Validation of Smoke Transport Models with Airborne and Lidar Experiments

Final Report

Joint Fire Sciences Program Project # 08-1-6-09

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I. Abstract

This document reports our success in achieving the objectives and accomplishing the deliverables proposed in the project “Validation of Smoke Transport Models with Airborne and Lidar Experiments”. This final report is divided into four sections. Section 1, the Background, describes the purpose of the project and summarizes the project objectives and how accomplishment of these objectives addresses the original research solicitation JFSP AFP-2008-1, Task 6. The Background section also provides relates the project purpose material on smoke dispersion and air quality forecasting systems. The goal of Section 2 is to illustrate how the accomplished tasks contribute towards the project objective of providing smoke dispersion and fire environment datasets to validate smoke dispersion and air quality. Section 2 provides a summary description of the study area, the fire events studied, and the data collected for each fire. The study methods for collecting primary data (airborne and Lidar observations) and ancillary data (e.g. burned area, fuels, and weather) are described in Section 3. The primary deliverable of this project is a dataset for the evaluation of plume rise and smoke dispersion models. The structure and content of this dataset is described in Section 3. The project results for each fire event studied are reported in Section 4. On a fire event basis, Section 4 summarizes each fire, describes the specific primary and ancillary observations collected for each fire, and provides an inventory of the data files contained in the project dataset. The final section provides a list of accompany documents (deliverables) and a bibliography of publications and presentations delivered by this project.

II. Background and Purpose

Primary emissions from wildland fires are a significant source of criteria pollutants ($PM_{2.5}$, CO), black carbon (BC, a subset of $PM_{2.5}$), greenhouse gases (CO_2, CH_4), and a vast array of other gases, including non-methane organic compounds (NMOC). Photochemical reactions of NMOC contribute to ozone (O_3) production and the secondary formation of $PM_{2.5}$. The production, transport, and transformation of these primary and secondary pollutants from fires must be better understood in order to minimize and mitigate their impact on human health, economic activity, scenic integrity, and ecosystem resiliency. Additionally, wildland fire emissions present significant air regulatory challenges associated with National Ambient Air Quality Standards (NAAQS) and the Regional Haze Rule as well as efforts to reduce greenhouse gas emissions.

Air quality regulators, land managers, and atmospheric scientists all rely on smoke emission – atmospheric chemistry modeling systems (hereafter referred to as “smoke modeling systems”) to predict, evaluate, and manage the impact of fire emissions on air quality. A diagram of a generic smoke modeling system is shown in Figure 1. These systems include multiple, sequential modeling steps, each of which may be achieved using a combination of input data and models. Simulated smoke impacts are the culmination of multiple, complex modeling steps, and reflect the propagated uncertainties and limitations of the precursor modeling stages (e.g. fuel consumption and plume rise height) and the atmospheric chemistry transport models (e.g. transport, chemistry, and non-fire emissions) in the final step. There is an urgent need to quantitatively characterize the uncertainties, biases, and application limits of smoke modeling systems and to develop improved systems that may be utilized by air regulators, land managers, and air quality forecasters with confidence. Accurately describing and predicting the dynamics of smoke plumes and subsequent smoke transport is a major uncertainty in determining the impact of fire emissions on air quality.

This project, "Validation of Smoke Transport Models with Airborne and Lidar Experiments", which addresses JFSP AFP-2008-1, Task 6, 'Smoke and Emissions Models Evaluation', has measured key variables with the spatial and temporal resolution required to validate plume rise models and high-resolution smoke dispersion models. A ground based, mobile Lidar (Light Detection And Ranging) instrument and airborne instrumentation packages were deployed to acquire measurements of smoke plume dynamics, smoke aerosol distribution, chemical composition, and meteorological conditions in, and around, the plumes of active wildland fire events in the western United States. The Lidar measures plume rise height, dynamics, dispersion, and aerosol optical properties. The airborne instrument packages, deployed on US Forest Service aircraft, measured the distribution of aerosol mass density and major trace gas (CO, CO_2, and CH_4) concentrations. Eleven wildland fires were investigated between August 2009 and August 2011, allowing the research team to measure plume rise and smoke transport over a wide range of meteorological conditions, fire activity, fuel, and terrain conditions. The datasets collected in this project will support the Smoke Emissions Model Intercomparison Project (SEMIP; http://www.airfire.org/projects/semip/ , Joint Fire Science Program Project #08-1-7-10) and the broader fire and smoke research community. The field observations collected in this project provide critical data necessary for the evaluation of smoke dispersion and air quality forecasting models, and hence support the provision of quantitative information regarding the uncertainties, biases, and application limits of the models examined.

The fundamental purpose of this research project was to acquire the data necessary for the evaluation of smoke dispersion and air quality forecasting systems (Figure 1). The datasets produced in this project will support model evaluation studies that provide a quantitative assessment of the uncertainties, biases, and application limits of the models examined. This project has obtained model validation data by measuring prognostic variables (plume height and the concentrations of aerosol, CO, CH_4) of plume rise models, smoke dispersion models, and atmospheric chemistry transport models (ACTM) with the spatial and temporal resolution required to quantitatively validate a wide range of models. The subcomponent models of smoke modeling systems, such as plume rise and fire effects models rely on a variety of fire environment data as input including ambient meteorological conditions, fuel type, fuel loading, and fuel condition. In addition to measuring the distribution of model prognostic variables in the vicinity of active fire events, the project has assembled datasets of fire environment variables which are the critical input for the subcomponent models of smoke modeling systems. The purpose of this project was to collect in-situ observations for the evaluation of smoke modeling systems. The project objectives **did not** include model evaluation activities.

