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Supplementary material

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

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Supplementary Material

Supplement A: Setup of model simulations and experiments

WRF-SFIRE-CHEM

(1) Plume evolution: Simulations for the planned experimental burns were performed for all three planned FASMEE sites. The one for the Fort Stewart scenario was performed for February 14th 2013 to estimate the range of expected vertical velocities, plume top height and the burn duration needed so that the plume can reach a quasi-equilibrium state, as well as to provide an insight into the impact of the ignition procedure on plume evolution. It used a multiscale setup of 5 nested domains with the atmospheric resolutions of 36km, 12km, 4km, 1.33km, 444m, and 148m, 41 vertical levels, and the fire mesh of 30m.

(2) Impact of the ignition procedure: As the aerial ignition procedure is generally fast and difficult to be precisely captured by scanning IR systems, it is important to know how important the ignition itself is for further plume evolution. In order to assess that, 5 different ignition procedures were simulated: a single ignition point, a single ignition line of two different thicknesses, a set of 3 parallel lines, and a set of 5 parallel lines. All ignition lines were oriented approximately perpendicular to the mean wind.

(3) The most critical parameters: A sensitivity analysis was conducted to identify the most critical model parameters impacting vertical plume velocities, plume top height, and smoke concentrations. This analysis also provided information about how the model's sensitivity to a given parameter changes spatially. Generated maps of the sensitivity of simulated plume velocities, plume top height, and smoke concentrations to parameters such as fuel moisture, fire heat flux, and heat extinction depth provided a visual recommendation where variations in model

parameters tend to impact plume dynamics in the most pronounced way, and consequently where the plume should be sampled.

(4) Fuel moisture, heat extinction depth, heat flux and rate of spread: These properties were analyzed using the repeated Latin Hypercube Sampling (rLHS). This method not only informed where the measurement should be taken to constrain model parameters but also allowed to find the relative contribution of the analyzed parameters to variances in the variables of interest (McKay et al. 1979; McKay 1995; Saltelli et al. 2004). The results from this analysis is presented in Kochanski et. al 2018.

WFDS and other models

An approach called "the burner method" was used with MesoNH, WFDS-LS, WFDS-PB, WRF-SFIRE and Daysmoke to understand and compare the impacts of fire intensity, wind, and stability on smoke development. The burner method can be used to simulate smoke generation and transport using measured rather than simulated the heat and mass generated by the fire. Thus, any model that explicitly resolves plume dynamics will be provided with sufficient information to model plume rise without having to model wildland fire behavior, which either requires too much computational resources with more complete physics-based fire spread models or is subject to largely unknown errors with simple fire spread models.

A stationary burner was represented by a line fire of 750 m long by 25 m deep and heat release rate per unit area (HRRPUA) of 2000 kW m^{-2}, which is characteristic of fires observed during the International Crown Fire Experiment (Stocks *et al.*, 2004). This fire is larger, in depth and HRRPUA, than most of the candidate FASMEE burns. However, its depth is large enough that the physics based model WFDS-PB can be used. Two ambient wind speeds as described by the vertical profile $u(z) = u_o(z)^{1/7}$ where u_o= 1 m/s or 5 m/s are used for the upwind boundary condition and initial condition. Also, for each u_o value, two lapse rates of 0 and -6 °C/km were used. The line fire is 500 m downwind of the inflow boundary. The computational grid resolutions are 50 m for the atmospheric weighted models of MesoNH and WRF and 5 m for WFDS-PB. WFDS-LS was run with both 5 m and 50 m resolutions. Daysmoke is the simplest of the models considered and operates by representing the flaming area as a circle with a 155 m diameter, which has the burned area equivalent to the burned area of 25 m × 750 m for the line fire. For Daysmoke simulation, various values of exit temperature, exit velocity, and effective diameter were used.

Daysmoke and PB-P

(1) *Weather conditions for anticipated smoke plume:* Daysmoke was simulated for hypothetical burns at Ft Stewart using the weather conditions during February 5-8, 2011 to identify the weather systems that would produce the desired smoke plumes from prescribed burns for the FASMEE field campaign (Liu *et al*. 2018). A weak and a strong trough moved though the modeling region on the first and last day of the simulation period, respectively, and a weak ridge occurred between the two days. The weather conditions changed remarkably from warm and moist to cool and dry during the 4-day period.

(2) Sub-plumes: Observations of plumes from large-perimeter prescribed burning reveal the presence of sub-plumes (or multiple updraft cores). Each single sub-plume has a smaller diameter than a plume of the entire fire. It would be more impacted by entrainment and thus would be expected to grow to a lower altitude. Two types of sensitivity techniques were applied using Daysmoke to understand the dependence of smoke plume rise on multiple core number. One technique called “the 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). 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.

(3) Nightime drainage and fog: 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. Simulations were made with PB-P to understand the formation and distribution of smoke drainage and resultant fog, which can affect local visibility and traffic. A prescribed burn conducted on October 18, 2016 in the Kaibab National Forest, AZ was examined. A vehicle accident occurred on I-40 approximately 35 km west of Flagstaff, Arizona during the early morning of the next day.

CMAQ

The CMAQ modeling system has been applied for specific wildfire events (Baker et al. 2016) and configured to represent actual burn units at locations that routinely perform prescribed burns in the southeast (Fort Stewart) and western (Fishlake National Forest) U.S. to illustrate model capability at different grid scales and aspects that need constraint with field study measurements. Model simulations are focused on O_3 and $PM_{2.5}$ impacts because both of these pollutants have known negative health impacts and regulated with National Ambient Air Quality Standards (NAAQS). An 868 acre burn unit planned to be part of FASMEE at Fort Stewart, GA was modeled for each day of 2013 to understand seasonal variability in photochemical O_3 production to inform the time period selection for southeast field study measurements.

