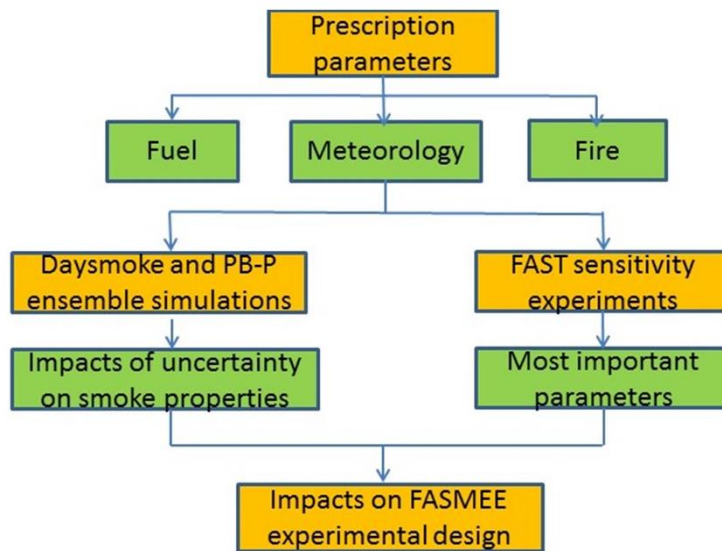


Figure 2 Procedure of Daysmoke and PB-P simulations and sensitivity experiments.

#### 4. Key findings from simulations and experiments

##### a. Daysmoke is able to estimate plume rise of Rx burns at reasonable accuracy

The simulated plume rise values of the 703C burn were higher at about 1250 m for core numbers 1-4, decreasing to about 1150 m for core numbers 6 and 8, and further decreasing to about 1000 m for core numbers 10, 12, and 14. The observed height was lower at about 970 m. The maximum bias was about 280 m, occurring with the low core numbers. The bias decreased with increasing core number. Similar core number dependence was found for the 608A burn. The plume rise values were lower, ranging between about 950-1150 m. The observed plume rise was nearly 900 m. The maximum bias was comparable to that for 703C burn. It was much different for the 704A burn where there were no consistent changes of the simulated plume rise, and the simulation underestimates the measured value.

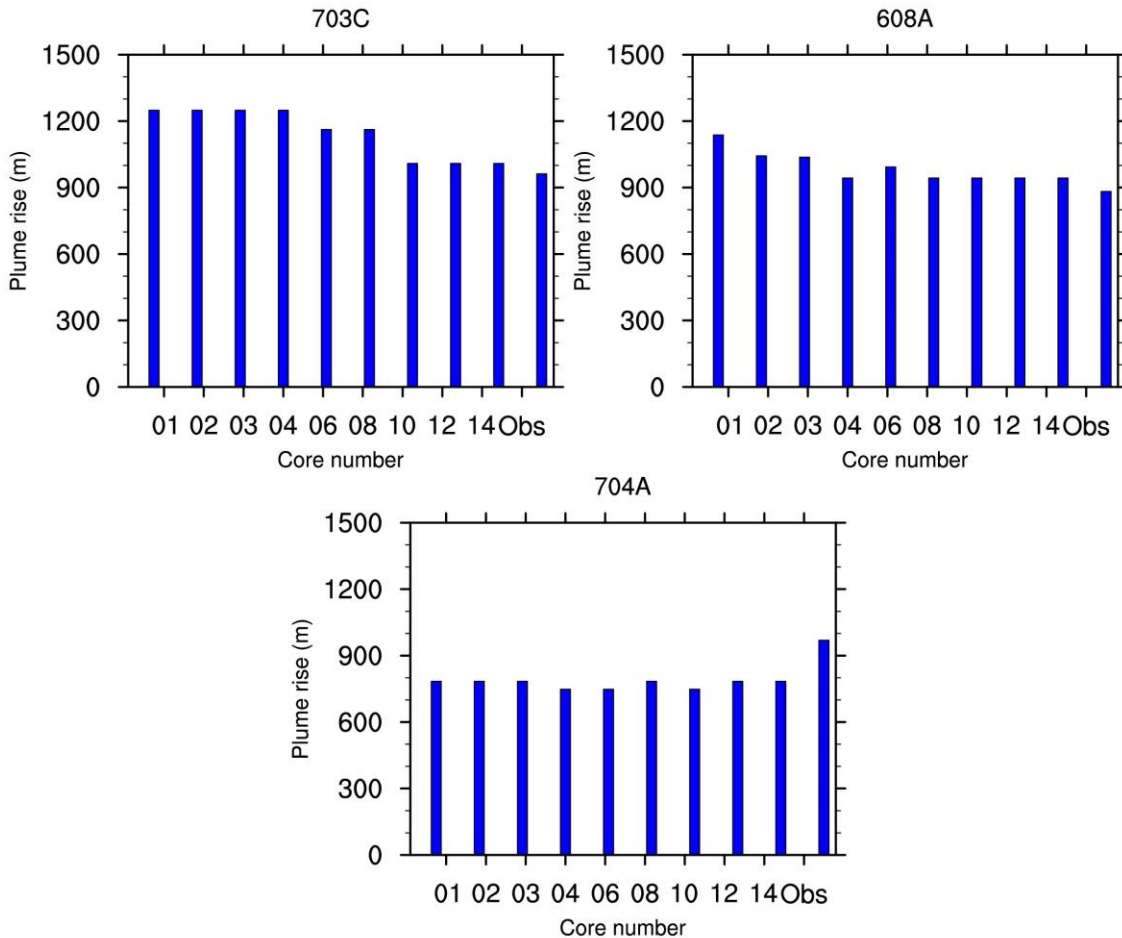


Figure 3 Plume heights of Rx burns during the RxCADRE campaign. The three panels are for Blocks 703C, 608A and 704A burned on February 6, 8, and 12, 2011, respectively. The left 9 bars are simulated using Daysmoke with varied plume core numbers. The last bar is ceilometer measurement.

## b. Smoke behaviors dramatically change at daily basis depending weather patterns

A front moved through Ft Stewart during February 5-8, 2011. The weather patterns changed from warm and moist to cold and dry (Figure A2). Winds blew from the west for the entire period of the simulation. Strong southwesterly wind prevailed on Feb 5. Wind speed became much weaker next two days, and increased again with northwesterly wind last day. The wind shift leads to changes in the direction of smoke transport, from eastward over a narrow belt area on February 6, to southeastward diversely on February 8 (Figures A3 and A4). Smoke plume height simulated with Daysmoke varied daily (Figure 4), increasing from about 700m on February 5 to about 900 m on February 6, and further to 1400 m on February 7. It then decreased to about 1000 m on February 8.

