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U.S. EPA Smoke Emissions, Chemistry, and Transport Modeling

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ABSTRACT

Photochemical grid models such as the Community Multiscale Air Quality Model (CMAQ) are used to estimate local to continental scale O_3, PM, and haze for scientific and regulatory assessments. Field data from specific and well characterized wildland fires is critically important to improve wildland fire emissions estimation approaches, plume transport, and plume chemical evolution in photochemical transport models to further confidence in predictive capabilities to support future scientific and regulatory assessments related to wildland fire impacts. The Fire and Smoke Model Evaluation Experiment (FASMEE) field campaign provides a unique opportunity to obtain surface, canopy, and upper air measurements of specific fire events to better constrain the dynamic nature of smoke emissions and the physical and chemical evolution of smoke plumes from fire events by combustion regime (flaming to residual smoldering). It is anticipated that measurements from this field study will lead to improved 1) fire characterization (size, location, etc.), 2) emission rates for different fuel types and combustion component; 3) PM, VOC and nitrogen speciation by fire type and phase of combustion; 4) allocation of plumes spatially and temporally; 5) near-fire and downwind plume chemical evolution; and 6) optical properties of plumes. This field study will also provide valuable information to improve other less anticipated aspects of fire emissions and air quality modeling as work intensifies in this research area.

Burn units at Fishlake NF and Fort Stewart, GA planned for inclusion in FASMEE phase II were modeled to illustrate potential impacts on primary and secondarily formed pollutants. Additionally, a prescribed fire at Monument Peak in Fishlake NF from June 2, 2016 was replicated to illustrate how similar the planned burn unit at Manning Creek may be in terms of local to regional scale smoke transport and chemistry. The Manning Creek burn unit showed impacts similar in magnitude to the Monument Peak burn unit but smoke was transported to a different area downwind. Applying CMAQ with finer horizontal grid resolution (1 km compared to 4 km) resulted in higher predicted smoke impacts locally and downwind. The model predicted that O_3 formation was inhibited at the fire location due to large amounts of fresh NO emissions but was produced further downwind at both the Fort Stewart and Fishlake burns. The Fort Stewart burn unit was modeled to burn on every day for an entire year to understand potential seasonal differences in smoke levels and composition. The region has enough solar radiation and temperatures are warm enough for O_3 to form in all months of the year, although O_3 formation was lowest in November and December. This suggests a field study in the southeast U.S. with the intention of examining photochemical changes in smoke should be done outside of those months. Colder weather with typically lower surface layer mixing tend to result in higher concentrations of primarily emitted $PM_{2.5}$ than warmer seasons based on the Fort Stewart annual simulation. These real and hypothetical burns provide case studies to illustrate the need to evaluate and constrain each component of the modeling system.

INTRODUCTION

Many counties in the eastern and western U.S. exceed levels of the O_3 and PM National Ambient Air Quality Standards (NAAQS) and mandatory Class I areas (e.g. most National Parks and some Wilderness Areas) must be on a path to natural visibility conditions under the Regional Haze Rule. It is important to adequately determine the contribution from wild-land fires to O_3 and $PM_{2.5}$ for air quality planning purposes to develop effective strategies to meet the level of the NAAQS, regional haze goals, and other purposes such as supporting an exceptional events demonstration. In addition, fires emit a variety of climate forcers (e.g., carbon monoxide, carbon dioxide, black carbon, brown carbon) that need to be understood to better characterize the impacts of climate improvement scenarios.

Wildfires impact O_3 concentrations by emitting known precursors (NO_X and VOCs) that can react to form ozone within the fire plume or can mix with emissions from other sources to generate O_3 (Wiedinmyer et al., 2011). Also, in some situations, including near wildfires, O_3 formation may be inhibited or muted due to O_3 titration by enhanced NO concentrations and reduced solar radiation available to drive photochemical reactions (Jiang et al., 2012). Fire also directly emit particles and precursors (e.g. NO_X, SO_2, NH_3, VOCs) that can react in the plume and with the surrounding atmosphere and form secondary $PM_{2.5}$. The magnitude and ratios of emissions from wildland fires vary greatly depending on fire size, fuel characteristics, combustion efficiency, and meteorological conditions (Akagi et al., 2012). As a result of variable emissions, radiative impacts, and non-linear O_3 and $PM_{2.5}$ production chemistry, chemical production from fires is very complex, highly variable, and often difficult to predict (Jiang et al., 2012).

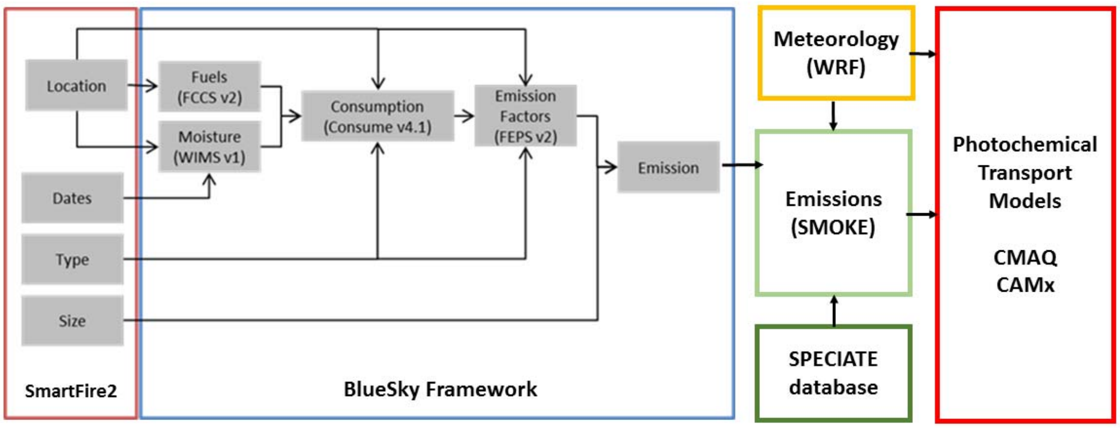
The Fire and Smoke Model Evaluation Experiment (FASMEE) field campaign provides a unique opportunity to obtain surface, canopy, and upper air measurements of different specific fire events to better constrain the dynamic nature of smoke emissions and the physical and chemical evolution of smoke plumes from fire events. Coordination with other fire related field campaigns such as NSF's 2018 WE-CAN, NOAA's 2019 Fire Influence on Regional and Global Environments Experiment (FIREX), and NASA's 2019 FIRECHEM will provide even more robust information to support the evaluation and development of smoke emissions and chemical treatment in regional scale modeling systems. Prescribed burns are planned as part of FASMEE for the southeast U.S. in the dormant season and western U.S. during the early spring or late fall seasons.