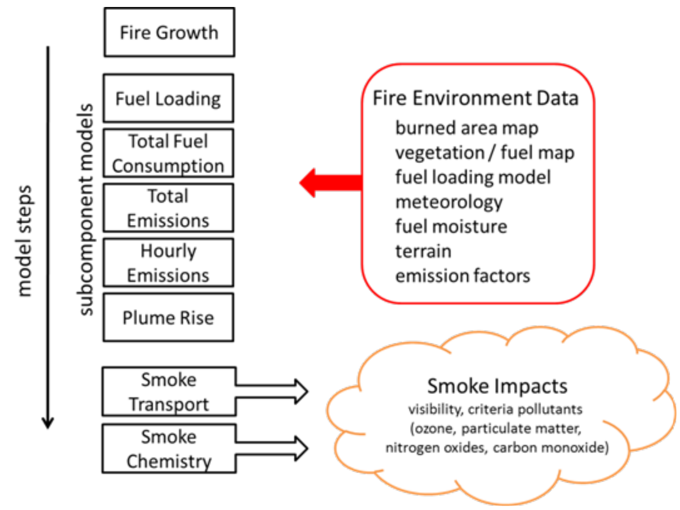

Figure 1. Generic smoke dispersion – air quality forecasting system.

III. Study Description

This section provides a summary description of the methods and instrumentation employed in this project for the collection of primary data (plume height, smoke dispersion, and emissions) and fire environment data (burned area, fuels, and weather). The location and dates of the fires sampled are also provided (Table 1). The documentation included with the project dataset provides a far more detailed description of the methods and instrumentation used in this study.

Three classes of primary data were collected: observations of plume height, measurements of emissions, and measurements of the temporal and spatial distribution of aerosol and trace gases released by the fires. Observations of plume height were obtained through the deployment of a ground based, mobile Lidar and atmospheric chemistry instrumentation deployed on an aircraft platform. Lidar measurements of light backscattering were processed with a specially developed analysis methodology to provide estimates of plume height. In addition to Lidar observations, the aircraft platform provided measurements of plume height by obtaining vertical profiles and transects of smoke concentrations (aerosol and CO) as well as ocular estimates based on GPS elevation when the aircraft was level with the top of the smoke plume / smoke layer.

Emission factors (EF) are a key input to fire emission models that provide the spatially and temporally resolved emission sources required by smoke modeling systems to simulate air quality impacts of fires (Figure 1). Using an aircraft platform, we obtained measurements of $PM_{2.5}$, CO_2, CO, and CH_4 concentrations in fresh smoke and in the background atmosphere upwind of the fires. These measurements can be used to determine EF for the measured species and the modified combustion efficiency (MCE), which can be used to estimate EF for a wide range of reactive gases emitted by fires (see Urbanski et al., 2013 and references therein).

Smoke dispersion models and atmosphere chemical transport models (ACTM) predict smoke impacts on air quality by simulating the temporal evolution of the three-dimensional concentrations fields of smoke aerosol ($PM_{2.5}$), CO, O_3, and other pollutants produced by fires. In this project, an aircraft platform was used to measure the spatial distribution of aerosol, CO, and CH_4 concentrations downwind from wildland fires using vertical profile and horizontal transect sampling modes. These concentration fields measured from 0 to 50 km downwind of the fire provide the observations needed to evaluate the concentration fields simulated by smoke dispersion and ACTM's. Additionally, the vertical concentration profiles at the source may be used to evaluate the vertical emission profiles used to initialize smoke dispersion/ATCM simulations.

Airborne Sampling Methods

The airborne smoke sampling acquired measurements of fresh emissions, smoke vertical profile, plume height, and smoke dispersion (i.e. the spatial distribution of emissions downwind of the fire). These measurement objectives were accomplished using three flight sampling modes: 1) fresh smoke samples near the fire, 2) vertical profiling at distances of up to 50 km downwind of the source and 3) horizontal transects at distances of up to 50 km downwind from the source.

Sampling Mode 1: Fresh smoke on the edge of the plume column was sampled at multiple elevations. These measurements of $PM_{2.5}$, CO_2, CO, and CH_4 concentrations in fresh smoke can be used to validate quantitatively the emissions of these species predicted by emission models. When paired with background air samples obtained at similar elevations upwind of the plume, the fresh smoke samples can provide the emission factors (EF) for the measured species and the modified combustion efficiency (MCE), which is a measure of the relative mix of flaming and smoldering combustion.

Sampling Mode 2: Vertical profiles may be obtained either with spiral or step increase profiles. Spiral vertical profiles, centered on the plume downwind from the source are taken from above the smoke plume/smoke layer to the lowest practical elevation. Step increase vertical profiles involve short (~10 km) horizontal transects, roughly perpendicular to the long-axis of the smoke plume (i.e. the direction of smoke transport), taken at multiple elevations. In addition to the vertical distribution of smoke, vertical profiles which ascend above the smoke plume/smoke layer provide a measurement of plume height.

Sampling Mode 3: The third sampling mode traverses the plume horizontally, roughly perpendicular to the direction of smoke transport, at multiple locations downwind of the source. The horizontal transects were usually executed at the approximate level of maximum smoke density. During some flights, horizontal transects were obtained at multiple vertical levels.