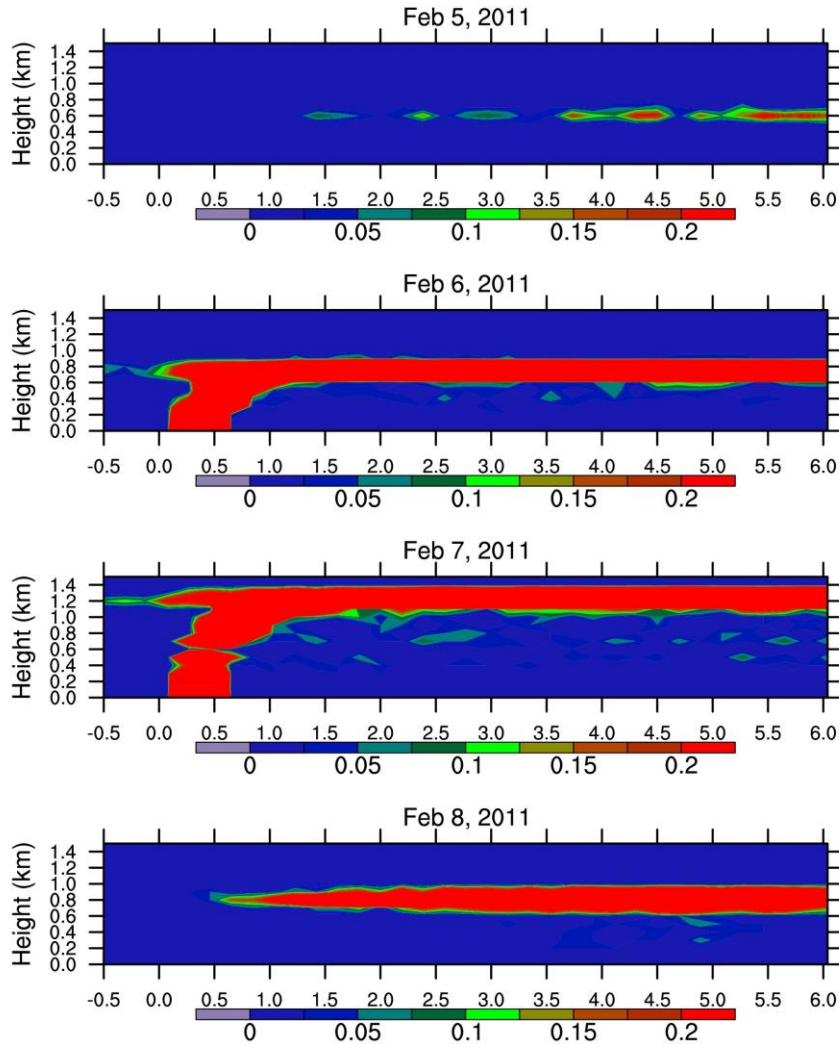


Figure 4 Horizontal (x, km) and vertical (z, km) section of smoke plume from hypothetical burns at Ft Stewart during February 5-8, 2011 (unit: particle number per grid cell) simulated with Daysmoke.

The night-time simulations of burns in Ft Stewart with PB-P have identified possible conditions of collocation of smoke and fog after midnight of the first burn day (Figure 5, top), which were lifted before dawn. Relative humidity was below the model threshold to warn of the potential of a smoke/fog mixture. However, there was no indication of fog and plume capture by local drainages in the third night (Figure 5, bottom), when the atmosphere turned to dry after the cold front passage.

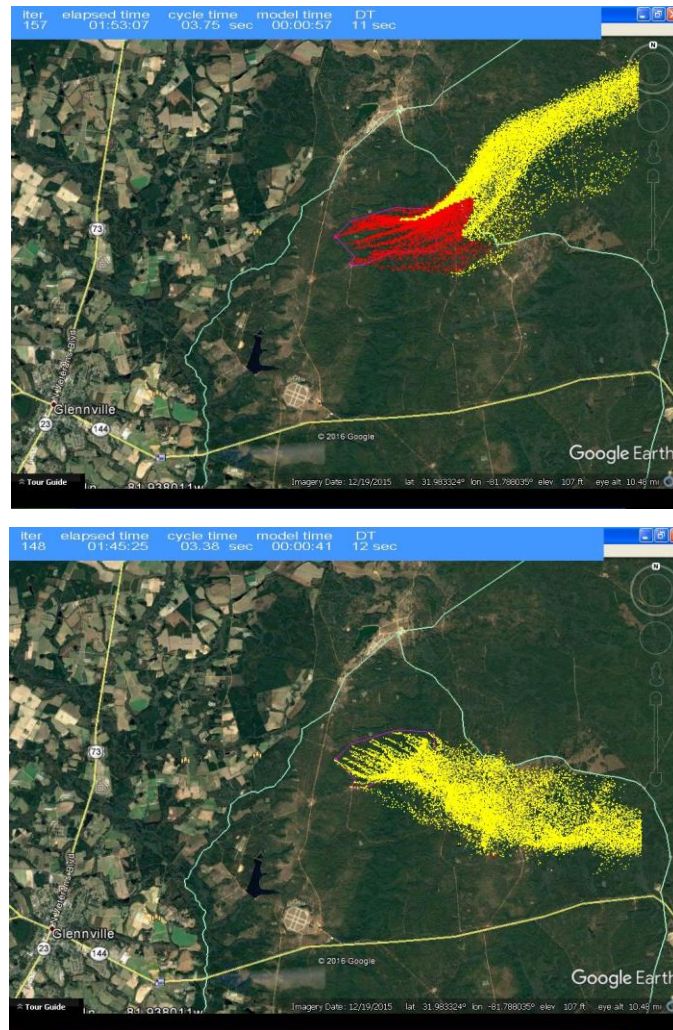


Figure 5 The PB-P simulated smoke plume in Ft Stewart at midnight on February 6 (top) and 8 (bottom), 2011. The yellow and red dots are smoke particles and fog.

**c. Plume rise decreases remarkably with increasing number of smoke multiple cores**

The simulated plume rise (Figure 6) and vertical profiles (Figure 7) for the burn at Ft Stewart show two types of dependence on plume core number. Plume rise and the layer of peak particle number generally decreased with increasing core number for the first three days, similar to the 703C and 608A cases in Eglin (Figure 3). However, they changed little with core number for the last day, similar to the 704A case in Eglin.

The FAST results (Figure 8) also indicate the importance of the multiple core property, which is one of the two most important parameters. The other is thermal stability. Each parameter contributes to about one third of total variance. The third important parameter is entrainment coefficient contributing to about 16%.

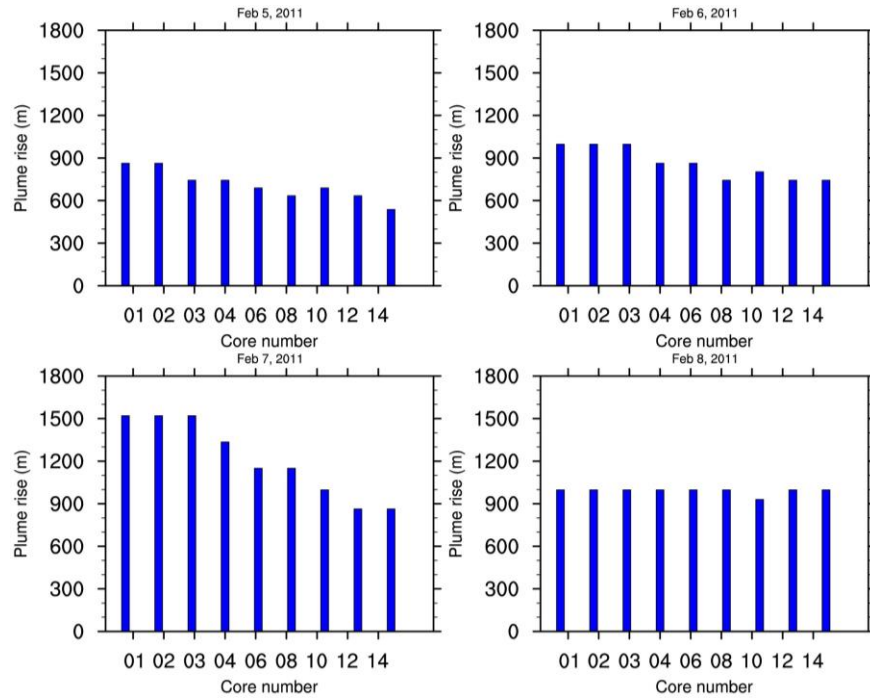


Figure 6 Plume heights of hypothetical Rx burns at Ft Stewart during February 5-8, 2011 simulated with Daysmoke. The bars are plume core numbers.



