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

Validation of Smoke Transport Models with Airborne and Lidar Experiments

Fiscal Year 2009 Progress Report

SUMBITTED 30 SEPTEMBER 2009

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1. Introduction

Wildland fire is a significant source of fine particulate matter ($PM_{2.5}$, particles with a diameter less than 2.5 μm) and nitrogen oxides and volatile organic compounds that can contribute to ozone (O_3) production and secondary organic aerosol formation. The Regional Haze Rule, recently revised National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (the 24-hr ambient standard was reduced from 65 to 35 μg m^{-3}), and the proposed tightening of O_3 standards will increase the pressure on land management agencies to address the air quality impact from wildfire, wildland fire use, and prescribed burning. Land management agencies need rigorously tested, accurate models to quantify the contribution of fire emissions to air pollution (e.g. $PM_{2.5}$ and O_3) and visibility impairment. 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. While many smoke plume models exist, few smoke plume observational datasets are available to properly validate these models and quantitatively assess their uncertainties, biases, and application limits.

This project, which addresses JFSP AFP-2008-1, Task 6, 'Smoke and Emissions Models Evaluation', is measuring 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 (**Li**ght **D**etection **A**nd **R**anging) instrument is deployed along with an airborne instrumentation package 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 northwestern United States. The LiDAR measures plume rise height, dynamics, dispersion, and aerosol optical properties. The airborne instrument package, deployed on a Cessna aircraft, measures the 3-D distribution of aerosol mass density and major trace gas (CO, CO_2, and CH_4) concentrations. Multiple wildland fires will be investigated over 2 years, allowing the research team to measure plume rise and smoke transport over a wide range of meteorological, fire activity, fuel, and terrain conditions.

Section 2 of this report provides background material on smoke dispersion and air quality forecasting systems. The goal of the 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 3 provides a detailed report on the project's progress and achievements. Section 4 summarizes continuing and future work associated with the project.

2. Background

The fundamental purpose of our research project is to acquire the data necessary for the evaluation of smoke dispersion and air quality forecasting systems. A diagram of a generic smoke dispersion / air quality forecasting system is provided in 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 is obtaining **model validation data** by measuring prognostic variables of plume rise, smoke transport, and smoke chemistry models with the spatial and temporal resolution required to quantitatively validate a wide range of models. The subcomponent models, 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 3-D distribution of model prognostic variables in the vicinity of active fire events, the project will also create a database of fire event variables which are the critical input for the subcomponent models of smoke dispersion and air quality forecasting systems.

2.1 Fire Environment Data

2.1.1 Fire Growth

Fire growth is determined by mapping the area impacted by a fire event over time. Mapping of fire progression provides the spatial information on the area impacted by fire and enables an estimate of the burned area and fuels involved. Fire growth may be determined from a combinations of incident perimeters and satellite observations (e.g. MODIS and Landsat).

2.1.2 Fuel Loading

Fuel loading – in simplest terms, the mass of fuel per a unit area – provides input needed to estimate fire behavior and fire effects. The complexity of a fuel loading map constructed for a specific fire event may be as minimal as the mass of above ground carbon per unit area or it may provide a detailed estimate of fuel loading according to components (canopy, down dead wood, litter, live, duff, etc.) and size classes. Fuel loadings are estimated by combining a fire area map with a fuel or vegetation type map and a fuel loading model. A fuel loading model is a representation of a fuel complex that provides fuel descriptors required as input for fire effects models. The complexity of a fuel loading map is determined by the requirements of the fire effects models employed for a particular application. The simulation of smoke impacts requires temporal and spatial estimates for a range of fire effects – fuel consumption, fire phase (flaming, smoldering), heat release, and emissions.

2.1.3 Fuel Consumption

Fuel consumption is typically estimated using models such as FOFEM, CONSUME, and FEPS. For input, fuel consumption models generally require fuel loading by fuel type and size class and information on fuel moisture. Meteorology, terrain (slope, aspect) and canopy cover all play a role in determining fuel moisture. Some fuel consumption models, such FOFEM and CONSUME, simulate the amount of fuel consumed during each phase fire (flaming, smoldering). Fuel consumption models may also provide an estimate of heat released by fire.

2.1.4 Emissions

Wildland fires emit a wide range of pollutants that degrade air quality. The composition and intensity of emissions depends on the type and amount of fuel burned and the fire phase – smoldering or flaming combustion. Emission intensities for a species X are estimated using emission factors which prescribe the mass of X emitted per unit mass of vegetation consumed by fire. For a specific species X the emission factor depends on the vegetation or fuel type and the fire phase.

2.2 Model Validation Data

Smoke dispersion and atmospheric chemistry forecasting systems predict smoke impacts on air quality by simulating the temporal evolution of the 3-D concentration fields of smoke aerosol and other pollutants (e.g. CO and O_3). The LiDAR and airborne observations collected in this study will be used to validate the pollutant concentration fields simulated by these forecasting systems. This study will also provide observations of plume rise height for validation of the various plume rise models which are key subcomponents of smoke dispersion and air quality forecasting systems. These sub-grid scale plume rise models are typically embedded in the columns of host 3-D smoke dispersion and atmospheric chemistry models and are used to prescribe the vertical distribution of fire emissions. Predictions of three plume rise models and a smoke dispersion model are provided in Figures 2 & 3 to illustrate how the observations acquired in this study may be used to evaluate the performance of these models.