Airborne Instrumentation

The primary platform for the airborne measurements was the US Forest Service Region 1 (USFS R1) Cessna 206 aircraft. The project deployed the USFS R1 Cessna to wildfire events during August 2009, 2010, and 2011. Measurements for two prescribed fires included in this report were obtained as part of a separate research project (Department of Defense – Strategic Environmental Research and Development Program (SERDP) projects RC-1648 and RC-1649) that used the US Forest Service Region 4 Twin Otter aircraft as the sampling platform. Details of the SERDP projects may be found in Yokelson et al. [2013]. During the 2009 and 2010 field deployments measurements were obtained using the Missoula Fire Sciences Laboratory (FSL) legacy smoke sampling aircraft package (LAP). In 2011, a newly acquired flight ready Cavity Ring-down Spectrometer (CRDS) trace gas analyzer was deployed along with the nephelometer and GPS unit from the LAP.

Legacy smoke sampling aircraft package (LAP)

The LAP integrated three sampling systems – nephelometer, CO_2/H_2O analyzer, and canister sampler – into a single aircraft deployable unit. The LAP included a Garmin global positioning system (GPS), which provided time stamped aircraft locations (latitude, longitude, elevation above mean sea-level) at a 1Hz. The nephelometer was a Radiance Research Model 903 integrating nephelometer that measured light scattering at 530 nm every 2 seconds. The nephelometer was installed with a 2.5 µm cut-off cyclone in the sampling line to limit the measurements to $PM_{2.5}$. Nephelometer measurements of light scattering by particles can be related to particle mass concentration through a mass calibration. The LAP nephelometer was calibrated each year of the study in the FSL combustion chamber (details are provided in the dataset documentation). The LAP measured trace gases using a non-dispersive infrared instrument (LI-COR gas analyzer model LI-6262) which provided measurements of CO_2 and H_2O vapor at a rate of 0.5 Hz and a canister sampling system sampled ram air into 800-ml stainless steel canisters. The canister sampling unit was capable of both point sampling and integrated sampling. The canister samples were analyzed later at the FSL by GC/FID/RGD for CO_2, CO, CH_4, and several C2-C3 hydrocarbons. Details of the canister analysis are given by Hao et al. [1996].

Cavity Ring-down Spectroscopy (CRDS) trace gas analyzer

The flight ready CRDS trace gas analyzer (Picarro Inc., CA, USA, model G2401-m) deployed in August 2011 provided continuous measurements of CO_2, CO, CH_4, and H_2O at a data acquisition rate of 2 s. The analyzer tightly controlled the gas sample pressure and temperature at ±0.005 °C and ±0.0002 atm to provide stable, well-resolved spectral features and ensure high precision measurements. Frequent, in-flight, calibrations using 3 standard gases were used to maintain accuracy of the CRDS measurements and quantify the measurement precision. The in-flight standards were gas mixtures of CO_2, CO, and CH_4 in Ultrapure air and included or were cross-calibrated against two NIST-traceable gas mixtures (Scott-Marrin, Inc., Riverside, CA, USA).

Airborne Meteorology Measurements

The larger, more capable USFS R4 Twin Otter aircraft allowed the research team to deploy a wing-mounted Aircraft Integrated Meteorological Measuring System probe (AIMMS-20, Aventech Research, Inc.), which provided measurements of the ambient three-dimensional wind velocity, temperature, relative humidity, and barometric pressure at 1Hz. Details of the AIMMS-20 probe and a performance evaluation may be found in Beswick et al. [2008].

Lidar Measurement Technique in the Vicinity of Large Fires

Our mobile Lidar measures the elastically backscattered light signals as a function of range (or height) at two wavelengths simultaneously, in the infrared (1064 nm) and the ultraviolet (355 nm) regions of the spectra. The backscattered signals at 1064 nm are used for monitoring smoke plume dynamics and propagation. The signals at 355 nm are used for calculation of smoke particle optical properties. The range of the Lidar is up to 5-10 km, depending on atmospheric conditions. The range resolution may be set from 6 to 30 m. The scanning capabilities of the Lidar allow it to change the searching direction rapidly through 180° horizontally and 90° vertically.

Monitoring of smoke plume dimensions and behavior with Lidar requires that the regions with high levels of backscattering be discriminated from regions of clear atmosphere and the distance from the Lidar to the smoke plume edges must be established. In principle, Lidar can easily detect the boundary between different atmospheric layers. Subjective identification of heterogeneous areas, such as the atmospheric boundary layer or clouds, in Lidar scans through visual inspection is often a trivial matter. However, the use of an automated method to select these boundaries is a significant challenge. Generally, the heterogeneity boundaries in the atmosphere are not well defined, especially in smoke plumes, where the dispersion processes create a continuous transition zone between clear air and the dense part of a plume. The challenge of objectively identifying smoke plume dimensions was addressed by the development of an improved methodology for the use of the Lidar vertical scans obtained in areas of smoke plumes [Kovalev et al., 2009].

Fire Environment Data

The project's primary source of burned area information for fire events was fire perimeter polygons mapped by incident management teams. The maps are a digital representation of the fire boundary derived from airborne infrared imagery or GPS coordinates recorded along the fire perimeter through aerial and/or ground based survey. These incident perimeter polygons are produced to support fire management activities, not map the area burned, and as discussed in the dataset documentation, several characteristics of these fire perimeter maps must be considered when they are applied for modeling emissions.

