FINAL REPORT

Title: Development of a comprehensive plume dynamics and meteorology study plan for FASMEE

JFSP PROJECT ID: 16-4-03-1

May 2017

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Abstract

The goal of this project was to develop the Plume Dynamics and Meteorology portion of the Study Plan for the Fire and Smoke Model Evaluation Experiment (FASMEE). The Investigators participated in regular meetings with the other discipline leads, modeling leads, and the science leadership team; field trips to examine potential sites for the eventual burns; contacted peers and vendors relevant to plume dynamics and meteorology; developed draft budgets, measurement plans, and specifications for those measurements; and helped with the initial draft of the Study Plan. This report summarizes the Plume Dynamics and Meteorology elements of that Study Plan.

Objectives

The scope and specific deliverables related to the FASMEE Phase 1 FON and Task Statement (16-4-03) were modified by direction of the Joint Fire Science Program as details about the overall FASMEE funding process coalesced. The final discipline-lead deliverables for Phase 1 were:

- Proposing an observational study design for observations in their discipline area
- Writing up a study design
- Determining observational specifications required for the [Phase 2] Funding Opportunity Notice
- Draft Study Plan sections on each discipline, draft budgets, draft appendices of measurements by discipline, and other documents detailing the design for review, including their relationship to the current state of the science

This project made significant contributions in terms of gathering and providing information, and writing Study Plan Appendices. However, aggregating this information, drafting and finalizing the FASMEE Study Plan and Phase 2 FON are responsibilities that fall on the FASMEE Leadership Team. These deliverables will be provided to the JFSP directly from the FASMEE leadership Team.

Background

The plume of a fire is initially driven by the fire's behavior (e.g. intensity, geometry and their variation in time) but as it develops it is increasingly controlled by the three-dimensional temperature, humidity, and wind structure of the atmosphere. Stability and wind shear strongly control the development and propagation of the updraft, and as that updraft moves farther from the fire the relative influence of these atmosphere increases. A variety of fire field studies have included attempted to measure fire plumes or meteorology around fires. The most notable are Project Flambeau (United States; Countryman et al. 1969); Operation Euroka (Australia; Williams et al. 1970); The International Crown Fire Modeling Experiment (Canada; Stocks et al. 2004); FROSTFIRE (United States; Hinzman et al. 2003); FireFlux (United States; Clements et al. 2007); and the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE, United States; Ottmar et al, in press). For an extensive review of fire plume research and relevance to operational fire management, see Potter (2012) and relevant chapters of Werth et al. (2011). These studies provided insights into the basic structure of fire plumes, but none focused specifically on the plume dynamics, or were large enough in scope to yield data that could inform models of wildfire plumes.

Capturing these complex atmospheric processes is part of FASMEE's focus. To accomplish FASMEE's goal of improving smoke and fire modeling systems, it is necessary to capture as much information as possible about the meteorological conditions in and around the fires studied, including the circulations produced by the fires themselves and any feedback processes between the fire and the atmosphere. This includes, for example, the vertical profile of the winds entering the fire from the upwind side; the turbulence spectrum of winds in the profile, as they are affected by the vegetation structure; the same wind profiles on the downwind side of the fire; the structure of the fire's plume, including distinct updrafts and downdrafts along the active combustion front as they evolve during the burn; temperature and moisture properties of the air in the plume.

Historically, these properties and processes are among the least studied aspects of fires. Yet, they influence fire behavior through modification of the airflow feeding the fire, and smoke through lofting and entrainment. This is largely because they are the most difficult to measure. They span the full area of the burn, as well as upward from the ground to the top of the smoke plume. They require instruments capable of surviving the fire's heat, or able to measure remotely. Those instruments have not existed for very long, and are generally expensive. Evolution of other aspects of fire and smoke models, however, has brought them to the point that lack of data on these above-ground properties is arguably their greatest limitation.