A modeling system including the Community Multiscale Air Quality (CMAQ) has been applied for historical and planned future prescribed fires at potential host site locations in the southeast and western U.S. The planned future fires include burn units identified by the FASMEE Phase I process and host agency as actual areas that will be burned as part of the field studies planned for FASMEE Phase II. Model estimates of O_3 and $PM_{2.5}$ are provided and used to illustrate how FASMEE and other coordinated field campaigns (e.g., WE-CAN, FIREX and FIRECHEM) could provide useful data toward model evaluation and development. Broad aspects of the modeling system needing additional evaluation include the fire location and burn area, fuel type, fuel consumption, emission factors, emissions speciation (for VOC, PM, and oxidized nitrogen gases) and temporalization, plume rise, plume transport, plume chemical evolution, and plume optical properties.

METHODS

An integrated modeling system used to support U. S. Environmental Protection Agency rules and air quality standards development and NOAA's operational O_3 and $PM_{2.5}$ forecasting will be used for estimating primary and secondary pollutant impacts from specific hypothetical and real wildland fire events (see Figure 1). The Weather Research and Forecasting (WRF) model (http://www.wrf-model.org/) will be 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 the Community Multiscale Air Quality (CMAQ) three-dimensional Eulerian photochemical transport model (https://www.cmascenter.org/cmaq/). Further, the SMOKE model uses wildland fire emissions generated using the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SmartFire) - BlueSky framework (http://www.airfire.org/bluesky/) that is provided by the U.S. Forest Service. All of these models are well documented, freely available to the modeling community, and have been extensively used to support both regulatory and scientific air quality assessments.

Figure 1. Schematic of modeling system components relevant for wildland fire modeling.



CMAQ treats emissions, atmospheric chemistry, and physical processes such as deposition and transport. These types of 3D processes are appropriate for assessment of near-field and regional scale reactive pollutant impacts from specific sources (Baker and Kelly, 2014), specific wildland fire events (Baker et al., 2016; Kansas Department of Health and Environment, 2012) or specific source sectors (Fann et al., 2013). CMAQ 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.

Aerosol treatment includes ISORROPIA II inorganic thermodynamic model (Fountoukis and Nenes, 2007), secondary organic aerosol production from precursor yields and subsequent partitioning between gas and aerosol phase and representation of oligimerization processes (Carlton et al., 2010). CMAQ attenuates photolysis rates based on black carbon but does not have a robust implementation of attenuation for brown carbon due to uncertainty in optical properties of brown carbon.

All models use a Lambert conic conformal projection centered at -97,40 with true latitudes at 33 and 45. The assumption for the radius of the Earth is a 6370 km. All non-wildland fire emission sources (anthropogenic and biogenic) are based on 2011 National Emission Inventory with 2013 specific information for specific point sources where available to provide a realistic chemical environment for the fire.

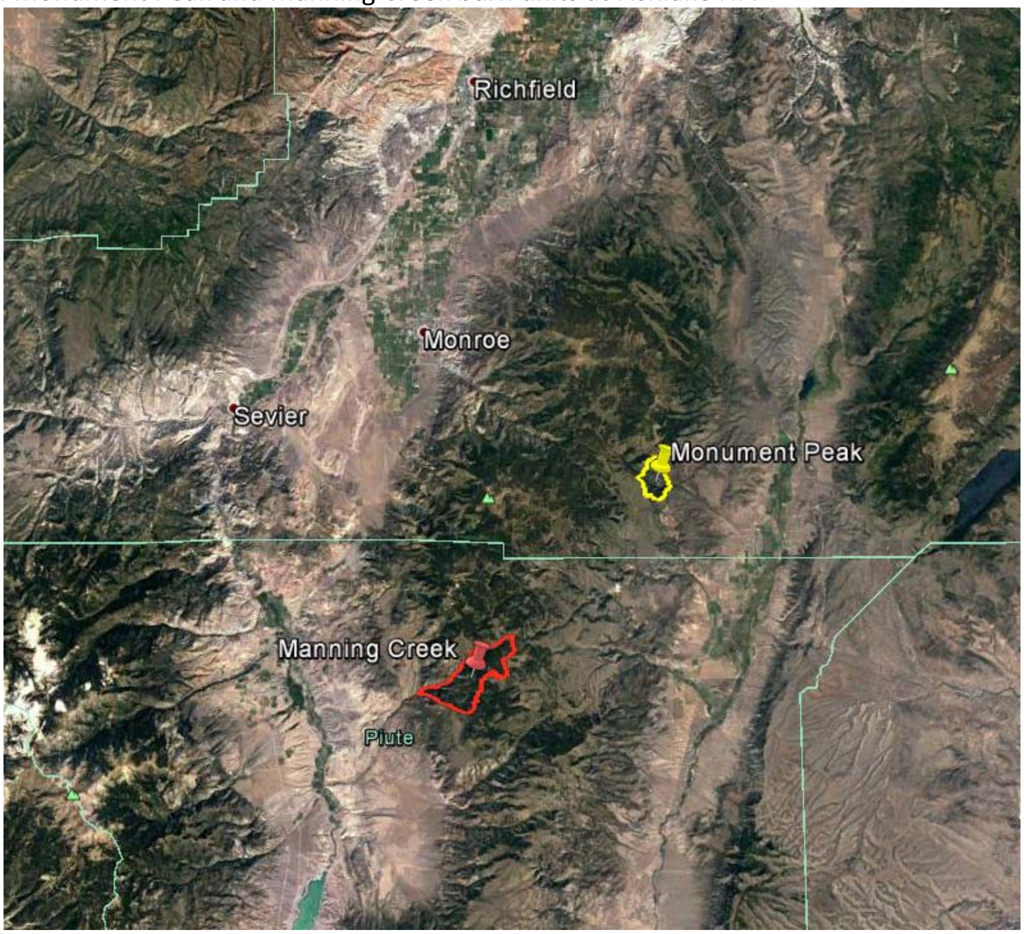
Western U.S. Burn Scenario

The modeling system was applied for a burn unit at Fishlake NF that may be part of the FASMEE Phase II field study (Manning Creek) for June 2-4, 2016 coincident with an actual prescribed fire at Monument Peak. CMAQ and WRF were applied with 4 and 1 km sized horizontal cells and 35 vertical layers from the surface to 50 mb (see Table S1). Emissions were estimating using the BlueSky framework for both burn units based on fire location and burn area: actual for Monument Peak and planned for Manning Creek. Table S2 shows the daily emission rates of key pollutants. Burn units for Monument Peak and Manning Creek are shown in Figure 2.