The dataset surface fuel load for the area burned was estimated from a geospatial overlay of the incident fire perimeters with a USDA Forest Service Remote Sensing Application Center (RSAC)/ Forest Inventory Analysis Program (FIA) map of forest type group [Ruefenacht et al. 2008; http://fsgeodata.fs.fed.us]. The forest type group map was combined with the fuel type group (FTG) fuel classification from a recent study by Keane et al. [2013]. The FTG fuel classification of Keane et al. [2013] was assembled from FIA fuel estimates for ~13,000 plots and covers 19 forest type groups of the western US. The classification includes fuel loading for six fuel bed components: litter, duff, and 1-hr, 10-hr, 100-hr, and 1000-hr dead wood. Keane et al. [2013] did not include canopy fuels and herb and shrub fuels due to the lack of data. For this project, the FTG fuel loadings were augmented with estimates of herbaceous and shrub fuel loadings after Lutes et al. [2009]. The canopy fuel loading (CFL; kg m^{-2}), which is the canopy fuels likely to be consumed in a fully active crown fire (needles, lichen, moss, and live and dead branch wood less than 6 mm in diameter) [Scott and Reinhardt, 2001], was estimated using canopy geospatial layers from the LANDFIRE project [LANDFIRE, 2012]. The derivation of the CFL is described in detail in the project dataset documentation.

Surface weather observations from the interagency Remote Automatic Weather Stations (RAWS) located throughout the US (http://raws.fam.nwcg.gov/). RAWS locations and data were accessed through the Real-time Observation Monitor and Analysis Network (ROMANS; http://raws.wrh.noaa.gov/roman/) developed by MesoWest at the University of Utah. RAWS provide hourly observations of temperature, dew point temperature, relative humidity, wind speed, wind gust speed, wind direction, precipitation, solar radiation, and 10-hour fuel moisture. The RAWS data was augmented with NFDRS 1000-hr fuel moisture from the US Forest Service – Wildland Fire Assessment System data archive [WFAS, 2012].

The dataset includes fire event information on fire behavior, fire size, fuels, and weather conditions extracted from the daily Incident Status Summaries, known as the ICS-209 reports. The ICS-209 reports were accessed from the National Wildfire Coordinating Group's Historical Incident ICS-209 Reports archive (http://fam.nwcg.gov/fam-web/hist_209/report_list_209).

Study Sites

This project acquired observations of plume height, smoke dispersion, and emissions and collected ancillary data for 11 fire events between August 2009 and August 2011. Nine of the fire events occurred in the interior mountain west and were sampled during the month of August. The locations of these fires are mapped in Figure 2. Two of the fires sampled were prescribed burns on Vandenberg Air Force Base in California and Marine Corps Base Camp Lejeune in North Carolina. The fire names, codes, locations, and dates studied are provided in Table 1.

Table 1. Study Sites

Fire Name	Fire Code	Location	Date(s) Sampled
Big Salmon Lake and Hammer Creek	BSLHC	Bob Marshall Wilderness, Montana	August 17, 22, 28 of 2011
Saddle Complex	SC	Bitterroot National Forest, Montana and Salmon-Challis National Forest, Idaho	August 24,25,26, 27 of 2011
North Fork Prescribed Burn	NF	Clearwater National Forest, Idaho	August 13, 2011
Kootenai Creek	KC	Bitterroot National Forest, Idaho	August 4, 26, 27, 28 of 2009
Mill Flat	MF	Dixie National Forest, Utah	August 21, 22 of 2009
Rooster Rock	RR	Deshutes National Forest, Oregon	August 4, 5 of 2010
Twitchell Canyon	TC	Fishlake National Forest, Utah	August 12,13, 17 of 2010
Whitehawk Complex	WHC	Boise National Forest, Idaho	August 27, 2010
Banner	BNR	Salmon-Challis National Forest, Idaho	August 25, 2010
Vandenberg AFB Grant A Prescribed Burn	GBA	Vandenberg Air Force Base, California	November 11, 2009
Camp Lejeune Unit ME Prescribed Burn	CLME	Marine Corps Base Camp Lejeune, North Carolina	March 1, 2010

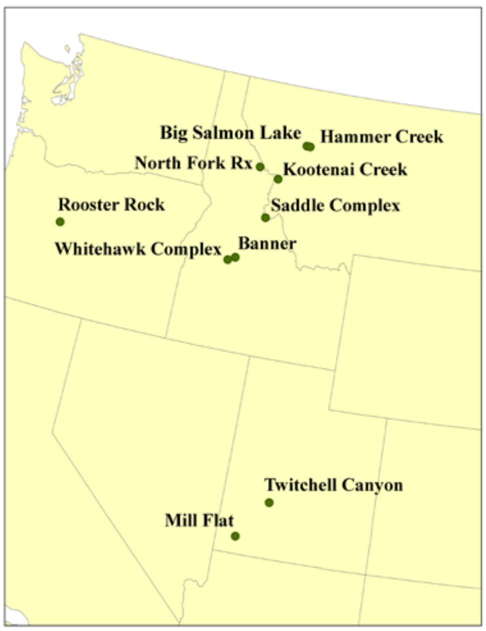

Figure 2. Study sites (prescribed fires at Vandenberg AFB and Marine Corps Base Camp Lejeune are not shown)

Key Results – Project Dataset

The purpose of this project was to measure key variables with the spatial and temporal resolution required to evaluate plume rise models and high-resolution smoke dispersion and air quality forecasting models. The measurements obtained in this project have been package into a comprehensive dataset that has been delivered to the Joint Fire Science Program and the Smoke Emissions Model Intercomparison Project (SEMIP; http://www.airfire.org/projects/semip/). The project objectives and deliverables did not include model evaluation or assessment. Since this project was restricted to data collection, we provide a summary description of the project dataset rather than key findings. A comprehensive description of the dataset and guidance for the dataset's use for model evaluation is provided in the dataset documentation.