Based on these challenges and data needs, the co-leads for the FASMEE Plume and Meteorology discipline considered how to best obtain data on the following topics:

- Turbulent energy spectrum of the fire and environment
- Acceleration of the updraft at the base of the plume
- Cause and effect relations between surges in fire intensity and plume velocity
- Transient (nonsteady) characterization of airflow
- Entrainment rates as they relate to ambient wind profile and updraft strength
- Plume air temperature and moisture modification
- Pyrocumulus transitions, which change buoyancy as well as allowing aqueous chemical reactions in the smoke

The Plume and Meteorology leads worked with the Modeling leads to understand what types of data they need to evaluate and improve their models. These conversations worked towards finding a balance between the ideal data, and the feasible data. Plume and meteorology observations are among the most expensive and difficult to obtain, due to the moving nature of the plume, the heights at which data are needed, and the turbulent, hot conditions within the plume. Safety and technology imposed limitations on some of the ideal data. The Plume and Meteorology leads reviewed the scientific literature, contacted peers with relevant expertise, and investigated available technology to determine what is possible at the present time.

Working with the other discipline leads (Fuels and Consumption, Fire Behavior and Energy, Smoke and Emissions), the Fire and Smoke Modeling leads, and the FASMEE Leadership Team, the Plume and Meteorology leads then developed the Plume Dynamics and Meteorology Observational Plan. The plan as proposed reflects the combination of the basic meteorology needed to address the plume questions; the model evaluation data needs; and the needs of the other disciplines to support their observations.

The plan presented here does not address specific sites, but instead outlines a set of instruments, locations, and observations that should be applied to any site FASMEE ultimately chooses for the experimental burns. The final Plume Dynamics and Meteorology Observational Plan produced by the co-leads, presented below as the "Results and Discussion," includes a list of subtasks, a list of observations needed for FASMEE's success, and justification for those observations' specific characteristics.

Results and Discussion

FASMEE will address several critical topics associated with plume dynamics and fire meteorology, including the vertical profile of plume development, entrainment rates, turbulence dynamics, fire-wind interactions, and relationship of sensible heat flux and plume height. To be of practical use for firefighter safety and smoke transport, fire and smoke models must represent the processes behind fire-atmosphere interactions.

Plume Dynamics and Meteorology Subtasks

The measurements needed to address key topics in plume dynamics and fire meteorology overlap substantially, making it practical to address them collectively rather than individually (Figure 1). For FASMEE, a suite of instruments will be deployed to gather the data necessary to examine these questions and evaluate models' ability to reproduce the phenomena accurately. This suite includes ground-level temperature, humidity, pressure and wind sensors; tower-mounted sensors for the same quantities; unmanned aerial systems (UAS) to collect wind and turbulence data beyond heights where instrument towers are practical; and ground-based remote sensed turbulence and winds (Table 1). The instruments will be deployed in and around the burn unit, capturing ambient and inflow conditions, as well as conditions as modified by the combustion process (Figures 2, 3).

Plume dynamics and meteorology measurements will be collected in the following subtasks, organized by measurement platform:

- Airborne (UAS) in situ observations
- Tower-mounted in situ observations
- Ground-based in situ observations
- Ground-based remote sensing

Plume Dynamics and Meteorology Identified Observations

Table 1 identifies the measurements needed for the Plume Dynamics and Meteorology discipline, by platform. The main observational goals for the plume and meteorology discipline are to characterize the ambient atmospheric conditions upwind, within, and downwind of the burn unit, as well as the conditions within the plume core, throughout the evolution of the plume. Key meteorology observations will include surface and upper-air meteorological measurements quantifying the ambient atmospheric conditions and environment in which the fire and smoke plume evolve. These measurements include basic surface weather conditions surrounding the experimental sites as well as vertical profiles of temperature, humidity, and the three-dimensional winds. The observations are made with upper-air radiosonde soundings and remote-sensing profilers (e.g., sodar, LiDAR, microwave radiometer, radar). Surface measurements will be made as close to the burn-plot boundary as possible, while vertical profiling measurements will be located upwind and downwind from the experimental burn unit.