Supplement B: Burner method for smoke plume model development

Models that explicitly simulate gas-phase combustion and the thermal degradation of vegetation (e.g., FIRETEC and WFDS-PB) are likely to be too computationally demanding for routine simulation of large area burns (>10 ha) characteristic of most of the FASMEE burns. Other model approaches, such as WRF-SFIRE, WFDS-LS, and Daysmoke - Rabbit Rules Model (RRM) (Achtemeier *et al.* 2012), rely on simple fire spread models (with largely unknown errors) for the location and duration of the fire. In the context of smoke model validation, it would be advantageous to eliminate the need to simulate the fire, explicitly or implicitly, and use measurements to prescribe the heat and mass generated by the fire. An approach has been formulated that does this and is called the burner method (Mell and Linn 2017). The process would allow all of the above-mentioned models to be consistently applied to smoke plume rise and their outcomes compared. An example of this, an idealized burner representing a line fire was given in the Simulations and Experiments described in the main context of this paper.

The burner method is a process where the heat and mass generated by the fire is prescribed based on field measurements. The major benefit of the burner method for modeling is that it provides any model that explicitly resolves plume dynamics with sufficient information to model plume rise without having to model wildland fire behavior. The burner method also simplifies and focuses the measurements. The key measurements for this purpose are the minimum set that results in the determination, at all locations along the fire perimeter relevant to smoke plume formation, the time-course of heat and mass fluxes generated by the fire; that is, areas of active flaming are idealized as “burners”.

In general, the burner method needs the following measurements and information: (1) Characterize the location, fuel consumption rate, and flame residence time of areas aflame that are associated with sufficient heat generation to influence plume formation and rise. At a minimum, this should be measurement of head-fire regions along the fire perimeter. More specifically, the minimal set of measurements needed must include: (a) Flaming location and duration, which can be derived from qualitative airborne infrared or visible imagery at spatial and temporal resolutions sufficient for igniting and extinguishing the “burners”. (b) Fuel consumption rate from pre- and post-fire fuels measurements or time-integrated quantitative airborne infrared radiation to estimate total heat generated. This is used to estimate the heat release rate per unit area for model input. ROS, in combination with other data, can be used to estimate other flame front characteristics such as residence time (i.e., duration of flaming). The residence time may be more directly measurable from imagery, thus avoiding the need to determine the ROS. (2) Pre-fire vegetation and terrain measurements are needed to help develop the strategy for locating the ground-based fire measurements to support the determination of flame front residence time and burning rate per unit area from the airborne imagery. (3) Information gathered from fire operations experts and past experiments (e.g., RxCADRE) on expected fire behavior (e.g., fire depth, spread rates, and the influence of vegetation types), ignition procedures, and measurement performance (when available) for each candidate site. This is critical for assessing the scope, location, and the resolution of both the ground and airborne-based measurements.

Acronyms

AIRPACT - Air Indicator Report for Public Awareness and Community Tracking

ARPS-DEVS - Advanced Regional Prediction System - the Discrete EVent System

CAMx - Comprehensive Air Quality Model with Extensions

CAWFE - Coupled Atmosphere-Wildland Fire-Environment

CFD - Computational Fluid Dynamics

CAMx - Comprehensive Air Quality Model with Extensions

CMAQ - Community Multiscale Air Quality

ECMWF - European Centre for Medium-Range Weather Forecasts

EOL - Earth Observatory Laboratory

FASMEE - Fire and Smoke Model Evaluation Experiment

FAST - Fourier Amplitude Sensitivity Test

FCCS - Fuels Characterization Classification System

FEPS - Fire Emission Production Simulator

FIREChem- Fire Impacts on Regional Emissions and Chemistry

FIREX - Fire Influence on Regional and Global Environments Experiment

GFED - Global Fire Emissions Database

HMS - Hazard Mapping System

HYSPLIT - Hybrid Single-Particle Lagrangian Integrated Trajectory

IFS - Integrated Forecasting System

LDT - local daylight time

LES - large eddy simulation

LIDAR - Light Detection and Ranging

LST - local standard time

MCE - modified combustion efficiency

NAAQS - National Ambient Air Quality Standards

NCAR - National Center for Atmospheric Research

NEI - National Emission Inventory

NF - National forest

PBL - planetary boundary layer

PB-P - Planned Burn – Piedmont

PM - particulate matter

$PM_{2.5}$ - particulate matter that have a diameter of less than 2.5 micrometers

RAWS - Remote Automated Weather Station

rLHS - Latin Hypercube Sampling

ROS - rate of spread

RRM - Rabbit Rules Model (RRM)

RxCADRE - Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment

SEMIP - Smoke and Emissions Model Intercomparison Project

SMOKE - Sparse Matrix Operator Kernel Emissions

SRF - smoke research and forecasting

UCAR - University Corporation for Atmospheric Research

VOC - volatile organic compound

WE-CAN - Western wildfire Experiment for Cloud chemistry, Aerosol absorption and Nitrogen

WFDS - Wildland-urban interface Fire Dynamics Simulator

WFDS-LS - level set based component of WFDS

WFDS-PB - physics-based component of WFDS

WRF - Weather Research and Forecast model

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