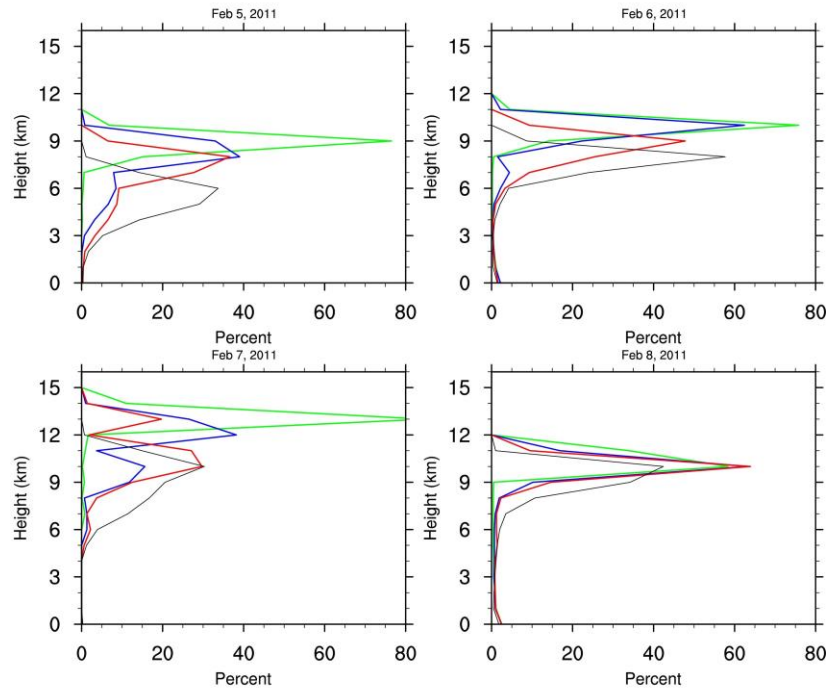


Figure 7 Vertical smoke plume profiles of hypothetical Rx burns at Ft Stewart during February 5-8, 2011 simulated with Daysmoke. The green, blue, red, and gray lines are for core numbers of 1, 2, 4, and 6. The values are normalized by dividing the total particle number of all vertical layers.

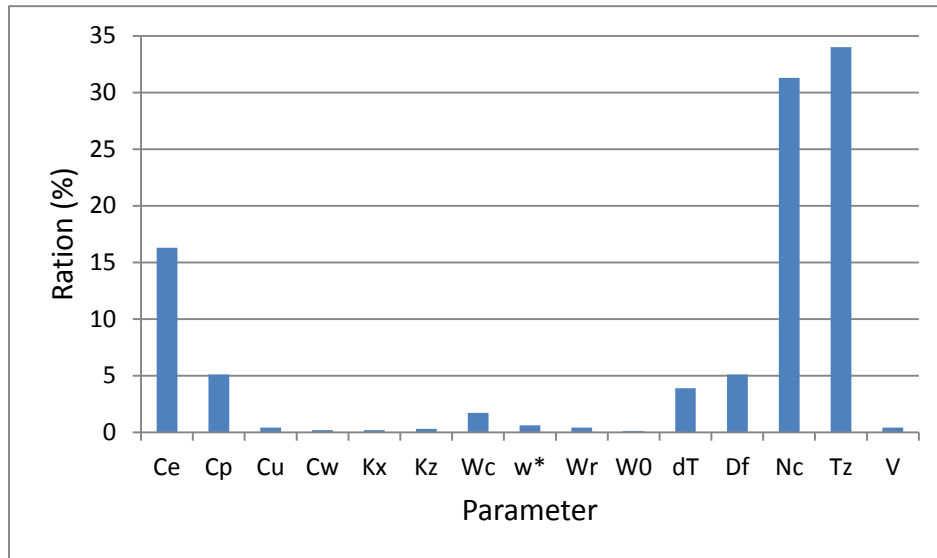


Figure 8 FAST sensitivity analysis of Daysmoke. The horizontal coordinate lists the model parameters (see Table A1 for their meanings). The vertical coordinate is the ratio (%) of partial variance of a parameter to total variance.

#### **d. Plume rise simulation is very sensitive to setup of “burner” method**

For the cases of strong surface wind, smoke plume tilts towards downwind with height (Figure 9). The smoke particles in the analyzed area is small because of a large number of particles are transported out of this area. Plume rise is about 800 m and changes little from constant vertical temperature profile to normal vertical lapse rate. In contrast, for the cases of weak surface wind, the number of smoke particles is large and plume rise is high. The height increases from about 1300 m with constant vertical temperature to 2000 m for normal vertical lapse rate. Thus, the impact of winds occurs for both thermal stability conditions, while that of stability occurs only for the weak wind condition. Plume rise increases with effective diameter, which is determined by heat flux and exit vertical velocity (Figure A5).

The inter-comparisons of the idealized burn cases among the smoke models examined are provided in the final report by JFSP project 16-4-05-1.

#### **e. Night-time smoke drainage and super-fog occurred often with Rx burns**

The PB-P simulation for Block 703C in Eglin (Figure 10, top) shows the plume with red dots, indicating likely presence of natural fog being transported toward population centers located west of the burn site. This plume had by 0800 LST 7 February 2011 been transported directly into Pensacola. The narrow “pencil like” structure of the plume as it approached Pensacola is an outcome of drainage flows within the broad river basin extending northeast from Pensacola Bay being channeled southwestward and converging with westward-moving air carrying the plume toward Pensacola.