To characterize the plume structures needed for plume-rise and coupled fire-atmosphere models, measurements are required within the plume from near the surface, or just above the fire front, to the top of the plume. These measurements include the three-dimensional winds and temperature, which can be measured using tall towers and remote sensing instruments. The tall towers allow multiple temperature sensors and anemometers to be placed within and above the canopy. Above this level, remote sensors such as Doppler LiDAR can measure the winds within the plume. Additional airborne platforms such as UAS will sample the middle plume region to collect both kinematic and thermodynamic measurements. Certain measurements in Table 1 are designated at

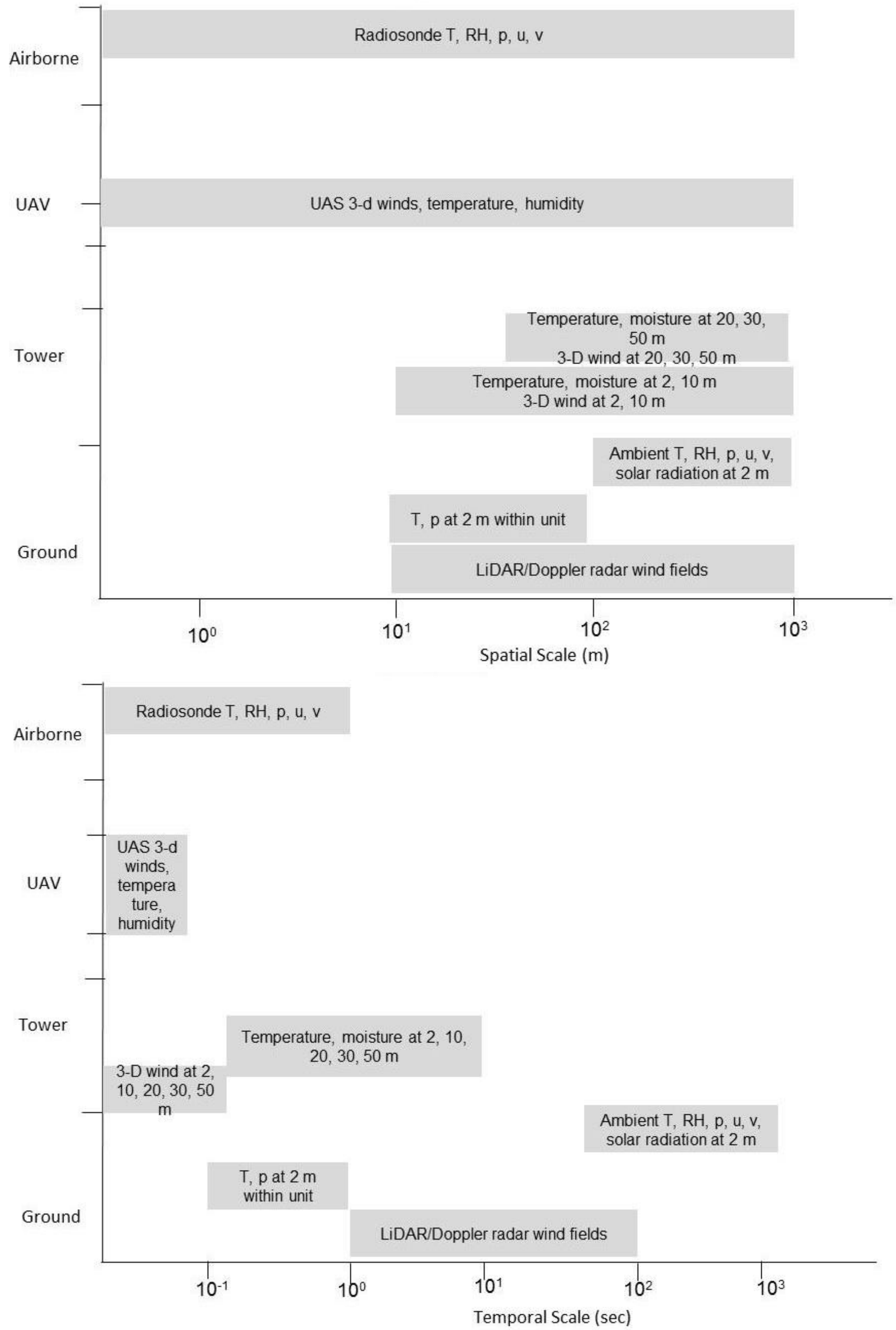

Figure 1: Hierarchical spatial (top) and temporal (bottom) sampling scales of plume dynamics and meteorology from ground to airborne measurements.

Table 1: Observational specifications for the plume dynamics and meteorology discipline.