2.2.1 Plume Rise

The ability of plume rise models to accurately capture the plume behavior of wildland fires is highly uncertain. The plume rise predicted by these models can be quite different for a given fire. Figure 2 shows hourly plume rise heights (ΔH) predicted by 3 different plume models for the Bugaboo Scrub Fire in southern Georgia on May 8, 2007. The importance of plume rise models in assessing the air quality impacts of fire emissions is demonstrated in Figure 3. Plume rise predictions from Figure 2 were used to vertically distribute fire emissions in two WRF-Chem simulations. Figure 3 shows the predicted O_3 surface concentration field at 1500 EST on May 8, 2007. Ozone is a secondary pollutant formed through photochemical reactions of volatile organic compounds and nitrogen oxides (both are emitted by wildland fire) and thus, the peak O_3 is downwind of the fire. The two plume rise models produce very different predictions of the fire's air quality impact. The predicted peak O_3 and high O_3 area (> 80 ppb) differs by about 100%, due solely to the different plume rise models.

LiDAR is a potent tool for measuring the physical dimensions of smoke plumes, especially plume rise height, ΔH. Using the Atmospheric Heterogeneity Height Indicator (AHHI) algorithm (see section 3.3) the maximum plume rise can be derived from a large volume of LiDAR data to provide an accurate time series of ΔH observations. Vertical profiles obtained with the airborne instrument package also provide a precise measurement of ΔH.

2.2.2 Smoke Dispersion

An example of an aerosol concentration field simulated with WRF-Chem, an air quality forecasting model, is given in Figure 4. Mobile LiDAR is an efficient tool for measuring the rise height and physical dimensions of smoke plumes. However, LiDAR alone cannot provide the observations needed to evaluate smoke dispersion models due to two key limitations: limited range (maximum of ≈ 12 km) and an inability to measure aerosol concentration. When suitable instrumentation is deployed on an aircraft, appropriate sampling maneuvers, such as vertical profiles and horizontal transects downwind of an active fire, can provide measurements for validating simulations results like that depicted in Figure 4.

2.2.3 Emissions

Aircraft based measurements of aerosol, CO_2, CO, and CH_4 concentrations in fresh smoke can be used to validate the model emissions of these species. Furthermore, enhancements of CO_2 and CO in smoke relative to the background air can be used to derive the modified combustion efficiency (MCE) of the fire. The emission intensities of many reactive compounds released by fires are proportional to the fire's MCE. Thus, CO_2 and CO measurements provide an avenue to estimate the emissions of a wide range of compounds (based on their MCE dependence). Further, the measurements of the MCE for multiple wildfire events in the western U.S. that are being obtained in this project address a crucial knowledge gap. While laboratory studies and field studies of *prescribed fires* have established X – MCE relationships (where X is a reactive compounds released by fires) , there are few measurements of MCE for wildfire events in the U.S. By providing measurements of MCE for wildfire events, this project will improve the emission estimates used as input for smoke dispersion and air quality forecasting models.

3. Accomplishments

The project duration is 3 years, with a start date of June 1, 2008 and a completion date of May 31, 2011. The primary deliverables of this project are:

- A comprehensive database of field observations and fire environment data for multiple fire events in the western U.S. for distribution to Smoke Emissions Model Intercomparison Project (SEMIP, JFSP project #08-1-6-10)
- Project final report describing: 1) the aircraft and lidar instrumentation systems, calibration and data quality control, 2) flight patterns and data processing, 3) the wildland fire events studied, and 4) field measurement results and data analysis
- Manuscripts for publication in peer reviewed journals

The comprehensive database is to be provided to SEMIP **by May 31, 2011**. The due date of the project final report is **May 31, 2011**. The final comprehensive database will be comprised of **model validation data** (plume rise, smoke dispersion, and emissions measurements acquired with mobile LiDAR and airborne instruments) and **fire environment data** for multiple fire events in the western U.S. The project's progress towards achieving the final deliverables is reported here according to key accomplishments:

- Laboratory calibration of the airborne nephelometer
- Development of a Project Aviation Safety Plan
- Development and publication of improved methodology for analyzing LiDAR observations of smoke plumes
- Deployment of LiDAR and airborne assets to wildland fire events during the summer of 2009
- Construction of a preliminary model validation dataset for the Kootenai Creek Fire

3.1 Laboratory calibration of airborne nephelometer

The primary airborne instrument deployed in this study is a Radiance Research nephelometer (model 903). A nephelometer measures light scattering by particles, which can be related to particle mass concentration through a mass calibration. In March of 2009 a set of experiments were conducted in the Missoula Fire Science Laboratory's combustion chamber for the purpose of calibrating the Radiance Research nephelometer. A total of 19 chamber burns were conducted using wildland fuels characteristic of the northwest U.S. – fir braches with needles attached and/or ponderosa pine needles.

The experiment used two filter sampling systems, each fit with a 2.5 µm cut-point cyclone. (A cyclone with 2.5 µm cut-point passes only particles with an aerodynamic diameter of less than 2.5 µm, i.e. $PM_{2.5}$). One of the filter sampling systems had been constructed several years ago and has been previously calibrated versus Federal Reference Method (FRM) $PM_{2.5}$ air samplers (the BGI, Inc. PQ200 and the Partisol FRM Model 2000) [Trent et al., 2000]. The second filter sampling system was constructed in January 2009 using the design of the legacy filter sampling system. The filter sampling systems were loaded with 37 mm Teflon filters which were weighed on site in the Missoula Fire Lab's environmentally controlled filter analysis room. The experiment protocol involved igniting a fuelbed in the chamber and allowing the chamber to fill with smoke. Once the nephelometer indicated the particle concentrations were no longer increasing and had leveled off, the filter samples were initiated. Sampling periods ranged from 15 – 57 minutes (µ=21 minutes, median = 25 minutes). The average decrease in nephelometer signal over the sampling period was 13% with a range of 6 – 28%. Between experiments one of the following occurred: 1) the chamber was completely flushed and a new fuel sample was burned to provide a complete sample of fresh smoke, 2) the chamber was partially flushed to reduce the smoke particle concentration, or 3) additional fuel was burned without flushing the chamber, to increase the smoke particle concentration and produce a mix of fresh and slightly aged smoke particles.