The project dataset consists of three primary data categories: plume height, smoke dispersion, and emissions and four ancillary data categories: burned area, fuels, weather, and incident status summaries. Plume height observations were obtained using both the ground based Lidar and aircraft platforms. Smoke dispersion and emissions data was collected by deploying one of two atmospheric chemistry instrument packages, the legacy aircraft package (LAP) or the CRDS trace gas analyzer package (CRDS), on an aircraft (USFS R1 Cessna or USFS R4 Twin Otter). A meteorology measurement probe was also deployed on the USFS R4 Twin Otter providing observations of ambient weather for the missions using this aircraft. An inventory of data collected in this project is provided in Table 2. The dataset consists of comma separated value (CSV) files and geospatial files (polygons of fire boundaries and fuel loading). The data files have been packaged in a data bundle organized by fire event as depicted in Figure 3. The data bundle includes format description files for each of the data file types. The data types of the CSV files are described in Table 2.

Table 2. Data Inventory

Fire	Plume Height		Smoke Dispersion		Emissions		Burned Area	Fuels	Weather	ICS209
	Lidar	aircraft	LAP	CRDS	LAP	CRDS				
Big Salmon Lake and Hammer Creek		X		X		X	X	X	X	X
Saddle Complex		X		X		X	X	X	X	X
North Fork Prescribed Burn				X		X	X	X	X	X
Kootenai Creek	X	X	X				X	X	X	X
Mill Flat		X	X				X	X	X	X
Rooster Rock		X	X				X	X	X	X
Twitchell Canyon		X	X				X	X	X	X
Whitehawk Complex		X	X				X	X	X	X
Banner		X	X				X	X	X	X
Vandenberg AFB Grant B Prescribed Burn		X	X				X	X	X[1]	
Camp Lejeune Unit ME Prescribed Burn		X					X	X	X[1]	

[1]Airborne observations of ambient weather conditions and surface weather observations

Table 3. Description of CSV data files

Data File	Description
acdata_fire_PlumeHeights.csv	Plume height measurements
acdata_fire_yyyymmdd_ProfileLog.csv	Log of airborne sampling flight profile
acdata_fire_yyyymmdd__SD.csv	Airborne smoke dispersion observations acquired with the CRDS trace gas analyzer and nephelometer
acdata_fire_yyyymmdd__SD_LAP.csv	Airborne smoke dispersion observations acquired with the Legacy Aircraft Package (LAP)
acdata_fire_yyyymmdd_SD_LAP_MET.csv	Airborne smoke dispersion observations acquired with the Legacy Aircraft Package (LAP) and airborne meteorology measurements
acdata_fire_yyyymmdd__SRCXX.csv	Emission measurements acquired with the CRDS trace gas analyzer and nephelometer
Fuels_fire.csv	Estimated pre-fire fuel loading of area impacted by fire
ICS209_fire.csv	Information on fire behavior, fuels, and weather conditions extracted from ICS-209 reports
LidarLidar_fire_yyyymmdd_PH.csv	Plume height measurements derived from Lidar observations
Weather_fire.csv	Surface weather observations from RAWS