Instrument / Technique	Temporal scales	Horizontal Scales	Vertical Scales	Observation
		Airborne *in situ*		
Radiosonde	Hourly	• 1m–1 km	• Variable, 2m	• T, p, qv, u, v,
UAS sonic anemometer with temp and RH	20 Hz	• Up to 1 km from plume	• Up to 500 m above ground	• T, qv, u, v, w, turbulence
		Tower-based *in situ*		
3-D sonic anemometer	20 Hz	• 100 m	• 10 m	• U, v, w, turbulence
Temperature and humidity	1-10 Hz	• 100 m	• 10 m	• T, Qv
		Ground-based remote sensing		
LiDAR	1-30 s	• 18 m	• 18 m	• Qv, u, v
		Ground-based *in situ*		
RAWS-type weather stations	1 min	• 500 m	• n/a	• T, qv, p, u, v, solar radiation
Temperature and pressure	1 Hz	• 100 m	• n/a	• T, p

frequencies of 10 Hz or higher. These are needed to characterize the turbulent character of the ambient and plume-influenced atmosphere.

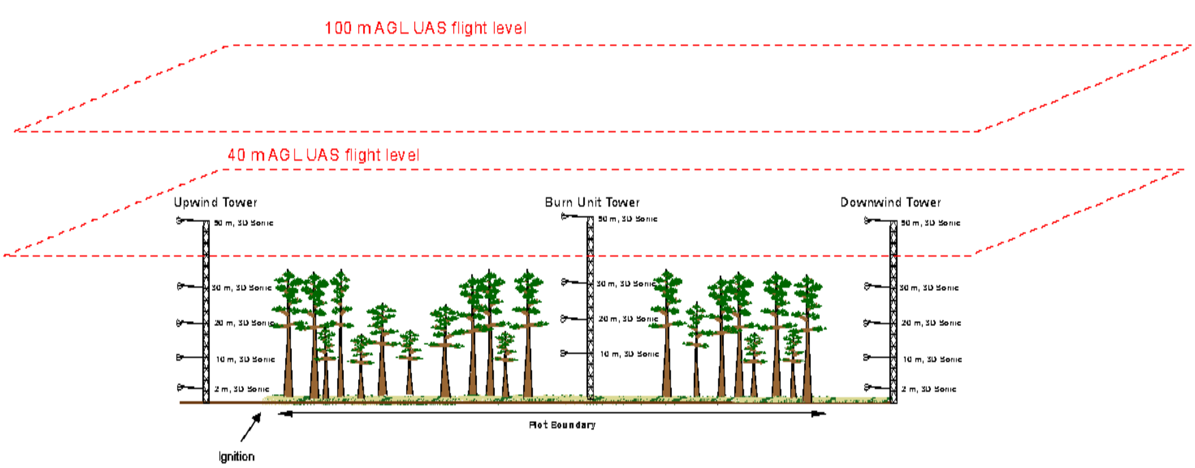

Figure 2: Sample diagram of a tower, by type of tower, showing vertical placement of instrumentation and/or vertical airspace distribution for manned and UAS operations.