The calibration data are given in Table 1 and the data points and resultant nephelometer calibration curve are shown in Figure 5. The average aerosol concentration during an experiment was derived from the aerosol filter mass loading, the filter sample volumetric flow rate, and the total sample duration time. As may be seen in Figure 5, the average nephelometer scattering is highly correlated with the aerosol concentration (r =0.96). The calibration coefficient of 0.213 µg m^{-2} agrees well with previous calibrations (e.g. Yokelson et al., 2007) and has a 1-σ uncertainty of $\approx$ 5%.

Table 1. Nephelometer calibration data

Experiment			**Aerosol Filter**			**Nephelometer**
expt. #	sample duration	percent drop	Mass	volume	conc.	average scattering
(#)	*(sec)*	*(%/min)*	*(µg)*	*(m3)*	*(µg/m3)*	*(1/m)*
1	1514	16.2	265.8	0.772	344.1	1055.7
2	1696	18.8	73.1	0.864	84.6	330.5
3	3432	27.5	52.1	1.768	29.5	118.6
4	1574	12.5	160.0	0.809	197.7	630.6
5	1252	11.2	65.6	0.647	101.4	423.9
6	1686	13.2	77.5	0.870	89.0	206.5
7	1202	8.6	128.8	0.619	208.1	752.0
8	922	6.2	328.1	0.475	691.4	3194.8
9	1610	28.1	76.5	0.832	92.0	356.7
10	1360	14.8	106.1	0.703	151.0	628.9
11	1204	13.8	140.0	0.623	224.8	1034.8
12	1204	9.5	160.0	0.625	256.2	1476.2

13	934	6.0	230.0	0.482	477.2	2099.1
14	1204	11.7	148	0.621	238.4	1271.1
15	2772	13.0	30.9	1.440	21.5	106.4
16	1790	19.7	210	0.926	226.8	1494.8
17	1246	13.0	250	0.644	388.2	2053.0
18	1204	13.2	290	0.621	467.1	2256.8
19	1204	12.1	200	0.622	321.7	1315.6

Humidification studies of biomass burning aerosol show that initial water uptake by these particles begins at a relative humidity between 40 – 80%, depending on the vegetation type [Day et al., 2006]. During previous airborne studies the relative humidity in the heated Radiance Research nephelometer sample cell was not observed to exceed 35%. Based on this previous experience and the aforementioned humidification study, we are confident that humidification effects on particle scattering are negligible and that the calibration curve obtained in the laboratory may be applied to the field measurements without adjustment for relative humidity.

3.2 Development of Project Safety Aviation Plan

The use of aviation for research is a potentially high-risk activity. This is especially true when the research involves an active fire event with fire aviation traffic. Risk management is used to mitigate the likelihood and/or severity of hazards and thus reduce the risks associated with an activity. Risk management for this project began with the development of the project Research Operations Plan for the aviation portion of the field deployment. Next, during the early summer of 2009, the project PI collaborated with the USFS Region 1 Supervisory Pilot (Michael Peitz) and the Northern Region Aviation Safety Manager (Eddie Morris) to develop a Project Aviation Safety Plan (PASP) based on the Research Operations Plan. The PASP was reviewed by the Region Aviation Officers for the Pacific Northwest, Rocky Mountain, Intermountain, and Northern Regions. The 2009 PASP will serve as a draft for the project's 2010 PASP. The 2009 PSAP will also be used as a template for future research projects employing airborne assets. The 2009 PASP has been included with this progress report (see section 5).

3.3 New LiDAR methodology

To monitor smoke plume behavior with LiDAR, the regions with high levels of backscattering must be discriminated from regions of clear atmosphere, and the distance from the LiDAR to the smoke plume edges should 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.

An improved methodology was developed for the use of the LiDAR vertical scans obtained in areas of smoke plumes for extracting information about the plume heights and their spatial and temporal changes. The new technique determines a special interception function and transforms it into what we define as the Atmospheric Heterogeneity Height Indicator (AHHI). The study presenting the development of this new LiDAR analysis methodology has been accepted for publication as a peer-reviewed article in Applied Optics and is currently in press [Kovalev et al., 2009]. The in press manuscript has been included with this progress report (see section 5).

3.4 Summer 2009 Field Deployment

3.4.1 Summary of 2009 Northwest fire season

The focus of the project is wildfire events in the northwestern U.S., in particular Montana, northern Idaho, Washington, and Oregon. This area corresponds to the regions organized as the Northern Rockies and Northwest Geographic Area Coordination Centers (GACC). The primary target of the project is large, long-duration events which exhibit active fire behavior over many days. Such events are favorable for successful field deployment. The aircraft research team may reach a fire event and begin science flights in less than 24 hours after a decision is made to deploy. However, the ground based LiDAR team typically requires more time for mobilization. The LiDAR team must complete several tasks before research may begin: travel to the incident, team check-in at the incident, coordination with the Incident Management Team, and identification of suitable location for deployment of the LiDAR. Once a decision has been made to deploy to an event, the LiDAR team may require 2 – 3 days before it can be positioned to acquire smoke plume observations. For this reason, large, long-duration events which exhibit active fire behavior over many days are most suitable for study in this project.

The study research plan is designed for deployment during August, the month of peak fire activity in this region, and the period when large, long-duration fire events are most frequent and most active. The 2009 northwestern U.S. fire season was extremely inactive and offered few promising fire events for study by the project. The fire season was dramatically different from the typical pattern of the previous decade (see Figure 6). In the decade preceding 2009, the median annual burned area in the Northern Rockies and Northwest was 1,007,000 acres. In 2009, fire occurrence and acres burned was well below that observed in 9 of the 10 previous years; through September 1, only 139,000 acres were burned by wildfire in the Northern Rockies and Northwest. By the end of August only 10 fires larger than 1000 acres, and 2 fires larger than 5000 acres, had occurred in the northwestern U.S. The lack of suitable fire events in the primary study region limited the success of the 2009 field deployment.