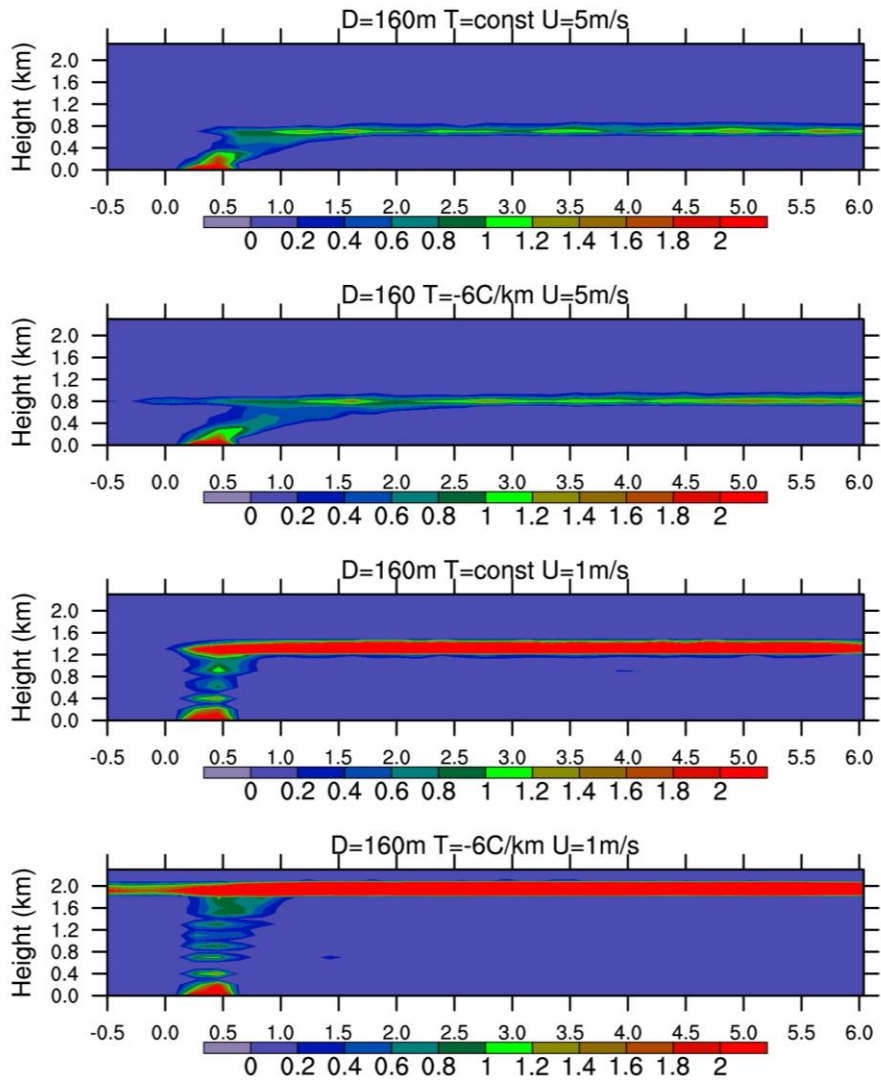


Figure 9 Horizontal (x, km) and vertical (z, km) section of smoke plume from idealized fire line burn (unit: particle number per grid cell) simulated with Daysmoke with different temperature (T) and wind (U) profiles. D is effective diameter.

The PB-P simulation for Block 608A (Figure 10, middle) shows smoke was captured and channeled by shallow drainages within the upper coastal plain. Winds blowing from the north were strong enough however to evacuate smoke from some of these drainages. Note how the smoke plume became more homogeneous once the plume had drifted into the flatlands of the lower coastal plain south of an east-west line through the middle of the image. The plume has reached coastal resort communities of Miramar Beach and Destin although the smoke would most likely have been widely dispersed and unnoticeable to residents of these communities.

The PB-P simulation for Block 704A (Figure 10, bottom) shows that the plume was confined to a drainage leading to the northwest. As stated, red dots identify smoke likely in the presence of fog.

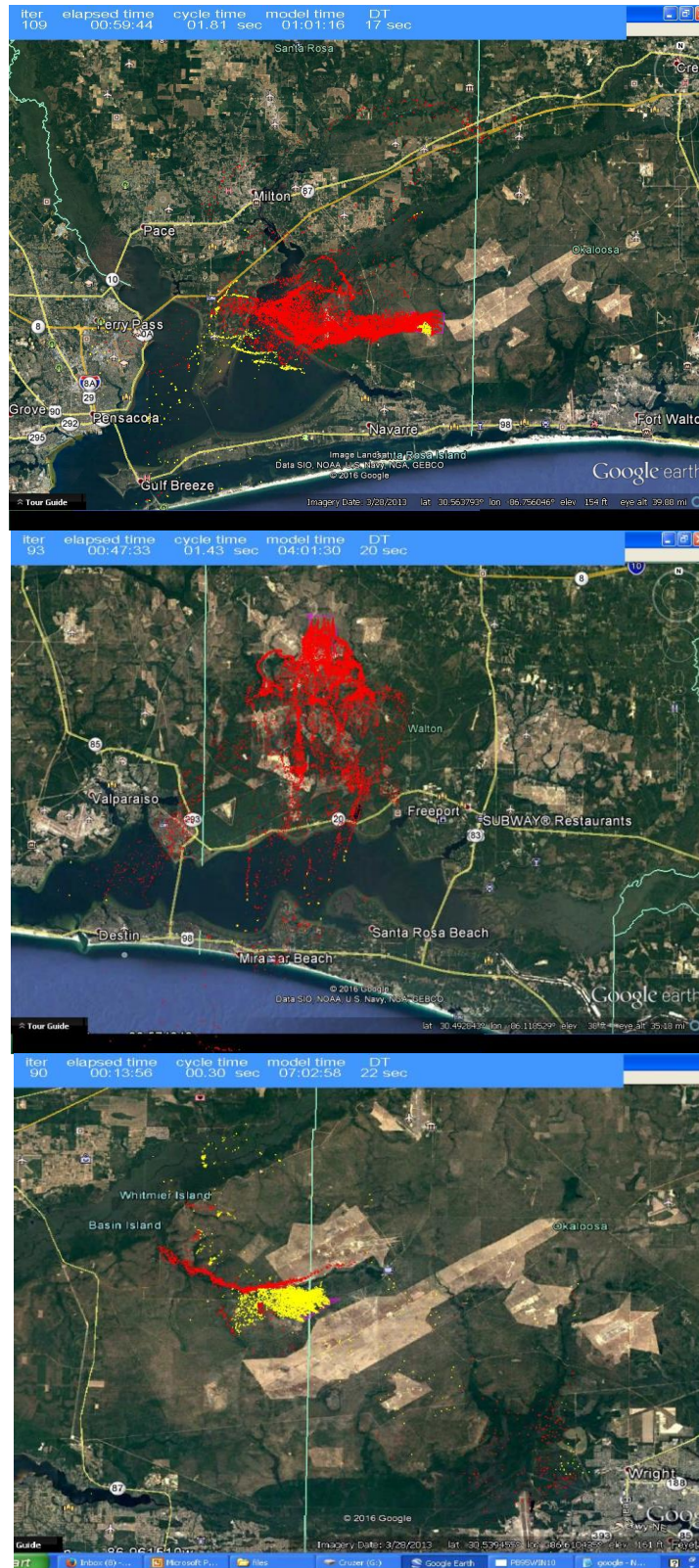


Figure 10 The PB-P simulated smoke plume in Eglin for Block 703C (top), 608A (middle), and 704A (bottom) on February 6, 8, and 12, 2017, respectively. The yellow and red dots are smoke particles and fog.

**f. Night-time smoke drainage and possible formation of super-fog could impact local visibility and traffic.**

Vehicle accidents occurred on I-40 approximately 35 km west of Flagstaff, Arizona, during the early morning of October, 19 2016. This was a superfog event associated with smoldering remnants of a Rx fire conducted along the north side of the expressway during October. An occurrence of superfog in the western U.S. is a rare event and it was of interest to determine whether PB-P could successfully place smoke at the accident site at the times of the accidents. Drainage/slope flows became well-established after midnight. Streams of yellow particles were oriented toward the south-southwest at 0300 LST the hour accidents along I-40 were first reported. This pattern continued through 0700 LST (Figure 11) with the exception that PB-P indicated collocation of smoke and natural fog at a drainage near the lower left corner of the image.

At no time during the simulation was natural fog collocated with smoke over I-40. Local NWS hourly observed temperatures and relative humidities were interpolated to the location of the Rx burn and used to calculate the potential for superfog. To the extent that fuel composition and fuel moisture from the Arizona burn compared with the same fuel data from southern pinelands, the SPI could give a reliable estimate for superfog potential. On a scale from zero to ten, the SPI scored a three at 0300 LST – the reported time of the first accidents. The SPI rose to eight at 0500 LST and rose to ten at 0700 LST. High values of the SPI were not expected for the southwestern U.S. given the climatologically dry conditions. However, these results show that these areas are not always free from the threat of superfog.