Table 1. Modeled prescribed fire location, fuel type, and timing.

Fire Name	Latitude	Longitude	Size (acres)	Start hour LST	End hour LST	Dominant fuel types
Monument Peak (Fishlake NF)	38.5445	-111.9529	800	16	23	50% aspen, 30% shrub, 18% mixed conifer-hardwood
Manning Creek (Fishlake NF)	38.4335	-112.0863	1000	16	23	75% mixed conifer-aspen, 20% aspen, 5% shrub
Fort Stewart	31.9797	-81.8285	868	11	14	Longleaf and loblolly pine

Figure 2. Monument Peak and Manning Creek burn units at Fishlake NF.

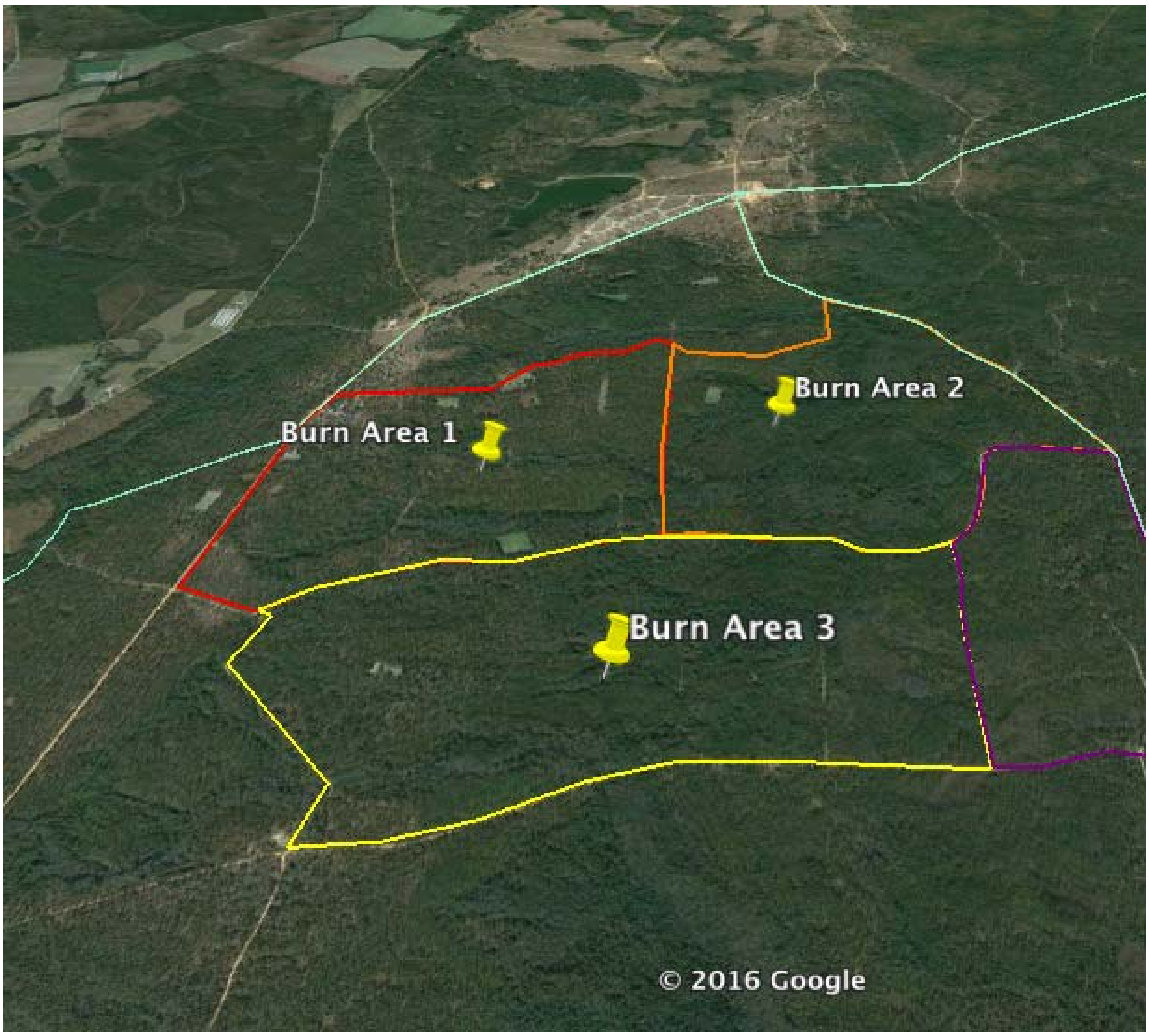


Southeast U.S. Hypothetical Burn Scenario 1

The modeling system was applied for a burn unit at Fort Stewart, GA that may be part of the FASMEE Phase II field study (see Figure 3) for each day of 2013 to illustrate seasonal variability in predicted secondary pollutant formation. CMAQ was applied with 4 km sized horizontal cells and 35 vertical layers from the surface to 50 mb. The vertical structure of the troposphere is shown using sigmas in Table S1.

The burn units at Fort Stewart consist of mostly long leaf and loblolly pine fuel types. The understory is typically wire grass, palmetto, and other hardwood. Coordinates, area size, and assumed start and end times are shown in Table 1. For this model simulation, burn area 3 (see Figure 3) was used as the hypothetical prescribed burn and was assumed to burn between the start and end hours in Table 1 for each day of 2013. Table S2 shows the daily emission rates of key pollutants for the hypothetical burn.

Figure 3. Overview of the northwest area of Fort Stewart with burn units set aside for future FASMEE burns. Burn area 3 was modeled for this assessment.



Southeast U.S. Hypothetical Burn Scenario 2

A second burn unit at Fort Stewart, GA was modeled for February 15, 2013. This simulation used an alternative set of prognostic meteorological input data which was taken from the WRF-SFIRE model which was applied both with and without the prescribed burn unit fire. WRF-SFIRE and CMAQ were applied with the same 40 vertical layers form the surface to 100 mb (see Table S1 for sigma structure) and 4 km sized grid cells. WRF-SFIRE output was re-projected to a Lambert conic conformal projection centered at -97,40 with true latitudes at 33 and 45 consistent with the CMAQ system.

WRF-SFIRE modeled the fire simulation from 10 am to 7 pm LST covering a total of 346 acres. Other emissions sources (anthropogenic and biogenic) are based on 2011 National Emission Inventory with 2013 specific information for specific point sources where available to provide a realistic chemical environment for the fire.