3.4.2 Deployments

The lack of sustained, large fire events significantly limited deployment opportunities in August, 2009. However, the project did manage to deploy the LiDAR and/or airborne research teams to 7 different fire events (Table 2). The success of the deployments, as gauged by the acquisition of observations for the validation model simulations (plume rise, smoke dispersion, emissions) was highly variable (Table 2). Aggressive and successful suppression activities quickly contained the Narraguinnep and Oden Road Fires. As a result, fire growth and overall fire activity was minimal while the research teams were deployed at these events. Deployments to the Kootenai Creek and Mill Flat fires were the most successful of the summer. Processing and initial analysis of the LiDAR and airborne data obtained during the field deployments is currently underway. The organization of fire environment data for each fire event is ongoing. A preliminary dataset has been assembled for the Kootenai Creek and some of the results are presented in Section 3.4.3.

Table 2. 2009 Project Field Deployments

Fire Name	Location	Date(s)	Model Validation Data Acquired			
			LiDAR plume rise	Aircraft plume rise	Aircraft dispersion	Aircraft emissions
Murray Douglas Prescribed Fire	Ovando, MT (-113.12,46.87)	May 18, 22	X			
Kootenai Creek Fire	Stevensville, MT (-114.24, 46.55)	Jul 21,22 Aug 4, 26-28	X	X	X	X
Narraguinnep Fire	Cortez, CO (-108.75, 37.65)	Aug 12			X	
Mill Flat Fire	New Harmony, UT (-113.38, 37.46)	Aug 21,22		X	X	X
Oden Fire	Omak, WA (-119.76,48.34)	Aug 24,25				X
Sand Basin Fire	Philipsburg, MT (-113.72, 46.187)	Aug 27		X	X	X
Middle Black Prescribed Fire	Clearwater NF,ID (-115.50, 46.84)	Aug 28		X	X	X

3.4.3 Kootenai Creek Fire – Preliminary Results

The project deployed to the Kootenai Creek Fire on 7 days in late July and August of 2009. Comprehensive measurements of plume rise, smoke dispersion, and emissions were obtained with the mobile LIDAR and airborne instruments (see Table 2). The fire location, aircraft flight path, measured aerosol concentration, and LiDAR scan transects from August 27 are shown in Figure 7. The aircraft flight path consisted of two 30 km segments, oriented perpendicular to the transport winds (i.e. the direction of the plume flow) and located ≈ 10 km downwind of the active fire. The flight segments were obtained at elevations of 1900 m and 2500 m above ground level. The aircraft sampling also included a vertical profile taken ≈ 10 km downwind of the active fire. Figures 8 and 9 present the aerosol concentrations measured during the airborne transects and vertical profile. Plume rise heights (ΔH) from the LiDAR observations and the aircraft vertical profile are given in Table 3. The observations in Table 3 may be used to validate plume rise heights predicted by models such as Daymsoke, PLUMP, and the Briggs equations. The aerosol concentrations (Figures 7-9) may be used to validate the concentration fields simulated by high-resolution smoke dispersion models, such as that depicted in Figure 4.

Table 3. LiDAR observed plume rise heights (ΔH)

Time (MDT)	ΔH (m agl)
12:12	2620
12:36	2790
13:10	3050
13:52	2970
15:21	2710
airborne observation	
15:55	2790

4. Continuing Work

The following project tasks will be accomplished during fiscal year 2010:

1. Complete the analysis of LiDAR and airborne observations acquired during the summer of 2009
2. Organize fire environment data for each fire event studied in 2009:

Fire Event Database	
Dataset	**Purpose**
• Incident fire perimeters • MODIS burn scar and active fire detections • Landsat images	Mapping of burned area mapping and fire growth Post-fire assessment of fire severity and fuel consumption
Landfire data layers • Existing vegetation type • Fuel loading models • FCCS • FB13 and FB40 Local fuel maps (e.g. Forest or District level)	Mapping of fuel / vegetation type and fuel loading Provides input for fire effects and fire behavior models
Landfire data Layers • aspect • slope • elevation	Estimation and mapping of fuel moistures Provides input for fire effects and fire behavior models
Meteorological data: • RAWS and NFDRS stations • Incident meteorological /fuel observations	Estimation of fuel moistures Provides input for fire effects and fire behavior models

3. Construct comprehensive dataset for each fire event studied in 2009
4. Delivery of 2009 dataset to the Smoke Emissions Model Intercomparison Project (SEMIP, JFSP project #08-1-6-10)
5. Plan summer 2010 field deployment and update Project Aviation Safety Plan
6. Summer 2010 field deployment

5. Appendix

Accompanying Documents

1. 2009 Project Aviation Safety Plan (JFSP-01-1-6-09_PASP.pdf)
2. In press publication: "Determination of smoke plume and layer heights using scanning lidar data" (Kovalev_etal_AppliedOptics_inpress_2009.pdf)

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Yokelson, R.J., Urbanski, S. P., Atlas, E. L. , Toohey, D. W., Alvarado, E. C. , Crounse, J. D. , Wennberg, P. O., Fisher, M. E., Wold, C. E., Campos, T. L., Adachi, K., Buseck, P. R., and Hao, W.M. (2007). Emissions from forest fires near Mexico City, *Atmos. Chem. Phys*., **7**, 5569-5584.