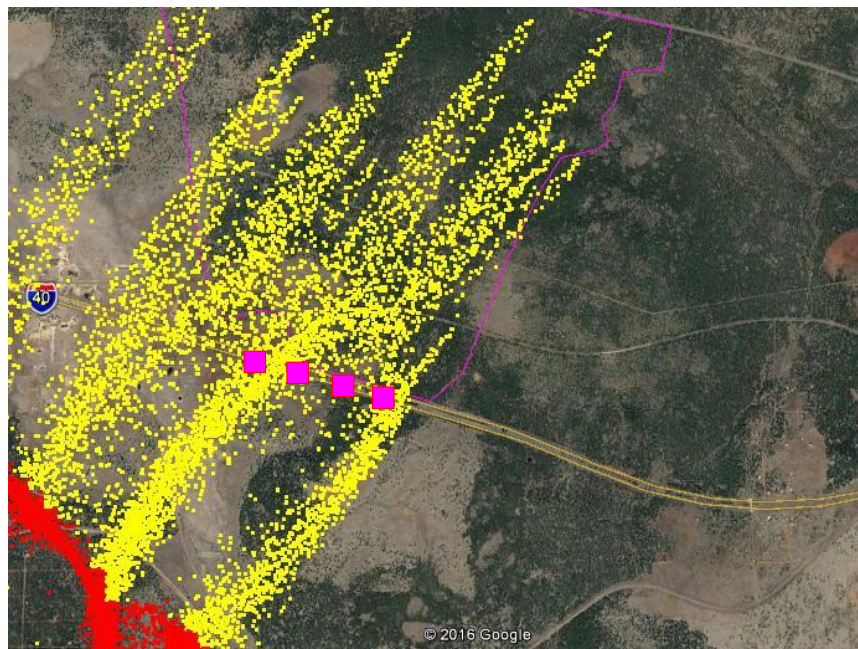


Figure 11. PB-P simulated smoke from smoldering combustion at 0700 LST, October 19, 2016 near Grand Canyon, AZ. The yellow and red dots are smoke particles and fog.

## **5. Participating in study plan development**

- a. The analyses of properties of Daysmoke and PB-P were provided. They are summarized Tables B1-B3 of Appendix B of the FASMEE Study Plan, together with other fire and smoke models participated in FASMEE project. See Appendix B of this report for the Tables.
- b. The priority FASMEE measurement needs for Daysmoke and PB-P were provided as Appendix B.4.1 of the Study Plan. See Appendix C of this report for the description.
- c. Desired burn and smoke conditions for Daysmoke and PB-P were provided as Appendix B.6.3 of the Study Plan. See Appendix D of this report for the description.
- d. Drafted Appendix E.3 (Simple plume systems) of the FASMEE Study Plan. See Appendix E of this report for a description.
- e. Drafted Appendix E.4 (How to estimate the number of multiple updrafts) of the FASMEE Study Plan. See Appendix F of this report for a description.
- f. Drafted Section 6 (The next generation of fire and smoke models), subsection D (How complex, explicit coupled fire models can inform simpler fire behavior and plume models that can be applied operationally) of the FASMEE Study Plan. See Appendix G of this report for a description.
- g. Drafted Section 6 (the next generation of fire and smoke models), subsection E (How resolved fuels and fire dynamics must capture critical plume structure). See Appendix H of this report for a description.

## **6. Conclusions**

Simulations and sensitivity experiments have been conducted with Daysmoke and PB-P for historical Rx burn cases in the Southeast and Southwest and hypothetical cases at the FASMEE sites. They provided information for developing the FASMEE Study Plan, including model capacity, gaps, and the data needs for model improvements, and desired burn and smoke conditions. Contributions were also made to the Study Plan by drafting subsections describing simple plume systems, estimation of the number of multiple updrafts, the approaches for complex, explicit coupled fire models to inform simpler fire operational behavior and plume models, and the issue of how resolved fuels and fire dynamics must capture critical plume structure.

The findings from the simulations and experiments suggest that:

a. The Daysmoke simulations of the historical burns during the RxCADRE experiments are able to reproduce some important smoke features. However, the simulated plume rise could be different from the measured values by as many as 200s meters, and too many simulated particles are located in the upper portion of the smoke plume. This indicates the need for some substantial improvements to the model. The Daysmoke and PB-P simulations and experiments of the hypothetical burn cases and /or idealized burn cases show the strong dependence of plume rise on fire properties such as energy and particle emissions, exit velocity and temperature, meteorological conditions such as wind and thermal stability, and smoke properties such as core number and entrainment. Thus, the comprehensive FASMEE measurements of these properties would be a key for improving Daysmoke and PB-P performance and increasing their capacity.

b. The Daysmoke experiments of the hypothetical burn cases at Ft Stewart using both “change and response” and FAST techniques show that the importance of the number of multiple smoke plume updrafts or sub-plumes to plume rise and smoke plume vertical profiles. Heat flux and exit velocity are among the properties essential factors for determining the plume effective diameter used in Daysmoke and they differ remarkably between smoke plumes with multiple and single core. The major contributors to the formation of sub-plumes include ignition pattern (such as complex tracks from aerial ping-pong ball ignition), inhomogeneous fuel distribution, interactions with local weather systems, etc. It is suggested that the FASMEE burns should be conducted under such conditions so that the field measurements would collect valuable and simultaneous data of these properties for understanding the multiple sub-plume dynamics (including merging of two or more updrafts during rising) and evaluating and advancing the modeling tools.

c. The Daysmoke and PB-P simulations and experiments of smoke plume rise, vertical profiles, and transport, drainage and fog formation show large variability for hypothetical Rx burns at Ft Stewart over a period of 4 days. Plume rise, for example, went from about 900 m on one day to about 1500 m next day. Night-time smoke drainage and super-fog formed on one night but not on another night. Wind is probably most important single meteorological element for plume rise and vertical profile modeling. Thus, weather conditions on the FASMEE experimental burn days are critical for obtaining anticipated smoke plumes for field measurements and could vary on daily basis at Ft Stewart.

d. The PB-P simulations of the historical burns during the RxCADRE experiment and in northern Arizona show frequent occurrence of night-time smoke drainage and possible formation of super-fog. They could significantly impact local visibility and traffic. The local wind field can transport smoke near the ground to distant locations – some near or within urban areas and others across roadways some distance from the locations of the burns. Thus, it is highly recommended to conduct night-time smoke measurements during FASMEE experiment in both the southeastern burn sites where the atmosphere is often moist favoring formation of super-fog and dense roads often close to residence areas, and the southwestern burn sites where the topography is complex and PB-P model is not enough evaluated.

## 7. Deliverables

Proposed Research and products	Delivery Dates	Status
Modeling simulations performed for selected sites	Fall 2016	Completed
Work with the FASMEE program to vet the observational design, help develop 2017 FON, and assist in building the final Study Plan	December 2016	Participated in study plan development

## 8. Other products /activities

1. Attended two FASMEE Workshops held in Seattle, WA.
2. Took part in visits to the Southeast and Southwest FASMEE burn sites.
3. Joined all regular conference calls (except one call due to out of town conference).
4. Presentation:  
Yongqiang Liu, Adam Kochanski, Kirk Baker, Ruddy Mell, Rodman Linn, Ronan Paugam, Jan Mandel, Aime Fournier, Mary Ann Jenkins, Scott Goodrick, Gary Achtemeier, Andrew Hudak, Matthew Dickson, Brian Potter, Craig Clements, Shawn Urbanski, Roger Ottmar, Narasimhan Larkin, Timothy Brown, Nancy French, Susan Prichard, Adam Watts, Derek McNamara, 2016, FASMEE Modeling Activity, FASMEE special session of the second international smoke symposium held in Long Beach, CA, November, 2016.
5. Manuscripts:
  - Liu et al., 2017, Fire and Smoke Model Evaluation Experiment (FASMEE): Modeling gaps and data needs, Proceedings of the second international smoke symposium held in Long Beach, CA, November, 2016, 1-13.
  - Liu et al., 2017, Fire and smoke modeling issues, gaps, and measurement data needs (Draft completed. To be submitted to International Journal of Wildland Fire). Developed based on the above proceeding manuscript.
  - Liu et al., 2017, Daysmoke and PB-P simulations and experiments of prescribed burns (under writing).