RESULTS & DISCUSSION

The regulatory modeling system used to estimate local to regional scale wildland fire impacts on O_3 and $PM_{2.5}$ is complex and includes numerous components that each need to be evaluated and constrained to develop a modeling platform that could be used to support testing of new science.

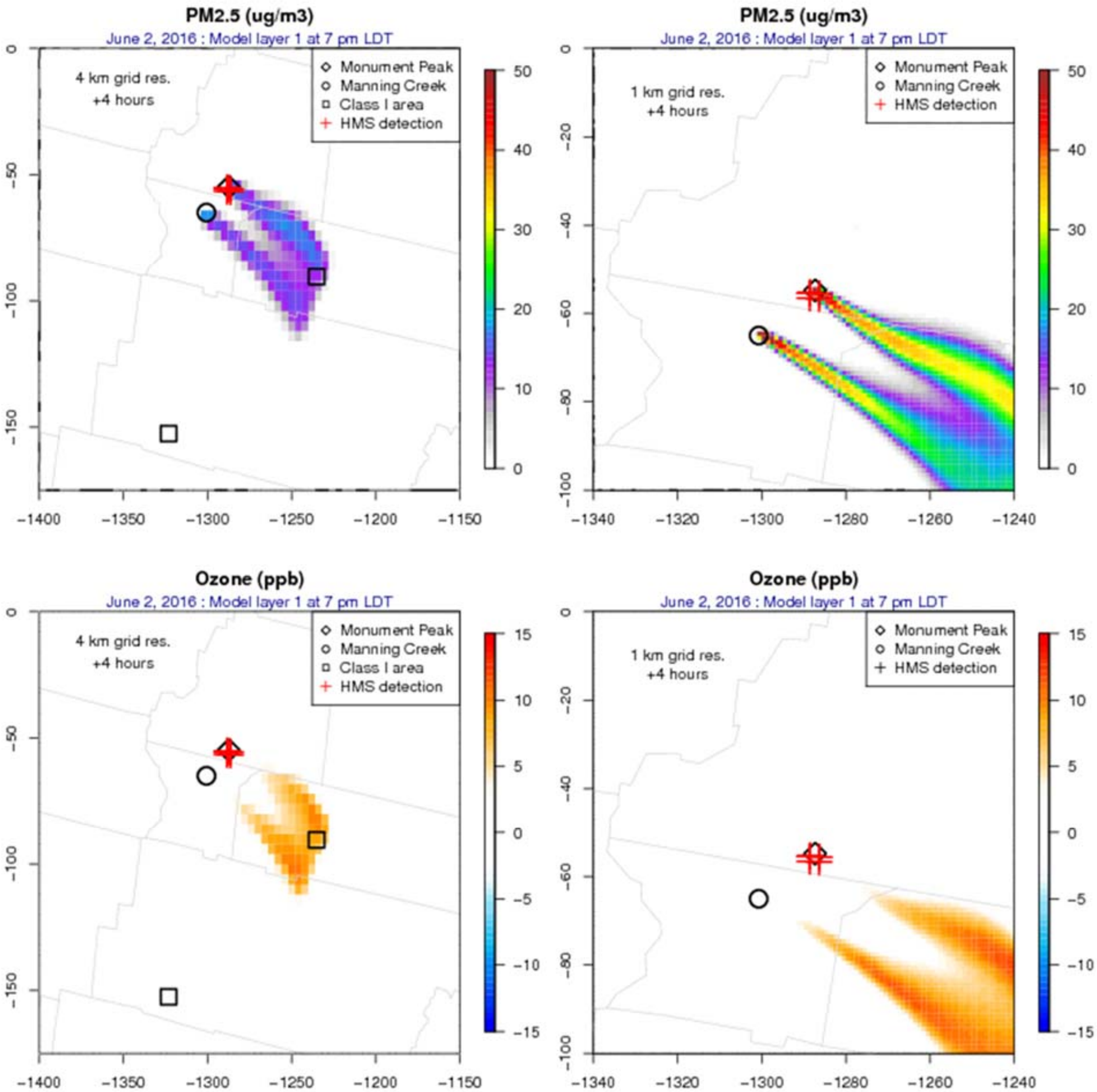
FIRE LOCATION & SIZE

Emissions estimated by the BlueSky framework require daily fire location, burned area, and type of fire (wild or prescribed) as input. This information is collected through the SmartFire2 system which combines satellite burn detection and burn scar area information with ground-based information about location and burned area from land management agencies. However, there are known limitations with satellite detection and burn area estimates which may overestimate small fires, miss small fires entirely due to nadir imaging capability of satellites, and confound estimates in a variety of other ways that could result in an inflation or deflation of wildland fire burn area.

Measurements taken as part of the FASMEE field study will be useful for model evaluation and development by providing very specific information about burn location, timing, and area burned that can be used to compare with the current SmartFire2 approach. The information could also be used to better calibrate burn location and size estimates for smaller sized fires burned as part of FASMEE and also for larger fires assessed for burn area as part of WE-CAN, FIREX, and FIRECHEM.

Each of the prescribed fires modeled here were estimated with known burn area from the host agency or a planned burn area anticipated as part of the upcoming FASMEE field study. The June 2 2016 Monument Peak burn at Fishlake NF is the only actual historical burn modeled as part of this assessment and was included in the Hazard Mapping System (HMS) satellite detection product with 4 separate detected locations (Figure 4). The detected locations compare well with the Monument Peak burn unit centroid estimate used for this assessment shows prescribed fires of that size can be recognized by satellites.

Figure 4. Modeled $PM_{2.5}$ and O_3 impacts from Monument Peak and Manning Creek burn units in Fishlake NF on June 2, 2013. Monument Peak was an actual prescribed burn and Manning Creek is a hypothetical scenario. Satellite fire detections are shown as red crosses (N=4).



EMISSION FACTORS

The BueSky framework takes fire location, type (wild or prescribed), and burn area as input to determine the fuel type, total fuel consumed, and daily emission factors for CO, $PM_{2.5}$, VOC, CH_4, NO_X, SO_2, and NH_3. The prescribed fires modeled as part of this assessment are based on known location, type, and burn area. Having that information is useful to constrain the inputs to BlueSky to known values to better isolate the skill of the BlueSky modules to estimate daily emissions. The dominant fuel types at both Fort Stewart and Fishlake NF were consistent between known field information and that estimated by the

CONSUME module. Coordinates chosen to represent a potential burn unit in the North Kaibab NF at Jacob Lake resulted in a biomass type of sagebrush shrubland which missed the extensive Ponderosa pine in the area.