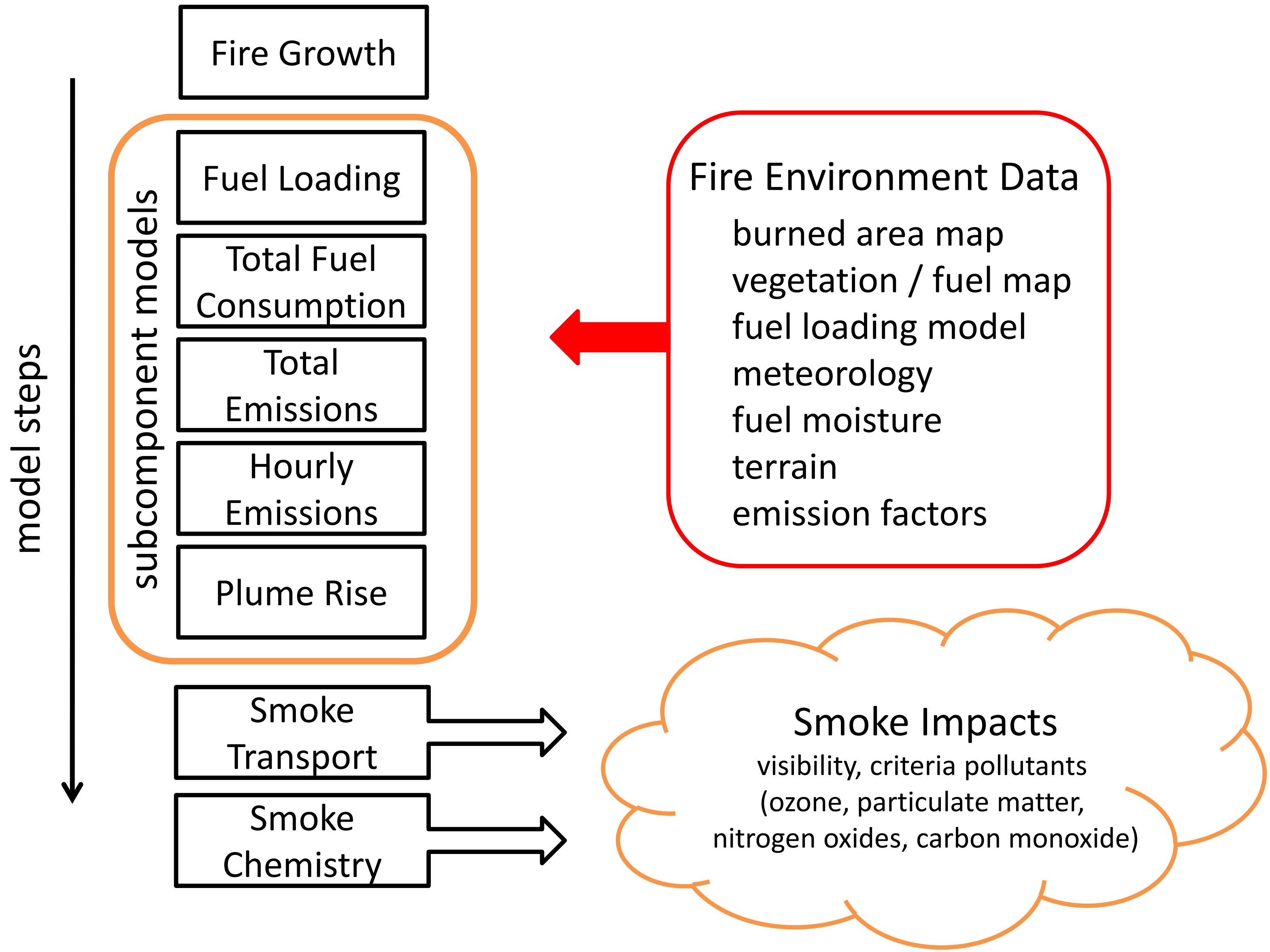


Figure 1. Generic smoke dispersion – air quality forecasting system

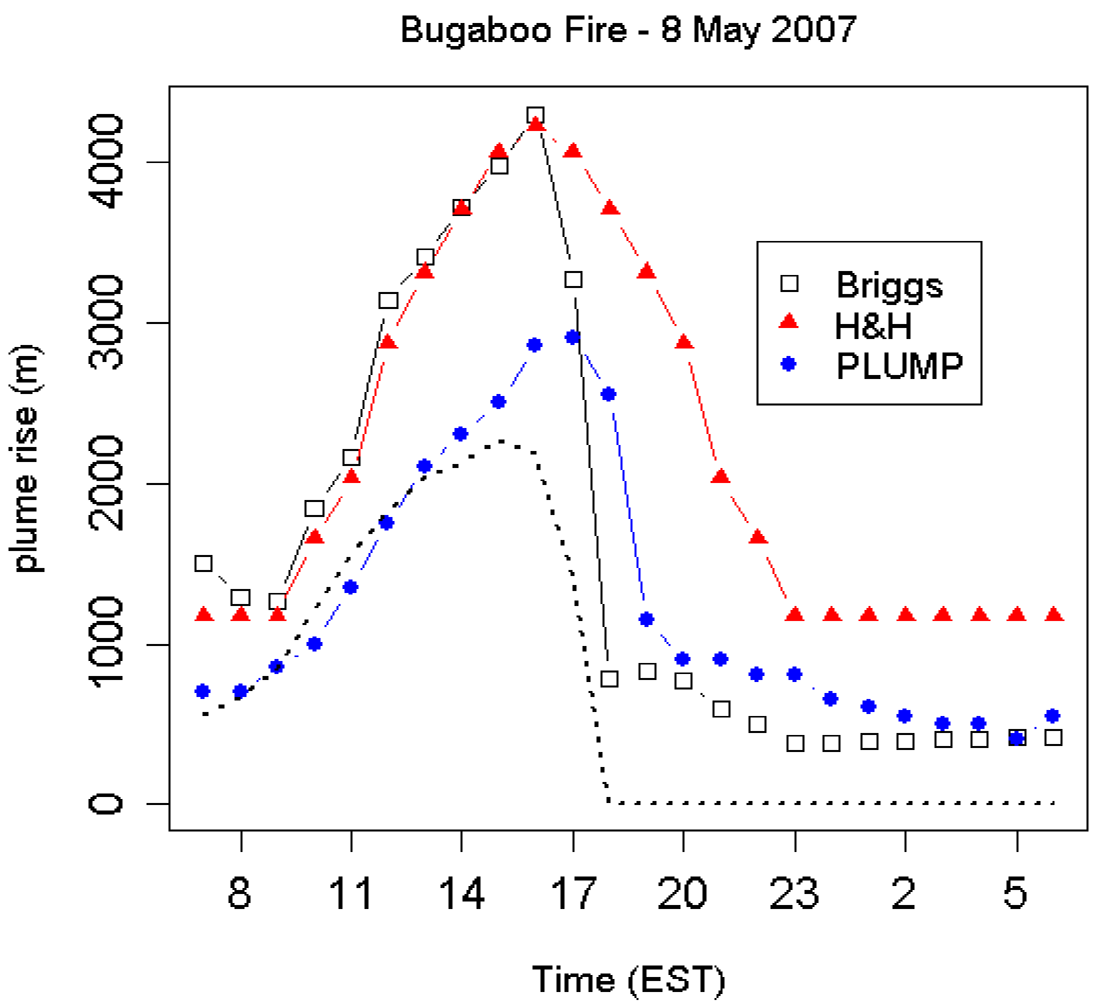


Figure 2. Predicted plume rise height (ΔH) for the Bugaboo Scrub Fire in southern Georgia