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- Ottmar R, Larkin S, Brown T, French N (2016) Overview of Fire and Smoke Model Evaluation Experiment (FASMEE), 2<sup>nd</sup> International Smoke Symposium, Long Beach, CA, USA, November 14-17, 2016.

**Appendix A** Tables and figures from Daysmoke and PB-P simulations and experiments

Table A1 Parameters used in the FAST sensitivity analysis for Daysmoke.

Model	Parameter	Meaning	Average	Range	Unit
ETM	$C_e$	Entrainment coefficient	0.18	0.05-0.8	(-)
DPM	$C_p$	Plume detrainment coefficient	0.03	0.01-0.05	(-)
	$C_u$	Air horizontal turbulence coefficient	0.15	0.05~0.2	(-)
	$C_w$	Air vertical turbulence coefficient	0.01	0.01~0.08	(-)
	$K_x$	Thermal horizontal mixing rate	1	0.5~1.5	km(m/s)/°C
	$K_z$	Thermal vertical mixing rate	1	0.5~1.5	km(m/s)/°C
	$W_c$	Plume-to-environment cutoff velocity	0.5	0.3~0.5	m/s
	$w^*$	Air induced particle downdraft velocity	0.01	0.0~0.00	m/s
LED	$W_r$	Large eddy reference vertical velocity	1	0.5~1.5	m/s
REM	$W_0$	Initial plume vertical velocity	Computed	10~40	m/s
	dT	Initial plume temperature anomaly	Computed	2~15	°C
	$D_f$	Effective diameter of flaming area	Computed	-10~10	m
	$N_c$	Number of updraft core	1	1~4	(-)
	$T_z$	Atmospheric thermal lapse rate	Observed	-2~2	°C/km
	V	Average wind speed	Observed	5~15	m/s



Figure A1 The development of more than 3 major sub-plumes from a Rx burn in Fishlake National Forest, UT during June, 2016 (Provided by Roger Ottmar).

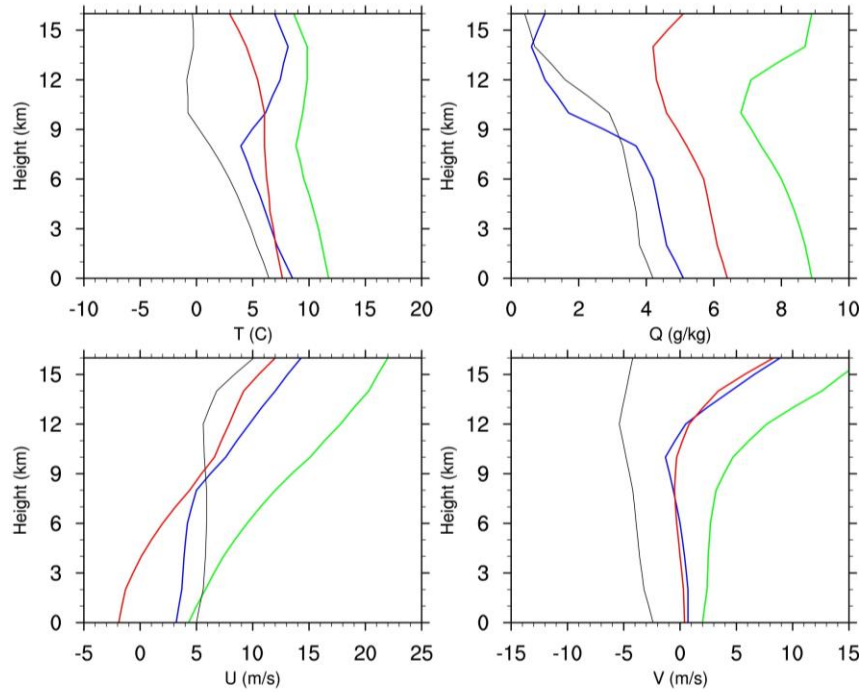


Figure A2 Vertical profiles of meteorological conditions at Ft Stewart simulated with Weather Research and Forecasting (WRF) model. The four panels are temperature, specific humidity, westerly wind, and southerly wind. The green, red, blue, and gray lines are February 5-8, 2011.

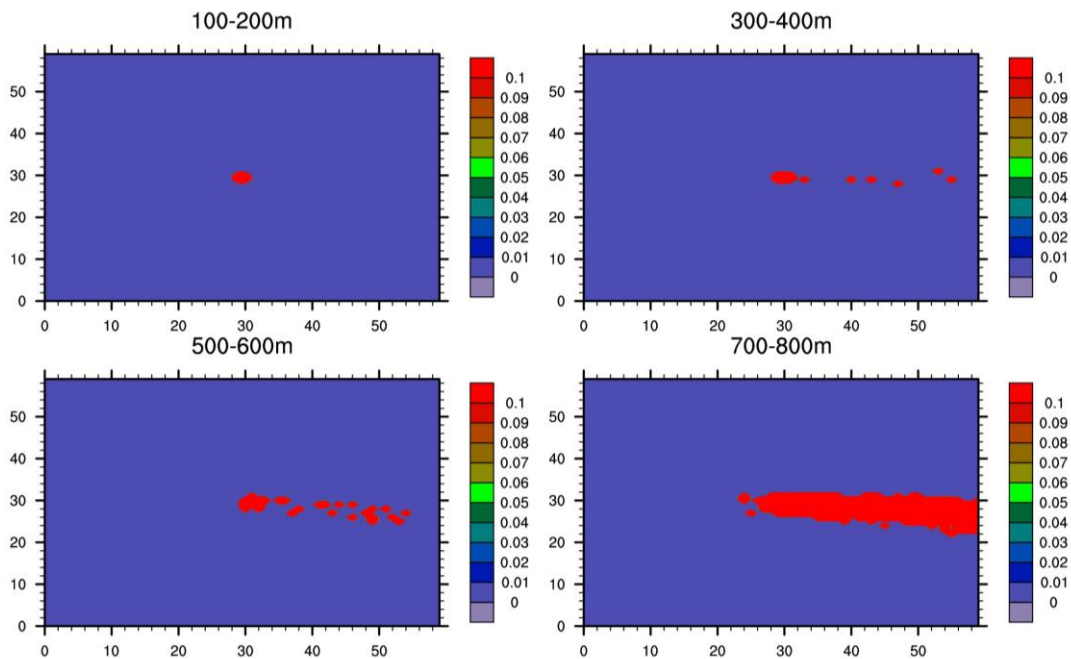


Figure A3 Transport of smoke from hypothetical burn at Ft Stewart on February 6, 2011 (unit: particle number per grid cell) simulated with Daysmoke. The four panels are different vertical layers. Horizontal and vertical are grids in x- and y-direction with grid size of 200 m.