Since no measurements of O_3, $PM_{2.5}$, and precursor species were taken at the Monument Peak burn on June 2, 2016 the emission factors estimated by CONSUME and emissions speciation estimated by SMOKE (using SPECIATE database information) cannot be evaluated or constrained for evaluation of modeled plume transport and chemistry in the CMAQ photochemical transport model. The FASMEE field study will provide extremely valuable near-fire measurements at the surface and above-canopy of O_3 and $PM_{2.5}$ precursors to evaluate the BlueSky framework emission estimates and also to constrain emissions input to the photochemical model so that plume transport and chemical evolution can be evaluated without being confounded with highly uncertain emissions estimates as input.

Another important opportunity for evaluating estimated emission factors will be information generated as part of the 2016 laboratory component of FIREX. A variety of fuel types, some of which were taken from Fort Stewart and Fishlake NF, were burned at the Missoula Fire Lab in the fall of 2016 and results including biomass specific emission factors should be available by the time each of the FASMEE field study components are completed. Ideally, this type of chamber work estimating emissions and speciation from different fuels and fuel combinations would continue with fuel samples from field studies planned in 2018 and 2019.

Field study data collected as part of FASMEE and laboratory biomass specific emission factors collected from studies such as WE-CAN, FIREX, and FIRECHEM will be characterized by combustion component (e.g., flaming, smoldering, residual smoldering) which will allow for an evaluation of BlueSky estimating emission factors by combustion component. This is important for secondary pollutant formation since emissions of certain precursors can substantially vary between the flaming and residual combustion phases.

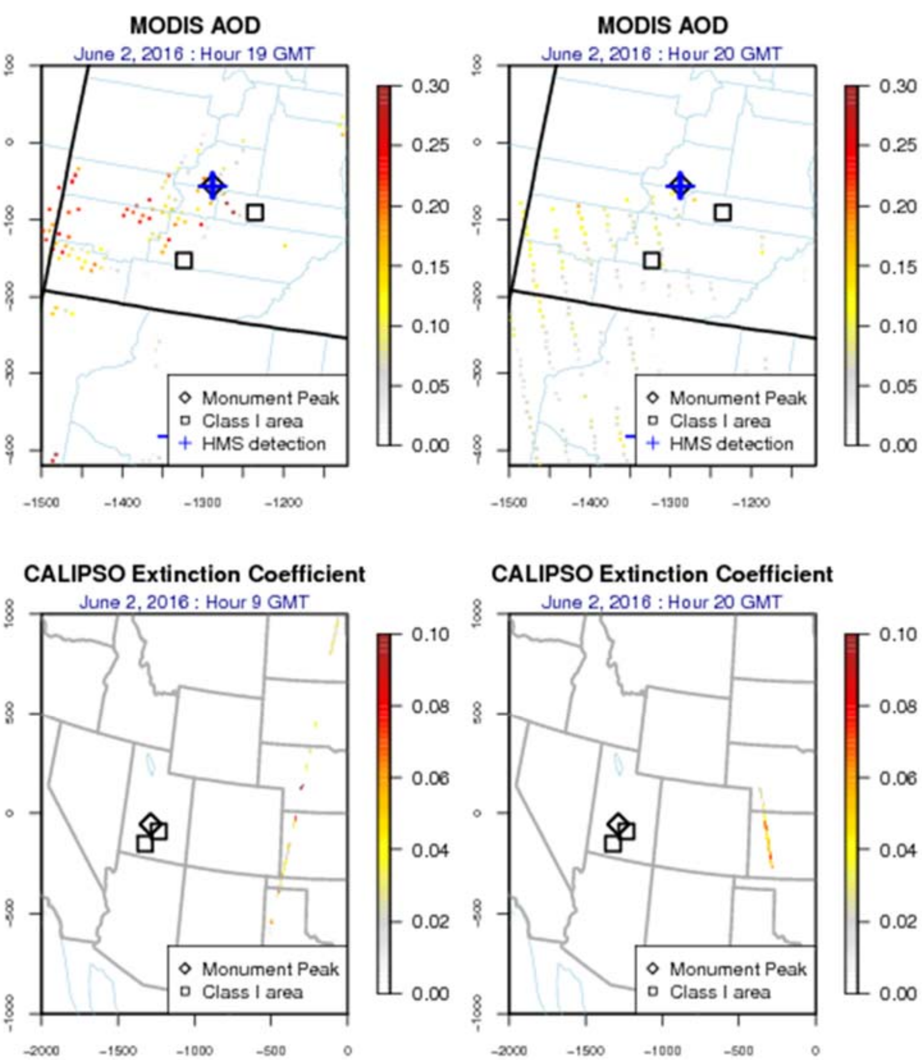
Speciation of O_3 precursor gases and $PM_{2.5}$ and $PM_{2.5}$ precursors are extremely important to appropriately characterize plume chemical evolution. Emitted VOCs have very different levels of reactivity towards O_3 formation and also have different potential for secondary organic aerosol (SOA) formation. The speciation of oxidized nitrogen gases (e.g., NO, NO_2, HNO_3, PAN, etc.) are important to accurately simulation local to regional scale O_3 production. $PM_{2.5}$ is largely comprised of organic aerosol but other components like elemental carbon have important radiative effects which means accurately spectating the $PM_{2.5}$ emissions estimated by CONSUME is important for modeling fire impacts on the environment and climate.

PLUME RISE AND TRANSPORT

Hourly emissions generated by the SMOKE model are input to the CMAQ photochemical grid model. Heat flux is estimated based on area burned to determine plume buoyancy and to distribute emissions from the fire vertically in the atmosphere. Currently CMAQ uses the Briggs plume rise approach which was originally developed for large industrial point sources (Paugam et al., 2016). The Briggs approach may be realistic for some types of fires but is unlikely to be appropriate for all types of wildland fires. The vertical plume extent modeled for the Monument Peak burn unit at Fishlake NF cannot be evaluated or constrained to evaluate chemical evolution due to the lack of measurements. The FASMEE field study should provide information about meteorology and levels of key pollutants from the ground, through the canopy, above canopy, and into the free troposphere to provide a 3-dimensional characterization of plume rise and transport near the fire. This type of information can be used to evaluate the model and serve as a platform for testing the implementation of new approaches for plume rise and near-fire transport and whether these approaches should vary depending on combustion component (e.g., flaming compared with residual smoldering).