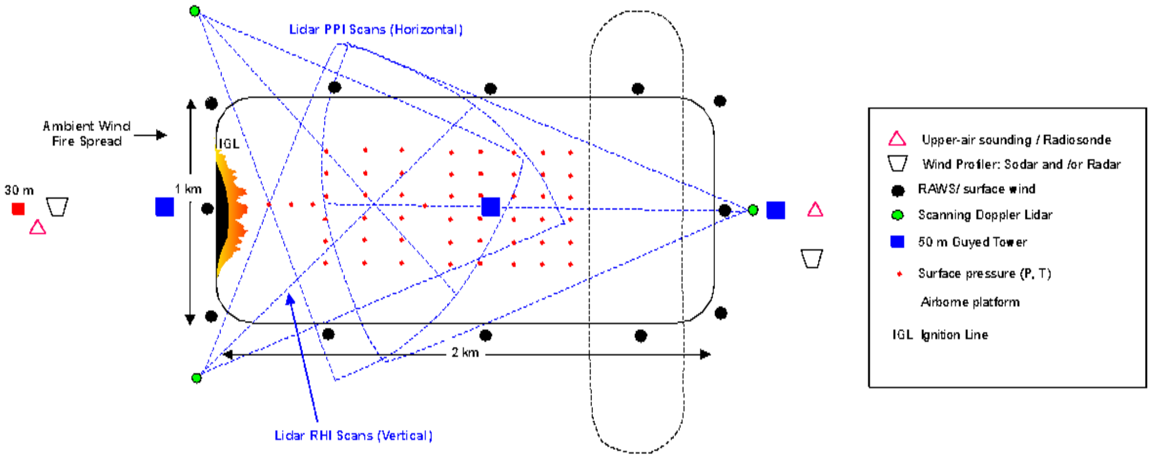

Figure 3: Schematic of a possible LiDAR sampling and meteorological observations in advance of the flaming fire front.

Meteorology and Plume Measurement Justification

Meteorology and fire behavior are the two most dynamic elements measured in FASMEE. Both fluctuate on time scales of less than a second. Although fire behavior is a shallow-plane phenomenon (vertical scale small compared to horizontal extent), the meteorology relevant to plume dynamics is fully three-dimensional. The plume is subject to the influence of turbulence, mean winds, temperature, and moisture over at least the full span of the fire's horizontal extent as well as the plume's vertical extent and beyond (e.g., capping inversions above the plume top). It is not feasible to capture the volumetric state of the atmosphere at the temporal and spatial scales of variability for the full extent of a fire. Technology does not exist to make the measurements near the fire, and expense precludes positioning instruments from the ground to the top of the plume throughout the burn area. The proposed measurements seek to maximize the potential to answer questions about plume structure, and to evaluate various models' plume representations, within the constraints of technology and cost. They allow evaluation of characteristics influencing plume behavior, in or near the plume, at temporal and spatial resolutions attainable in the field.

Ambient wind, temperature, and humidity through the troposphere will be obtained from radiosondes. Hourly upwind radiosondes will capture diurnal changes in these properties without interfering with aircraft operations. The wind shear and stability from these measurements are necessary to determine how they influence mixing and plume rise, respectively.

Mean winds on a vertical line (from the radiosondes) are by themselves insufficient to characterize the environment. They are also inadequate for determining how the fire's convective circulation modifies turbulent flow at, and downwind of, the plume. To accomplish these goals and complement the radiosondes, 50-m towers will be erected upwind and downwind of the burn units, with three more inside the unit perimeter. (Three towers is the minimum necessary to obtain data on airflow convergence and divergence.) Sonic anemometers on these will record winds and temperatures at 10 Hz, at various heights. These measurements will allow (1) characterization of turbulence and how it evolves across the burns, (2) computation of mixing of