Syntax Notes:
fire = fire code from Table 3.1
yyyymmdd = date, e.g. 20110827

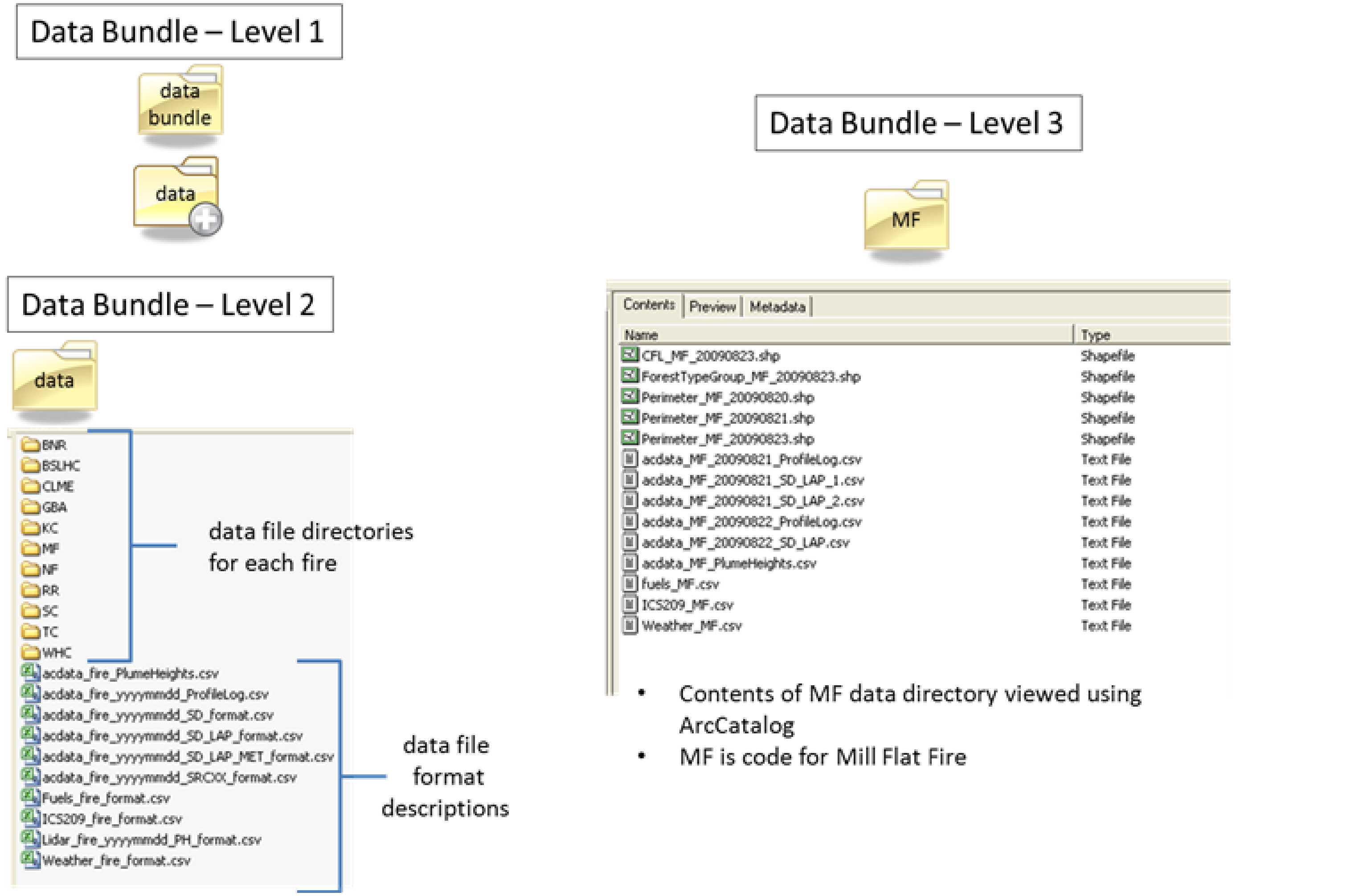

Figure 3. Data Bundle Structure

IV Management Implications

Air quality regulators, land managers, and atmospheric scientists rely on smoke modeling systems to predict, evaluate, and manage the impact of fire emissions on air quality. There is an urgent need to quantitatively characterize the uncertainties, biases, and application limits of smoke modeling systems and to develop improved systems that may be utilized by air regulators, land managers, and air quality forecasters with confidence. Accurately describing and predicting the dynamics of smoke plumes and subsequent smoke transport is a major uncertainty in determining the impact of fire emissions on air quality. The project dataset provides the observations needed to quantify the uncertainties, biases, and application limits of these models. The project dataset has been provided to SEMIP and will be available to the broader smoke research community, including the Forest Service Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS), for validation of smoke plume models and smoke dispersion / air quality forecasting systems. By contributing critical data to SEMIP and the broader fire and smoke science community, the proposed project will facilitate the efforts of researchers to provide air quality and fire managers at the Geographic Area Coordination Centers (GACC), Incident Commands, and federal and state agencies then will be able to confidently use the validated models to better predict the pollutant levels downwind from large fires.

While this project did not include model evaluation, the wildfire emissions data has been used in a study to evaluate published emission factors (EF) that are widely used to develop emission estimates for US wildfires [Urbanski et al., 2013]. Wildland fire emission inventories (EI) provide critical inputs for atmospheric chemical transport models used by air regulatory agencies to understand and to predict the impact of fires on air quality. Fire EF, which quantify the amount of pollutants released per mass of biomass burned, are essential input for the emission models used to develop EI. Over the past decade substantial progress has been realized in characterizing the composition of fresh smoke and in quantifying EF. However, most fire emissions studies of temperate ecosystems have focused on prescribed burning. Little information is available on EF for wildfires in the temperate forests of the conterminous U.S. Current emission estimates for U.S. wildfires rely largely on EF measurements from prescribed burns and it is unknown if these fires are a reasonable proxy for wildfires.

The project emissions data collected in August of 2011 was provided the fire combustion efficiency, quantified as the modified combustion efficiency (MCE), and EF for CO_2, CO, and CH_4. Our study average values for MCE, $EFCO_2$, EFCO, and EFCH4 were 0.883, 1596 g kg^{-1}, 135 g kg^{-1}, 7.30 g kg^{-1}, respectively. Compared with previous field studies of prescribed fires in similar forest types, the fires sampled in our study had significantly lower MCE and $EFCO_2$ and significantly higher EFCO and $EFCH_4$. While our analysis of the project field data provided EF for CO_2, CO, and CH_4; however, we used our study average MCE to estimate wildfire EF for 14 other species using EF – MCE linear relationships reported in the literature. The EF we derived for several non-methane organic compounds (NMOC) and $PM_{2.5}$ were substantially larger (by a factor of 1.5 to 4) than that reported for temperate forests in a two widely used reviews of BB emission studies. If the MCE of the fires sampled in this work are representative of the combustion characteristics of wildfires across western U.S. forests then the use of EF based on prescribed fires may result in a significant underestimate of wildfire $PM_{2.5}$ and NMOC emissions. Given the magnitude of biomass consumed by western U.S. wildfires, the failure to use wildfire appropriate EF has significant implications for the forecasting and management of regional air quality. The contribution of wildfires to NAAQS $PM_{2.5}$ and O_3 and Regional Haze may be underestimated by air regulatory agencies.

V. Relationship to other recent findings and ongoing work

Emissions – Over the past decade substantial progress has been realized in characterizing the composition of fresh biomass burning (BB) smoke and in quantifying BB EF [Akagi et al., 2011; Burling et al., 2011; Urbanski et al., 2009]. However, most BB studies of temperate ecosystems have focused on emissions from prescribed burning. Prior to this project little information was available on EF for wildfires in the temperate forests of the conterminous U.S. Current emission estimates for U.S. wildfires rely largely on EF measurements from prescribed burns and it is unknown if these fires are a reasonable proxy for wildfires. In August 2011 our project measured the modified combustion efficiency (MCE), and EF for CO_2, CO, and CH_4. Our study average values for MCE, $EFCO_2$, EFCO, and EFCH4 were 0.883, 1596 g kg^{-1}, 135 g kg^{-1}, 7.30 g kg^{-1}, respectively. The results are reported in Urbanski [2013]. Compared with previous field studies of prescribed fires in similar forest types, the fires sampled in this study in August 2011 had significantly lower MCE and $EFCO_2$ and significantly higher EFCO and $EFCH_4$. An examination of these results and 47 temperate forest prescribed fires from previously published studies [Burling et al., 2011; Urbanski et al., 2009; Hobbs et al., 1996; Radke et al., 1991] shows a clear trend in MCE across U.S. region/fire type: southeast (MCE=0.933) > southwest (MCE=0.922) > northwest (MCE=0.900) > northwest wildfires (MCE=0.883).