on May 8, 2007. Dashed black line is the WRF-SD predicted planetary boundary layer height. Briggs = Briggs equations, H&H = Harrison and Hardy empirical model.

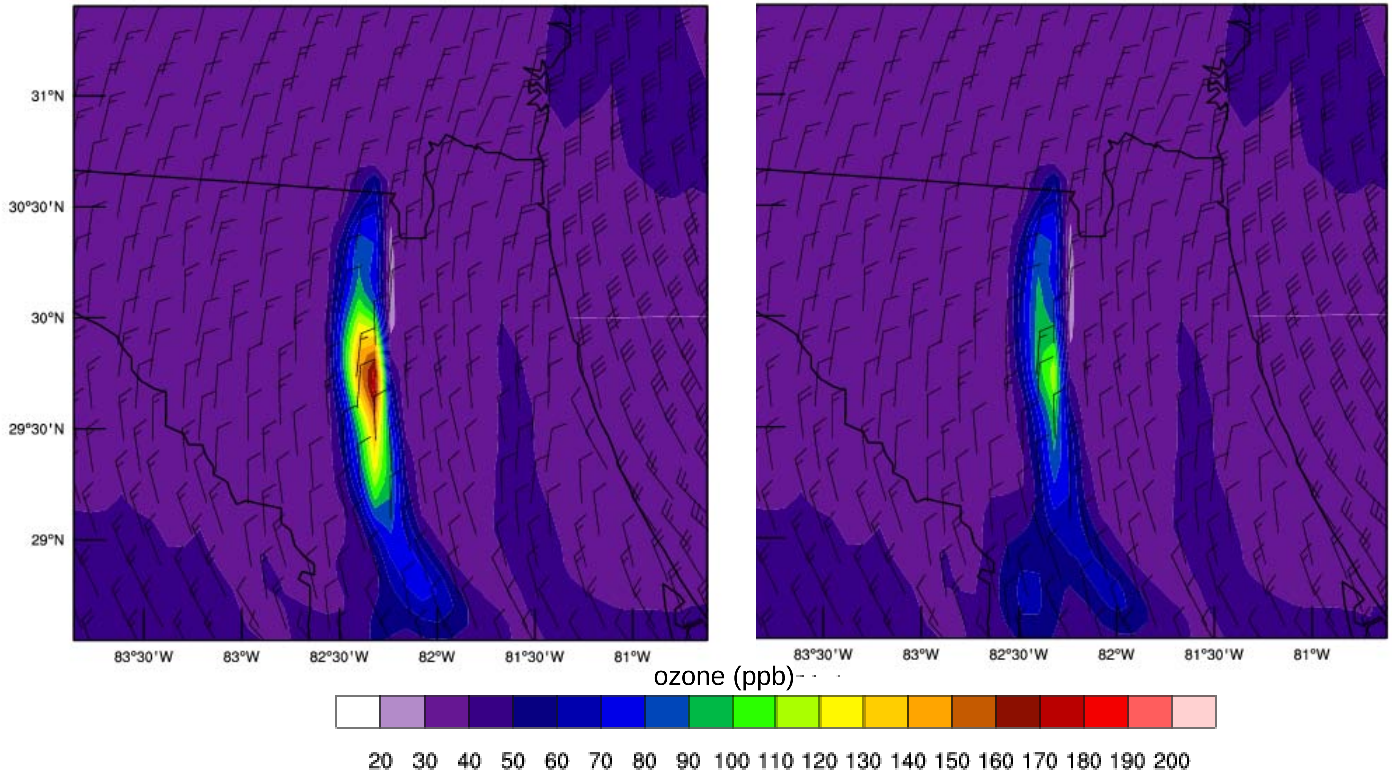
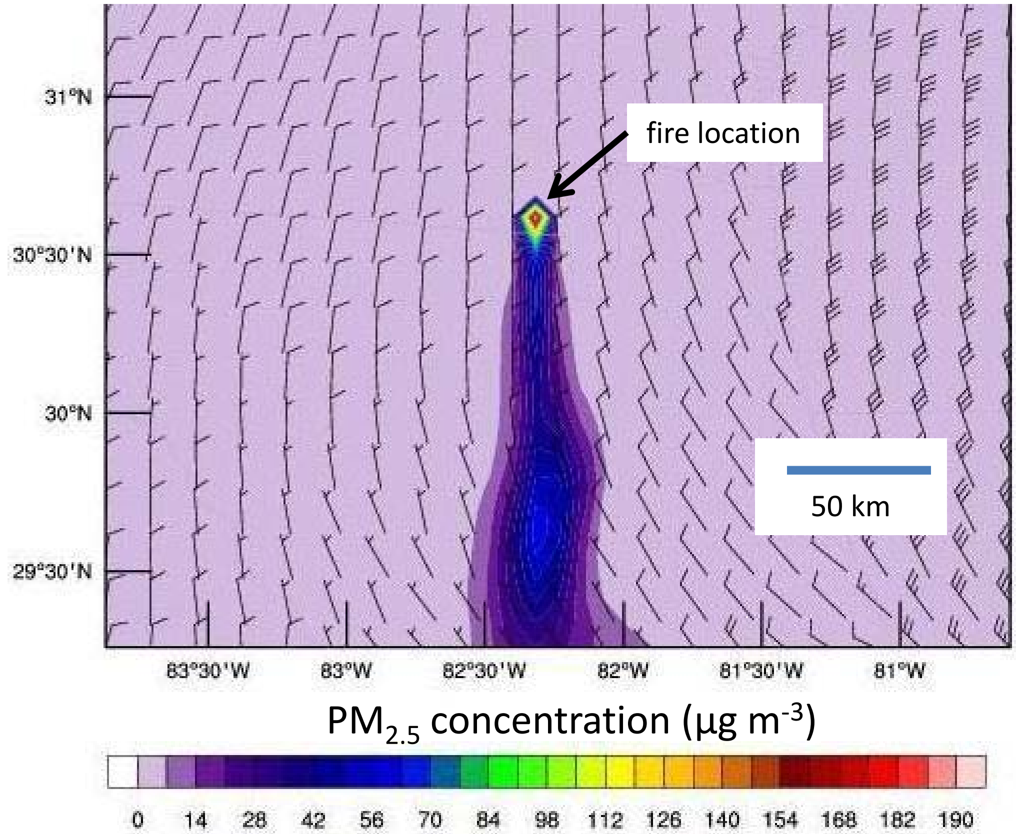