In particular, ground and aircraft based lidar estimates of aerosol backscatter provide extremely useful information about the vertical distribution of aerosol to support plume rise evaluation. Having vertical aerosol distribution transects through the fire plume from aircraft based lidar (either provided through FASMEE or NASA's FIRECHEM project) would provide information about both the vertical distribution and how that changes across the plume and as the plume moves downwind. Remote sensing based lidar such as CALIPSO provides another opportunity for vertical structure information. However, the satellite would need to be trained to overpass FASMEE prescribed burns in order to take advantage of that data. For instance, the CALIPSO product does not provide an overpass of the June 2016 Monument Peak prescribed fire in Fishlake NF (see Figure 5).

Figure 5. Satellite estimated aerosol optical depth (AOD) and extinction coefficient for available overpasses on June 2, 2016.



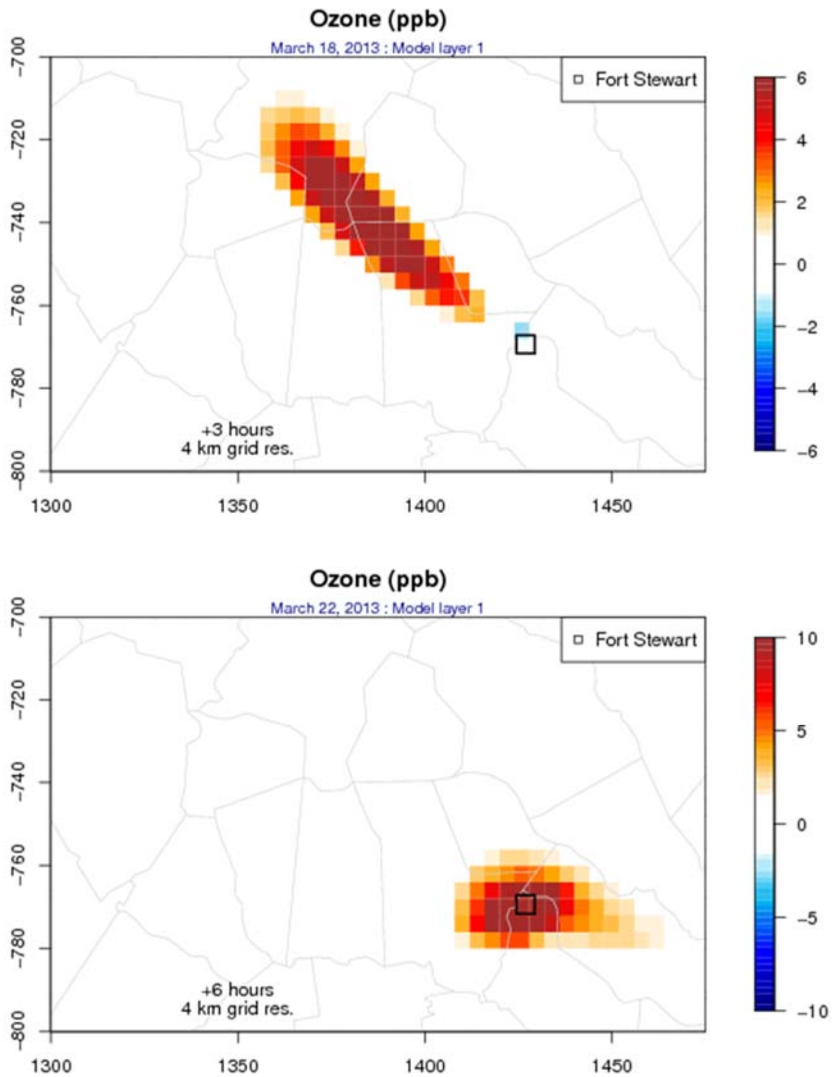
Regional scale plume extent in the horizontal direction can be informed from remote sensing information, most notably MODIS estimates of aerosol optical depth (AOD). This product can be useful for model evaluation but has limitations with respect to fires. These limitations may be better understood using data collected as part of the FASMEE prescribed fires. MODIS AOD for June 2 is shown in Figure 5 and illustrates the challenges associated with this product for evaluating smoke plume horizontal extent and also modeled total column aerosol. Cloud cover and reflective surfaces common in the western U.S. make AOD retrieval complicated and can result in no information being available. Also, as shown in Figure 5 for the Monument Peak prescribed fire it is difficult to differentiate impacts from that fire from other sources due to satellite product resolution, overpass timing, and other confounding issues already noted.

Since regional scale photochemical models track impacts of wildland fire to areas far downwind it is important to capture the physical processes important for nighttime plume rise and transport. While prescribed fires in the southeast may not flame overnight it is possible to have extended residual smoldering that can generate smoke overnight in the canopy. In these situations, or where wildland fires do burn overnight it is important to have information about the vertical extent of the plume to provide information for models to compare with while developing approaches for nighttime conditions that may need to be treated differently than daytime conditions. Also, it is important the modeling system capture the day to night transition and differentiate transport fate for smoke in the surface mixing layer, the free troposphere, and any residual layers in between.