The fires sampled in this work in August 2011 burned in areas reported to have moderate to heavy components of standing dead trees and dead down wood due to insect activity and previous fire, but fuel consumption data was not available for any of the fires. However, fuel consumption data was available for 18 prescribed fires reported in the literature. For these 18 fires Urbanski [2013] found a significant negative correlation ($r = -0.83$, p-value = 1.7e-5) between MCE and the ratio of heavy fuel (large diameter dead wood and duff) consumption to total fuel consumption. This observation suggests the relatively low MCE measured for the August 2011 fires in our study resulted from the availability of heavy fuels and conditions that facilitated combustion of these fuels. More generally, our measurements and the comparison with previous studies indicate that fuel composition is an important driver of variability in MCE and EF.

The emissions data collected and analyzed thus far in this is study provide EF for CO_2, CO, and CH_4; however, study average MCE may be used to estimate wildfire EF other species using EF – MCE linear relationships reported in the literature (e.g. Burling et al. 2011). In Urbanski [2013] August 2011 emission data was used to derive EF for several non-methane organic compounds (NMOC) and $PM_{2.5}$. The EF derived in Urbanski [2013] were substantially larger (by a factor of 1.5 to 4) than published prescribed fire EF. Wildfire $EFPM_{2.5}$ estimated in Urbanski [2013] is approximately twice that reported for temperate forests in a two widely used reviews of BB emission studies [Akagi et al., 2011; Andreae and Merlet, 2011]. Likewise, western U.S. wildfire $PM_{2.5}$ emissions reported in a recent national emission inventory [USEPA, 2012] are based on an effective $EFPM_{2.5}$ that is only 40% of that estimated in Urbanski [2013]. If the MCE of the fires sampled in this work are representative of the combustion characteristics of wildfires across western U.S. forests then the use of EF based on prescribed fires may result in a significant underestimate of wildfire $PM_{2.5}$ and NMOC emissions. Given the magnitude of biomass consumed by western U.S. wildfires, the failure to use wildfire appropriate $EFPM_{2.5}$ has significant implications for the forecasting and management of regional air quality.

Smoke Plume Rise - Our project measured smoke plume rise for 9 wildfires in Montana, Idaho, Utah, and Oregon and 3 prescribed fires in Idaho, California, and North Carolina. Smoke plume rise measurements were obtained on multiple days for most of the wildfires providing observations over a wide range of meteorological, fire activity, fuel, and terrain conditions. To best of our knowledge this project has produced the most extensive and well documented dataset of in-situ smoke plume rise measurements for US wildfires. The Joint Fire Science Program project "Evaluation and Improvement of Smoke Plume Rise Modeling" (#08-1-6-06, PI Y. Liu) measured smoke plume rise for 20 prescribed fires in the Georgia and the Florida panhandle [Liu et al., 2012]. The smoke plume rise dataset collected in Liu's JFSP project have been used in model evaluation studies to identify the important parameters in the Daysmoke plume model [Liu et al., 2010]. Given that Liu's JFSP project focused on prescribed fires in the Southeast our studies are complimentary.

A few recent studies have used plume rise data from the Multi-angle Imaging SpectroRadiometer (MISR) Plume Height Climatology Project to evaluate wildland fire plume rise models [Raffuse et al., 2012; Sofiev et al., 2012; Val Martin et al., 2012; Val Martin et al., 2010]. The MISR Plume Height Climatology Project dataset provides estimates of plume top height for 100's of fires in the Contiguous US. While the MISR plume height dataset provides many more observations than our project dataset, it has several limitations compared to our dataset. The uncertainty of the MISR plume top height measurement is 500 m [Kahn et al. 2007] while the uncertainty of our airborne and Lidar measurements is approximately 50 m. The horizontal resolution of our airborne measurements is 50 to 100 m depending on the sampling profile compared to the MISR nominal spatial resolution of 1.1 x 1.1 km [Ichoku et al., 2012]. The MISR dataset provides an estimate of the maximum plume height, but does not provide information on either absolute (e.g. concentration of CO) or relative vertical distribution of emissions which is a key input required for smoke dispersion and air quality models (see for Achtemeier et al., 2011). The return interval of approximately 16 days and requires limited cloud cover to obtain for a robust retrieval of plume height the result being that plume height is rarely sampled more than once for any given fire. Also, because the MISR overpass at mid-latitudes occurs around 10:00 LT the database does not include observations during the peak burning period of western US wildfires and does not provide information regarding the temporal variability of plume height. These limitations suggest the MISR dataset alone is not adequate for robust and through evaluation of smoke plume rise models.