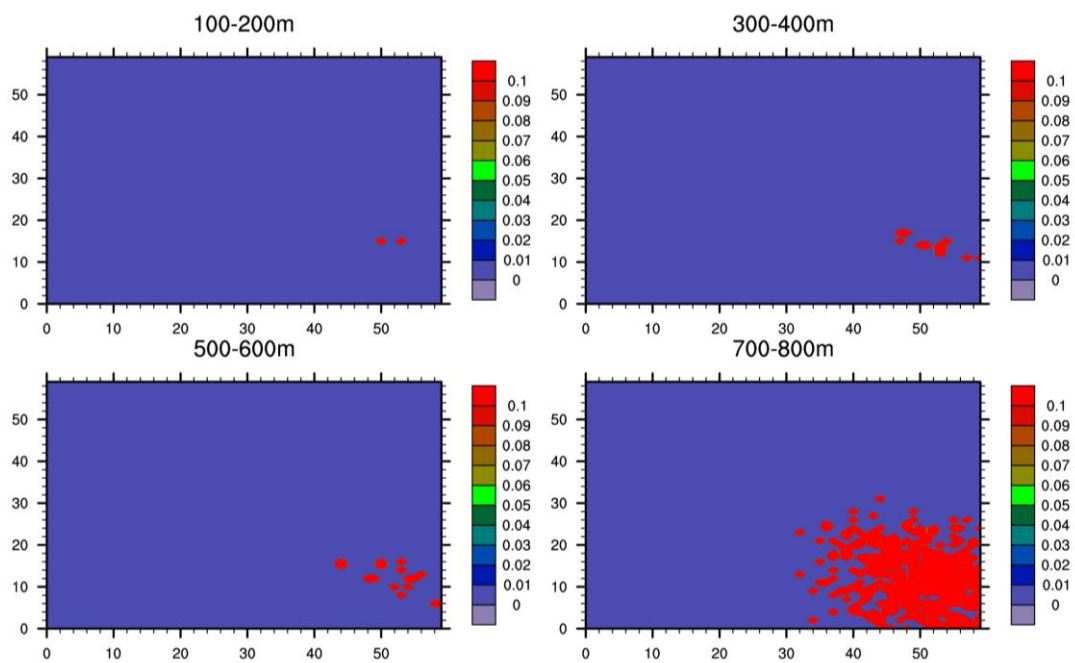


Figure A4 Transport of smoke from hypothetical burn at Ft Stewart on February 8, 2011 (unit: particle number per grid cell) simulated with Daysmoke. The four panels are different vertical layers. Horizontal and vertical are grids in x- and y-direction with grid size of 200 m.

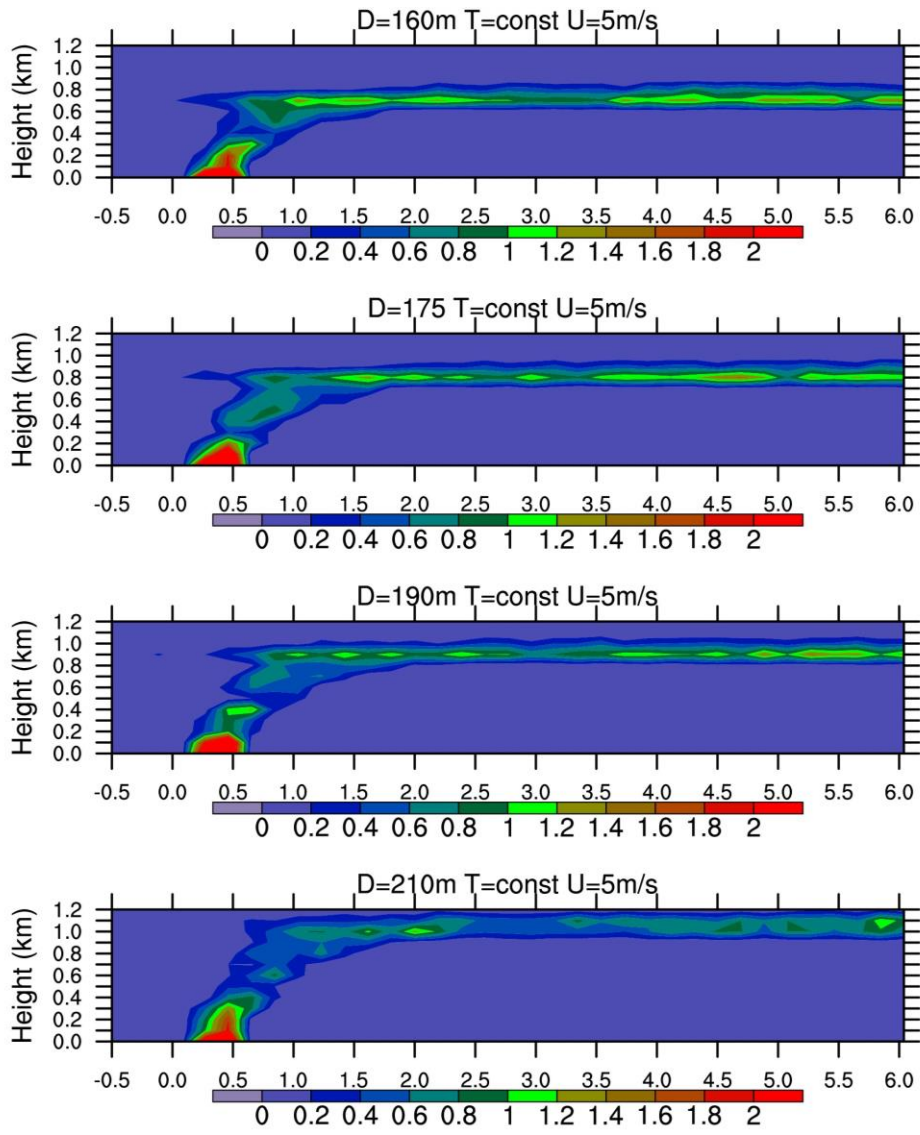


Figure A5 Horizontal (x, km) and vertical (z, km) section of smoke plume from idealized fire line burn (unit: particle number per grid cell) simulated with Daysmoke with different effective diameters (D). T and U are temperature and wind.

**Appendix B** Model properties, modeling issues and gaps, and priority measurement needs with Daysmoke and PB-P, together with other fire and smoke models participated in FASMEE project.

**Table B1:** 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 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, WFDS-LS, FIRETEC; cm ~m, WFDS-PB
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)

**Table B2:** Modeling issues and gaps.

Issue	Gap
Heat release	Need measurements of heat release along the fire perimeter; Improve vertical distribution of radioactive and convective heat near 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 vertical 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 required.
Smoldering and night smoke	Bulk emission factors not dependent on the burning stage; Nighttime 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 <sub>3</sub> , PM <sub>2.5</sub> , their precursors and important chemical intermediate species.
PM and gas speciation	PM, VOC, and nitrogen gas speciation not 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 effects 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 effects of pyro cumulus on vertical smoke distribution and fire behavior.

**Table B3: 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, and 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 <sub>3</sub> and PM chemical evolution	Speciated and size resolved PM, particle number and diameter and polarity; SO <sub>2</sub> , NH <sub>3</sub> , CH <sub>4</sub> , 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 <sub>3</sub> , CO, CO <sub>2</sub> , CH <sub>4</sub> , VOC speciation (incl. carbonyls); CH <sub>3</sub> CN, nitrogen gases	Validate and improve fire emissions estimates; O <sub>3</sub> and PM <sub>2.5</sub> chemistry
	Smoldering emissions	PM 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 <sub>2</sub> photolysis	Better representation of the radiative impacts of smoke

## **Appendix C** The FASMEE measurement needs for Daysmoke and PB-P

All measurement parameters needed for Daysmoke and PB-P models are the same as for WRF-SFIRE, but include these additional measurements:

1. Detailed tracks of ignition if aerial ignition is used. This measure is used to initialize the Rabbit Rules model (RRM) to produce multiple core number.
2. Multiple fire cells and smoke plume cores, including number, location, and size, and their variations with time. This measure is used to run Daysmoke using the burner method and evaluate the RRM simulation results.
3. Nighttime smoke movement, including emissions from smoldering stage, smoke drainage and fog formation, local wind, temperature, humidity, and air pressure. This measure is used to run and evaluate PB-P modeling.