Figure 3. WRF-SD simulated O_3 plume from the Bugaboo Scrub Fire on May 8, 2007. The plume rise heights used in the simulations were predicted with PLUMP (left panel) and Briggs equations (right panel). Winds units are knots (1 full barb = 10 knots) and ozone units are parts per billion.

Figure 4. Simulated aerosol concentration field for the Bugaboo Scrub Fire on May 8, 2007. Simulation by WRF-Chem air quality model.



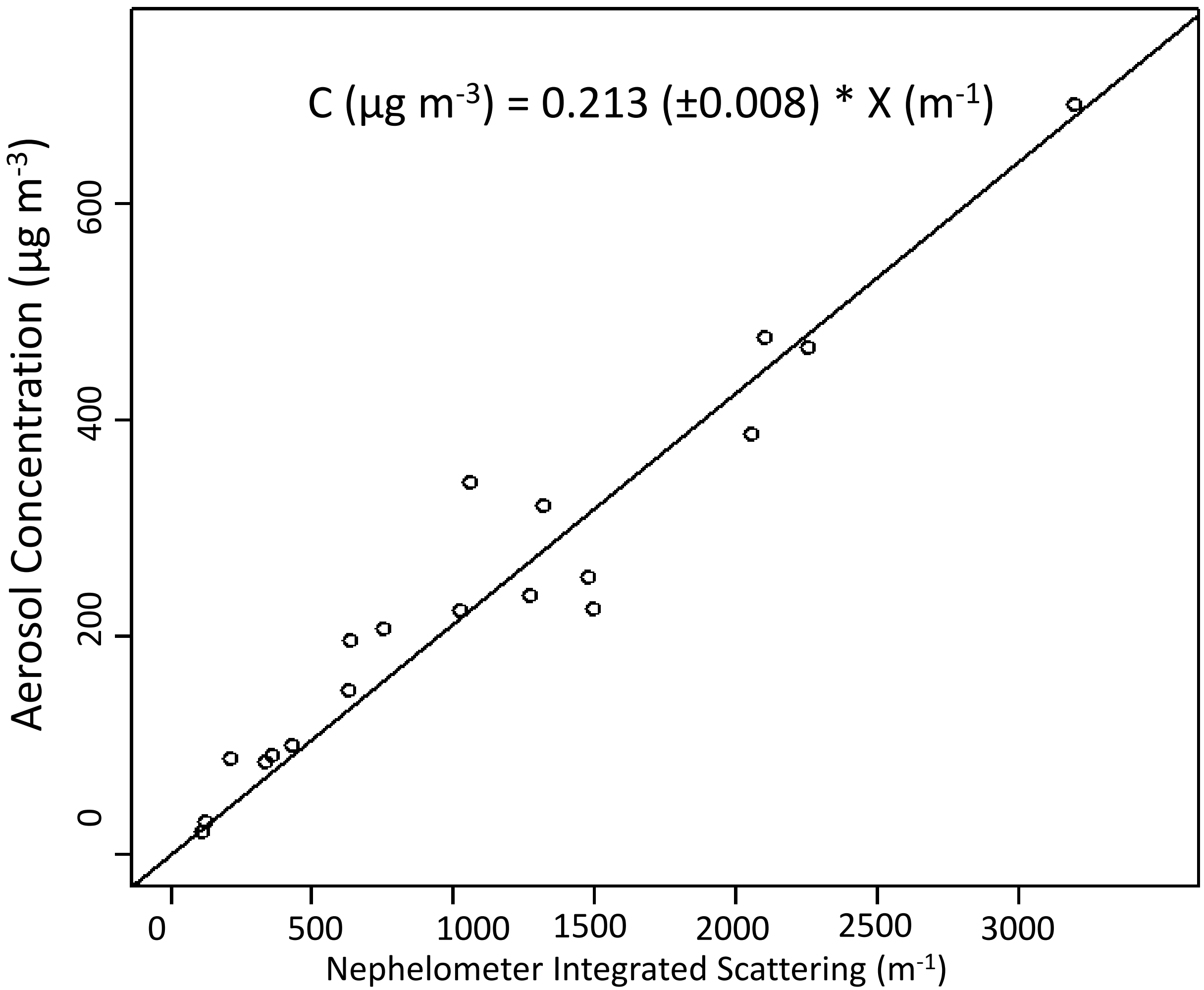


Figure 5. Aerosol mass concentration calibration of the Radiance Research nephelometer. The x-axis is the average scattering measured by the nephelometer over the sample period (units of inverse meters). The y-axis is the average aerosol