PLUME CHEMICAL EVOLUTION

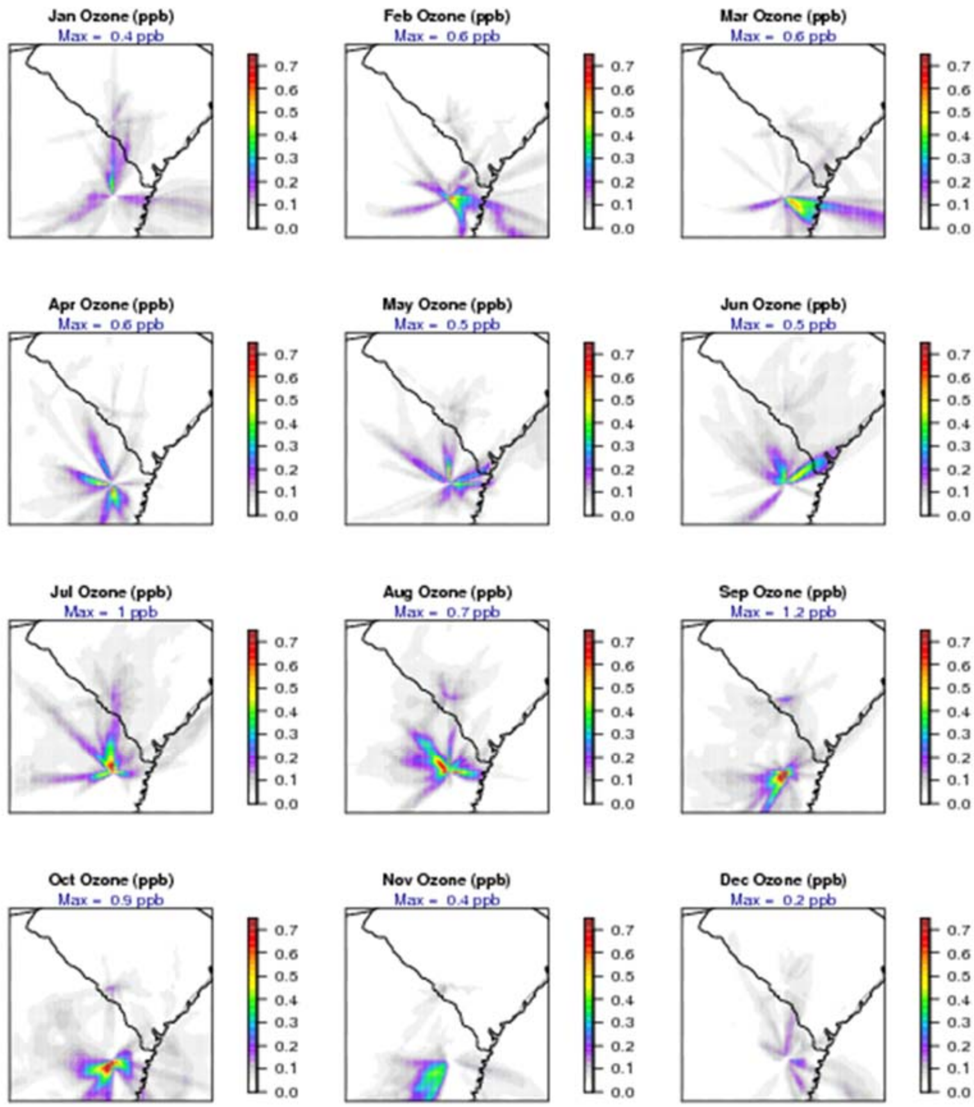
Photochemical grid modeling has been done for an area planned to be burned for the FASMEE field study at Fort Stewart, Georgia and Fishlake NF to estimate O_3 impacts from planned prescribed burns. At the Fort Stewart location, the planned prescribed fire and subsequent air quality impacts are simulated for each day of the entire year of 2013 to illustrate seasonal variability in O_3 formation. Model estimated O_3 from the hypothetical fire is shown for March 10, 2013 at 3 hours past ignition and March 22 at 6 hours past ignition (Figure 6). The top panel of this Figure illustrates near-fire O_3 inhibition with the cool color shading and formation downwind with the warm color shading. Near-fire inhibition is likely related to NO titration since photolysis due to fire smoke is not strongly attenuated in this version of CMAQ. Figure 6 shows that even during the cooler season O_3 can form from a typical prescribed fire in this region. This hypothetical prescribed fire can lead to much larger O_3 impacts especially during periods of stagnant winds as shown in the bottom panel of Figure 6.

Figure 6. Model estimated O_3 (ppb) on March 18, 2013 at 3 hours past ignition (top) and March 22, 2014 at 6 hours past ignition (bottom).



Modeling prescribed fires at both Fishlake NF and Fort Stewart show that O_3 production happening at 10 km downwind with O_3 inhibition closer to the fire due to fresh NO emissions destroying O_3 faster than it can be produced. Field study measurements are critically important to evaluate whether this modeled near-fire to local scale O_3 evolution in smoke plumes is realistic. The trend of higher O_3 impacts from this hypothetical prescribed fire is evident when looking at monthly average impacts. Monthly average impacts tend to be highest during the warm season and lowest during the cooler months with late fall (of 2013) being the least conducive to O_3 formation in this area. Monthly average O_3 impacts for this prescribed fire are shown in Figure 7.

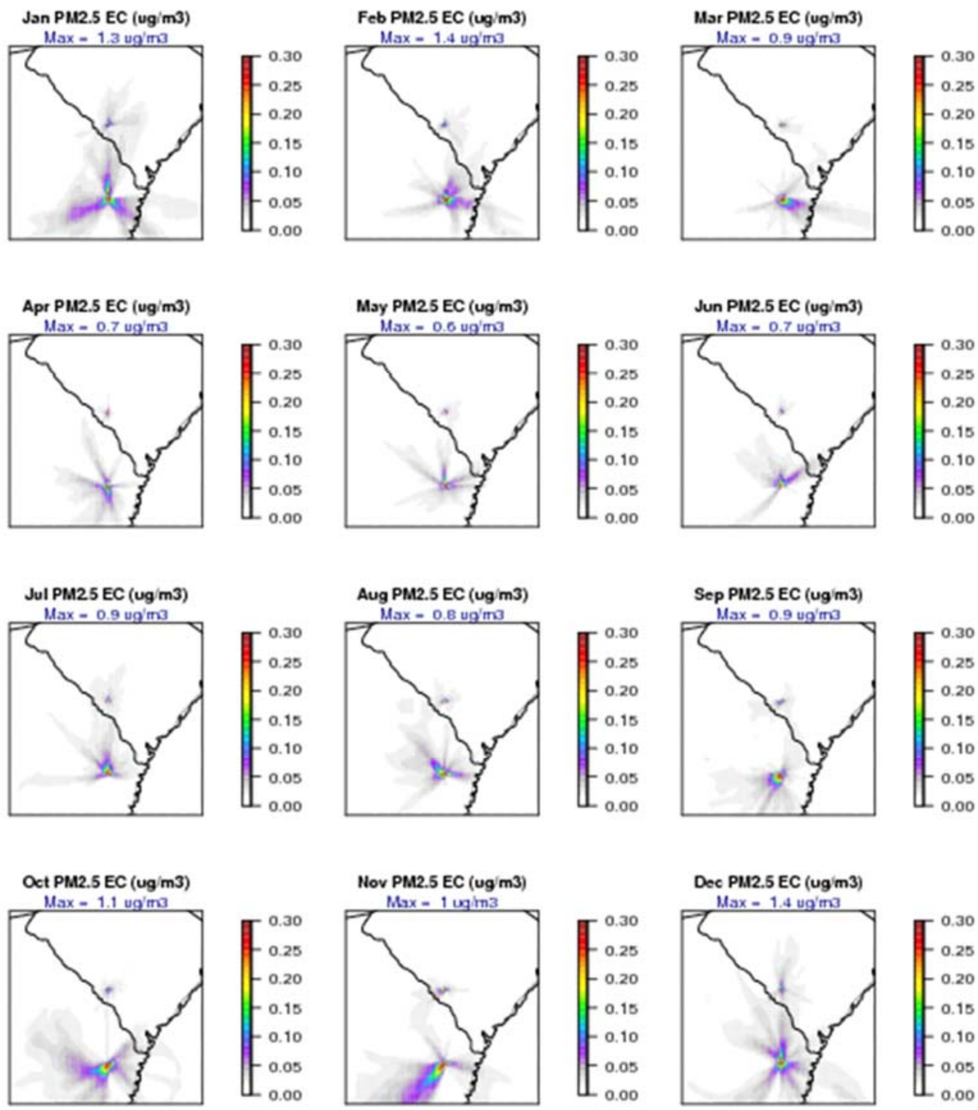
Figure 7. Monthly average O_3 impacts from the hypothetical prescribed fire.