ambient air with the fire plume), and (3) calculation of heat and momentum fluxes.
Shorter towers (3–10 m) distributed throughout the burn units, as conditions permit, will also hold 10-Hz anemometers to record airflow below and within the canopy. This region is particularly important for understanding near-field plume organization and airflow.
Airflow below the canopy is hindered by vegetation. Hot, buoyant plume air accelerates as it rises above the canopy, and the acceleration and mixing of this air must be determined to understand plume rise, and how smoke disperses over height. This region is too high for towers to reach and too turbulent for tethered balloon measurements. The only means available for observations here is 3D sonic anemometers with temperature sensors.
At each tower anemometer location, temperature and moisture must also be measured. These provide the thermodynamic components necessary to determine heat and moisture fluxes. A full surface energy budget station will be placed outside the burn area to measure the net surface radiation, sensible and latent heat fluxes, and soil heat flux. These data are necessary to quantify the mean surface energy budget not affected by the fire and plume.
All of these measurements emphasize point measurements, in vertical stacks, at a limited number of locations across and around the unit. Only remote sensing is capable of measuring airflow over the volume of the plume as it moves through the unit (Clements et al. 2008, Lareau and Clements 2016, Clements et al. 2016). The primary remote-sensing platform to be deployed for FASMEE is ground-based Doppler LiDAR. Multiple Doppler LiDARs will measure the kinematic structures above the canopy and tower array. The LiDARs provide a means to observe the smoke plume boundaries and plume top by recording the backscatter intensity at high spatial resolution. The LiDARs will also provide velocity measurements along the LiDAR beam, so that wind flow will be captured not only within the plume, but upwind and downwind as well. These measurements are critical to provide the modeling systems inflow and within plume boundary conditions. Furthermore, the three LiDARs are needed to provide measurements at multiple angles within and around the plume, to allow upwind and downwind characterization of flows and plume extent and dispersion. In this configuration, they also provide a virtual meteorological tower where they intersect within the plume so that wind observations can be made in the plume core.
Although the LiDAR will provide wind data, they will do so at a much lower temporal resolution than the sonic anemometers, which will preclude any turbulence analysis from LiDAR data. The only way to remedy this is the possibility of UAS-mounted sonic anemometers, with added temperature and moisture sensors. These will allow turbulence and flux calculations throughout the burn unit, at designated heights where plume entrainment and mixing are still vigorous. The addition of UAS-mounted sonic anemometers is necessary to sample the regions of the plume above the tall towers.

Plume dynamics and meteorology logistical needs

The measurements and instruments described above will require logistical support for tower installation, LiDAR positioning, UAS management, radiosonde release, and weather station installation.
<u>Towers:</u> 50-m towers will be installed by contractors. They will require access to the tower locations, including guy wire positioning. Towers must be installed in advance to allow subsequent instrument installation.
<u>LiDAR Positioning:</u> LiDAR must be either ground-based, with a clear view across the canopy top of the whole unit, or else scaffold-based to produce that clear view.

UAS management: UAS for meteorology needs to be included in airspace management planning across the burn unit. UAS will need to move with the plume, and be able to get measurements near the plume as well as up-wind and down-wind throughout the burn duration.
Radiosondes: Hourly sonde releases require filing NOTAMs with the FAA, as well as coordination with project aircraft.
Weather station installation: This requires access to a suitable site well before the burn in order to install the station and develop background meteorological context.
Power: Tower instruments and LiDAR will require electrical power. These should be the responsibility of the scientist(s) providing the equipment.
Communication frequencies: UAS and radiosondes will have radio communication requirements. Frequencies are not known at present, but they must be compatible with other RF instruments and devices.

Summary

The observational plan described above is designed to meet the goals of FASMEE, balancing the various questions and concerns, using the available technology, and complementing the observational and modeling needs of the other study leads. If the constraints on the project change, we believe this plan is adaptable to many other scenarios.

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