## **Appendix D** Desired burn and smoke conditions for Daysmoke

### *Fire and smoke with multiple cores / sub-plumes*

The number of sub-plumes is one of the factors for calculating heat fluxes in Daysmoke and therefore is important for plume rise. A major contributor to the formation of sub-plumes is ignition pattern (such as complex tracks from aerial ping-pong ball ignition). Thus, a desired burn includes multiple ignitions or burning in a manner that produces multiple cores.

### *Burns with well-defined exit properties*

Physically based smoke models simulate smoke structure and movements using the mass, momentum, energy, and water conservation laws, together with boundary conditions from the bottom, top, and lateral boundaries. As the bottom boundary conditions, exit temperature and vertical velocity along with particle and water emissions from the ground are needed. Exit temperature and vertical velocity have two properties: (1) their intensity, which would be obtained by the smoke plume dynamics and meteorological measurements during the FASMEE field campaign; (2) some reference height, defined as the base of the plume where flaming gasses and ambient air have been thoroughly mixed. Besides fire intensity, this height is influenced by canopy, whose drag can dramatically reduce not only exit velocity intensity but also the reference height. For smaller-sized Rx burns, for example, the height may be near 35 m above ground for a typical grassfire but only 10 m for forested lands with canopy. Thus, for the smoke plume measurements to be able to measure the exit properties, at least moderately intensive burning is desired where the canopy will consume to make sure the reference height will be above the canopy.



### *Nighttime smoke movement in areas with complex topography*

Nighttime smoke drainage and possible formation of super-fog could affect local visibility and traffic. The burns should include a smoldering stage to correspond with measurements fire emissions, wind, pressure, possible smoke drainage, and potentially fog.

### **Appendix E** Simple plume systems

Simple plume systems (SPSs) aim to provide some coarse features of smoke structure, such as plume rise, vertical profile, nighttime smoke drainage instead of concentrations and the geographic distributions of air pollutants such as PM<sub>2.5</sub> and O<sub>3</sub> produced by fire emissions. They may consist of conservation equations of mass, momentum, heat energy and water, but the related sources / sinks and dynamics are usually simplified or described using statistical tools. Atmospheric chemistry is usually excluded. Daysmoke and PB-P are examples of SPSs for day and night time smoke modeling, respectively. Land managers could use SPSs as a screening tool to predict local intensity and downwind extent of smoke plume and evaluate the impacts on air quality and road traffic. They also may be used to provide plume rise for complex air quality models.

The FASMEE measurements can be used to improve SPS modeling performance, develop new capacities, and increase scientific understanding of smoke plume dynamics, including:

- Vertical velocity and temperature at the height where fire and ambient gases are well mixed (exit velocity and temperature) are needed to drive plume rise in SPSs. These are often estimated based on heat release and other burning properties with large errors. The FASMEE measurements of fire heat and exit velocity and temperature will provide data for evaluation of existing empirical schemes. These data would improve plume rise simulation and the potential coupling capacity between fire and smoke modeling.
- Multiple updrafts are treated in SPSs by a formula relating their number to heat flux. The FASMEE energy and smoke measurements will provide data to evaluate this approach. These data can also help to develop a parameterization process to estimate the number of updrafts (see example in E.6). This would increase our knowledge of the roles of multiple updrafts in smoke dynamics.
- Entrainment is an important mechanism for smoke plume development. The entrainment rates depend on fire and meteorological conditions and vary with space and time, but are often specified with some empirical values in SPSs. The FASMEE smoke and meteorology measurements can be used to obtain more accurate empirical values and develop relations with smoke intensity and ambient

wind and temperature. This would improve the modeling skills of smoke plume rise and particle fallout.

- The development of smoke eddies is affected by ambient air flows, thermal stability, and canopy. These eddies are parameterized as stochastic processes in many SPSs, without consideration of canopy impacts or sufficient evaluation, because of the lack of high-resolution atmospheric turbulence measurements. The FASMEE smoke and meteorology measurements can help fill this gap.
- The FASMEE measurements will provide useful data to simulate and understand formation of smoke drainage and superfog and the effects of topography during nighttime. The SPS simulation skills are limited because of the lack of high-resolution weather information, especially at burned sites with complex topography. The FASMEE measurements help to specify nighttime smoke emissions, weather, and ground smoke particle measurements for model initialization and evaluation. Furthermore, current models have many assumptions that are often inaccurate. For example, the drainage in PB-P is assumed to be a shallow layer, which could be not appropriate in an area with a deep valley. Some of these assumptions could be removed through analysis of the FASMEE smoke and meteorological measurements.

#### **Appendix F** How to estimate the number of multiple updrafts

Many sub-plumes (see Figure E-6) form from variables such as the differences in heat released along the fireline, local terrain, wind channeling through vegetation of varying density, and natural atmospheric processes that organize convection. All of these variables are on fine scales and organize to eventually merge into stable columns (cores) of smoke. High-resolution fire energy measurements of structure and dynamic variation can be used to display clearly separate patterns related to ignition patterns and fuel structure. Some spatial tools such as wavelet transform can be used to identify the major separate spatial systems. Minimum size thresholds of the separate systems can be linked to individual smoke plume updrafts. One possible applications of FASMEE measurements is to develop a multiple sub-plume parameterization scheme. This scheme would provide the number of multiple updraft cores based on the measured fire energy and smoke plume number, using techniques such as similarity theory.

The Rabbit Rules Model (RRM) (Achteimeier et al. 2012) is a “rules”-based fire spread model to estimate the number of multiple updraft core number. It is in the very early stage of development and has not been systematically evaluated. The number is determined based on individual air pressure cells created by complex spatial patterns of ignition, fuel, emission, and interactions with the ambient atmosphere. One problem with RRM is that it sometimes may produce too many small air-pressure cells during the burning period, which probably does not

represent actual smoke plumes. FASMEE measurements provide high-resolution fire-radiative power and energy, air pressure, and smoke plumes. This will establish a cut-off scale to exclude using some air pressure cells to account for the number of multiple smoke updrafts.

**Appendix G** How complex, explicit coupled fire models can inform simpler fire behavior and plume models that can be applied operationally

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 such as a smoke plume is poorly described in most smoke models. For example, some simple smoke models use average heat fluxes over a large section of the burned area during different fire stages, which would affect modeling of fast varying small-scale and eddy structure of smoke plume and entrainment. The next generation of operationally applicable systems will improve the understanding and modeling of fire and plume dynamics. 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. The next-generation of complex, explicit coupled fire models will provide simple fire behavior and smoke models to include the impacts of these interactions.

**Appendix H** How resolved fuels and fire dynamics must capture critical plume structure

Current fuel and smoke modeling is used to provide bulk heat release and gas and particle emissions for smoke plume and the air quality impact modeling. The next-generation coupled models will further provide dynamical high-resolution distributions and temporal evolutions of these fuels and fire products for improving modeling of complex smoke structure. For example, multiple plume updrafts is one of the important plume structure features. This feature not only increases the horizontal heterogeneity of smoke but also changes the heat fluxes and therefore modifies smoke plume rise and vertical distributions. The formation and evolution of multiple smoke updrafts are related to fuels and fire dynamics including the ignition patterns and progression, fuel consumption, and fire spread and intensity, which determine how the individual fire cells develop, and merge into separate smoke plumes. The next-generation of coupled fire and smoke models will be able to capture the fuel and fire dynamical processes and provide information for determining the number of multiple updrafts.