VI. Future Work

Our project provides a comprehensive dataset for the evaluation of smoke plume rise models and high-resolution smoke dispersion and air quality models. The project dataset includes concentration fields of CO and $PM_{2.5}$ (inferred from nephelometer measurements of light scattering) which can be used to smoke dispersion and transport. However, while our measurements may be used to evaluate emissions, dispersion, and transport, the dataset does not enable assessment of plume chemistry. Simulation of most smoke impacts such as $PM_{2.5}$ and O_3 concentrations, regional haze, or the transport of black carbon to the Arctic, can only be realistically simulated using atmospheric chemistry transport models (ACTM), such as the Weather Research and Forecasting –Chemistry Model (WRF-Chem) or the Community Multiscale Air Quality modeling system (CMAQ). This point cannot be overemphasized. While a dispersion model provides a first order approximation as to where the smoke moves and where it may be thickest, quantitative smoke impacts such as the concentrations of criteria pollutants affecting a population center, result from highly complex, non-linear photochemical processes, and can only be accurately simulated using sophisticated atmospheric chemistry transport models. Evaluating plume chemistry requires in-situ, quasi-Lagrangian measurements of a wide range of reactive species, not just CO_2, CO, CH_4, and $PM_{2.5}$. Acquiring such measurements requires an airborne atmospheric chemistry payload that includes instruments for the measurement of speciated organic compounds, nitrogen oxides (NO_X) and O_3 and aerosol chemistry. A priority for future research should be an airborne measurement campaign that deploying a large, sophisticated atmospheric chemistry instrument payload to comprehensively measure the emissions and plume chemistry of large western US wildfires. Such a research project would require the participation of scientist from multiple research institutions with expertise in different aspect of atmospheric chemistry measurements.

Recent experiments have successfully deployed sophisticated atmospheric chemistry instrument payloads to study emissions and plume chemistry of prescribed fires [Akagi et al., 2011; Akagi et al., 2013]. The measurements obtained in these studies will be extremely valuable to atmospheric chemistry modelers working to unravel the complex chemistry of smoke plumes (see for example Alvarado et al., 2010; Alvarado et al., 2009). However, there are obviously significant differences between prescribed fires and wildfires. The fire behavior, combustion efficiency, emissions, fire environment, and quantity of emissions differ greatly between these fire types. Additionally, wildfires in the western US occur in the summer when atmospheric chemistry is very active due to high solar insolation and high temperatures; while the aforementioned studies were conducted in the fall. Emission from western US wildfires (outside of California) are released into an atmosphere with levels of anthropogenic pollution much lower than that found in the Akagi prescribed fire studies. Therefore it is likely that chemistry of western US wildfire emissions when mixed with the ambient air may be very different from that observed in the previous studies of prescribed fires. Finally, the magnitude and spatio-temporal concentration of western wildfire emissions [Urbanski et al., 2011] result in significant emissions being transported long distances compared with prescribed fire emissions whose impact is generally local.

VIII. Deliverables Cross-Walk

Proposed	Delivered	Status
(A) Dataset for the evaluation of smoke plume rise, smoke dispersion, and air quality forecasting models	A comprehensive final dataset including aircraft measurements, Lidar measurements, and fire environment observations, delivered to SEMIP project.	Completed. The project dataset has been delivered to Dr. Sim Larkin the SEMIP PI (http://www.airfire.org/projects/semip/). The project dataset is being prepared for submission to the USDA Forest Service Data Archive (http://www.fs.usda.gov/rds/archive/)
(B) Dataset report and documentation	(1) Summary of wildland fire events for each research flight. (2) Description of aircraft and Lidar instrumentation, instrument calibration, data quality control, and processing. (3) A detailed presentation of measurement results and analysis.	Completed. The dataset report and documentation has been included in the project dataset – proposed deliverable (A)
(C) Web Site for data archive	The project dataset submitted and published in the US Forest Service National Data Archive: (http://www.fs.usda.gov/rds/archive/)	In progress
(D) Primary Refereed Publications	(1) Urbanski, S. (2013) Combustion efficiency and emission factors for US wildfires, Atmos. Chem. Phys. Disc., 13, 33-76. (2) Kovalev, V. A., Petkov, A., Wold, C. and Hao, W. M.: Lidar monitoring of regions of intense backscatter with poorly defined boundaries, Appl. Optics, 50(1), 103–109, 2011. (3) Kovalev, V. A., Petkov, A., Wold, C., Urbanski, S. and Hao, W. M.: Determination of smoke plume and layer heights using scanning lidar data, Appl. Optics, 48(28), 5287–5294, 2009. (4) Kovalev, V. A., Petkov, A., Wold, C.,	(1) Under Review (2) Completed (3) Completed (4) Completed

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(E) Secondary Refereed Publications – work supported partially by project	(1) Akagi, SK., Yokelson, RJ, Burling, IR., Meinardi, S, Simpson, I, Blake, DR, McMeeking, GR, Sullivan, A, Lee, T, Kreidenweis, S, Urbanski, S, et al.: Measurements of reactive trace gases and variable O3 formation rates in some South Carolina biomass burning plumes, Atmos. Chem. Phys., 13(3), 1141–1165, 2013. (2) Burling, I. R., Yokelson, R. J., Akagi, S. K., Urbanski, S. P., Wold, C. E., Griffith, D. W. T., Johnson, T. J., Reardon, J. and Weise, D. R. (2011) Airborne and ground-based measurements of the trace gases and particles emitted by prescribed fires in the United States, Atmos. Chem. Phys., 11(23), 12197–12216, 2011. (3) Yokelson, R. J., Burling, I. R., Gilman, J. B., Warneke, C., Stockwell, C. E., De Gouw, J., Akagi, S. K., Urbanski, S. P., Veres, P., Roberts, J. M., Kuster, W. C., et al. (2013) Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires, Atmos. Chem. Phys., 13(1), 89–116, 2013.	(1) Completed (2) Completed (3) Completed
(F) Presentations and Proceedings conferences/symposia/workshops	See X. Additional Reporting for the list of conference and workshop proceedings and presentations	Completed

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X. Additional Reporting

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