Measurements of O_3, precursors, and important chemical intermediate species are needed to provide information to fully evaluate the photochemical evolution in smoke plumes. Further, optical information is needed about the smoke plume to provide more realistic information about how well smoke plumes attenuate incoming solar radiation which is necessary for photochemical reactions to occur. Photolysis rate attenuation where PM2.5 concentrations are highest has been shown to have notable impacts on O_3 production in smoke plumes (Baker et al., 2016; Jiang et al., 2012). Light scattering and absorptive properties of brown and black carbon (largest components of $PM_{2.5}$ in smoke) and photolysis rates should be measured to better constrain and improve model representation of photochemistry of wildland fire smoke.

Monthly average impacts on $PM_{2.5}$ elemental carbon are shown in Figure 8. The opposite trend is seen for primarily emitted particulate matter. $PM_{2.5}$ elemental carbon surface level concentrations are driven by the height of the mixing and tend to be highest during the colder months when the mixing layer is lower thereby increasing concentrations.

Figure 8. Monthly average $PM_{2.5}$ elemental carbon impacts from the hypothetical prescribed fire.



CONCLUSIONS

Planned field studies focused on prescribed and wild fires will provide useful data toward the evaluation and development of various components of the modeling system (Table 2). A well characterized wildland fire event in terms of fuel type, fuel loading, canopy, and surface characteristics used to estimate fire event emissions can be compared with methods (e.g. SmartFire and BlueSky components) currently being used for fire event emissions estimates in the National Emission Inventory (NEI). Better emissions estimates by fuel type and combustion conditions (e.g., flaming to smoldering components of the fires) are anticipated. Anticipated measurements will also lead to improved PM, VOC, and nitrogen gas 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 yet have significant impacts on both primary emissions and subsequent downwind secondary chemical pollutant production. Near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species along with distance and time from the fire event will provide critical understanding of near-fire chemistry and downwind chemical evolution of these pollutants during both day and night-time hours. Field study measurements will provide information for developing a better spatial allocation vertically of smoldering and flaming emissions for both prescribed and wild fires.

Table 2. Description of field study measurements needed to improve various components of the modeling system.

Modeling System Component	**Description of need toward evaluation and development**
Fire location, size, fuel type	Fire location, area burned, fuel type, fuel moisture, and fuel consumption will help evaluate existing approaches for estimating these parameters.
Emissions	Fire emissions of speciated $PM_{2.5}$, precursors to secondarily formed $PM_{2.5}$, and precursors to O_3 formation are needed by fuel type and combustion component (flaming to smoldering) to improve estimates of chemically speciated $PM_{2.5}$ and O_3 impacts from wildland fires. Speciation of VOC and nitrogen gases for different combustion conditions are not very well characterized yet have significant impacts on both primary emissions and subsequent downwind secondary chemical pollutant production. These measurements should improve VOC, nitrogen gas, and PM emissions speciation and better differentiate emissions and chemical production at different scales of plume aging.
Plume rise & transport	Fire plume rise and vertical allocation into the atmosphere is not currently well characterized in photochemical grid models. Warm and cold season field study measurements of heat flux, meteorology, and chemical measurements will allow for better spatial allocation vertically of smoldering and flaming emissions.
Plume chemical evolution	Near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species along with distance and time from the fire event will provide critical understanding of near-fire chemistry and downwind chemical evolution of these pollutants during both day and night-time hours. 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. Speciated $PM_{2.5}$ organic aerosol measurements are needed near the fire and at multiple distances downwind to better understand dilution impacts on $PM_{2.5}$ organic carbon evolution in fire plumes.

Fundamental science improvements are needed in fire emissions estimation, micro to regional scale smoke plume dispersion, micro to regional scale gas and particle chemical evolution of smoke plumes, and plume optical properties important for understanding climate impacts and also indirect chemical production impacts through photolysis attenuation. 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.

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Final Report for Joint Fire Science Program Proposal Number 16-4-05-4
SUPPORTING INFORMATION

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Table S1. Vertical layer structure (sigmas) of WRF and CMAQ from surface to model top.

Layers	Sigmas
35 (up to 50 mb)	1.0, 0.9975, 0.995, 0.99, 0.985, 0.98, 0.97, 0.96, 0.95, 0.94, 0.93, 0.92, 0.91, 0.9, 0.88, 0.86, 0.84, 0.82, 0.8, 0.77, 0.74, 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.4, 0.35, 0.3, 0.25, 0.2, 0.15, 0.1, 0.05, 0.0
40 (up to 100 mb)	1., 0.993, 0.983, 0.97, 0.954, 0.934, 0.909, 0.88, 0.8530455, 0.826091, 0.7991365, 0.772182, 0.7220022, 0.6741802, 0.6286237, 0.5852433, 0.5439528, 0.5046687, 0.4673103, 0.4317998, 0.398062, 0.366024, 0.3356156, 0.3067692, 0.2794191, 0.2535023, 0.2289577, 0.2057266, 0.1837522, 0.1629797, 0.1433563, 0.1248313, 0.1073555, 0.09088176, 0.07536444, 0.06075971, 0.04702533, 0.03412061, 0.02200639, 0.01064495, 0.

Table S2. Daily emission totals for Fishlake and Fort Stewart prescribed fires. All emissions units are tons/day.

Pollutant	Manning Creek	Monument Peak	Fort Stewart
ACRESBURNED	1,000.0	800.0	868.0
CH4	85.9	68.7	3.4
CO	1,756.5	1,405.2	65.6
CO2	20,449.9	16,359.9	1,299.9
NH3	28.8	23.1	1.1
NOX	23.4	18.7	1.8
Primary PM2.5	151.0	120.8	6.4
SO2	13.0	10.4	0.8
VOC	414.3	331.4	15.7