concentration derived from the aerosol filter mass loading, the filter sample volumetric flow rate, and the total sample duration. The open circles are data points from the 19 calibration experiments. The solid line is a linear least-squares best-fit with the intercept forced to 0. The slope of the best-fit line is 0.213 (±0.008) µg m^{-2} (uncertainty is 1σ), $r^2 = 0.93$.

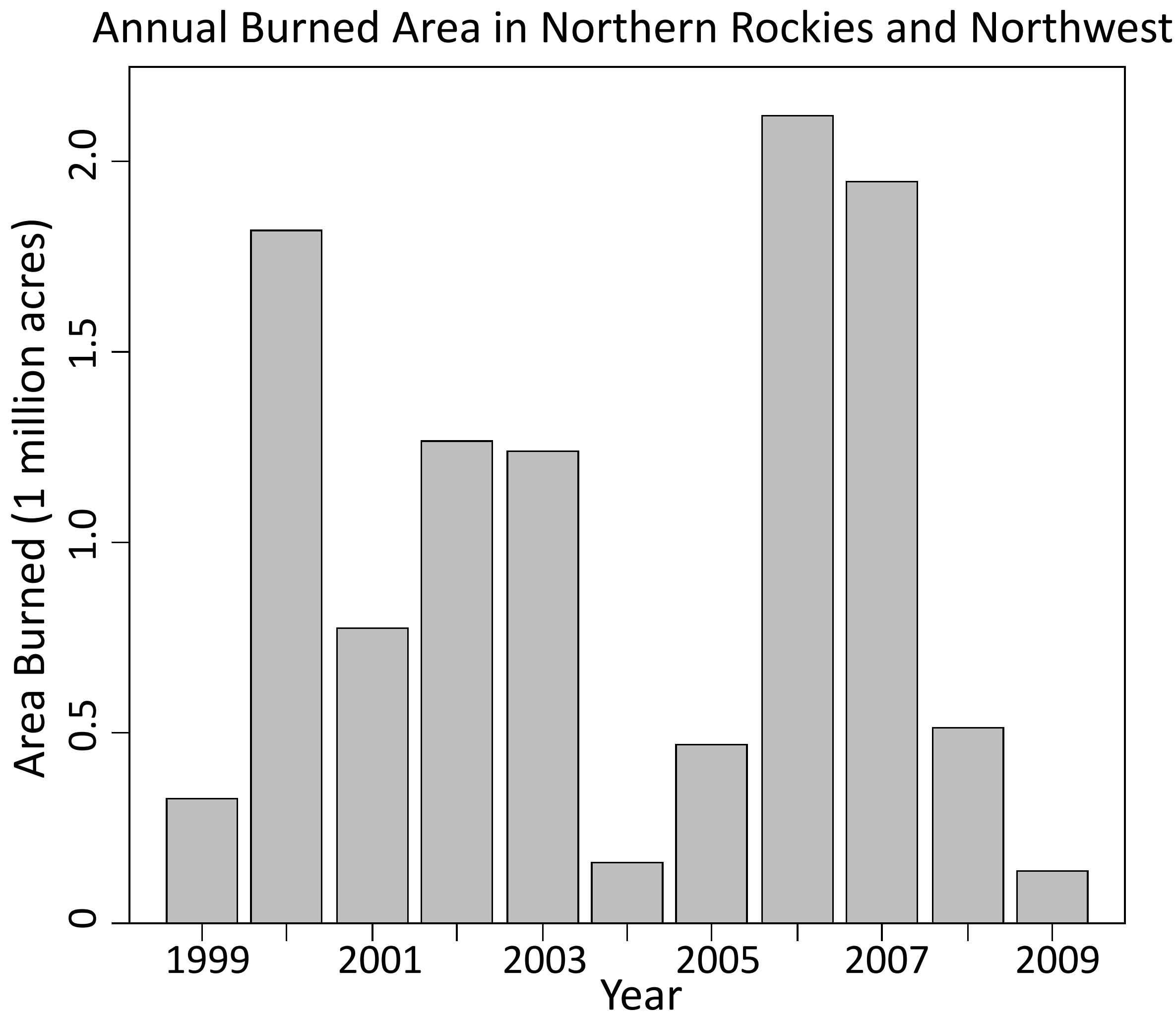


Figure 6. Annual burned area in the northwestern U.S. (Northern Rockies and Northwest GACCs) 1999 – 2009. Data for 2009 is through September 1. The median value for 1999 – 2008 is 1.0 million acres. The 2009 total through September 1 is 0.14 million acres. Data from NIFC IMSR.

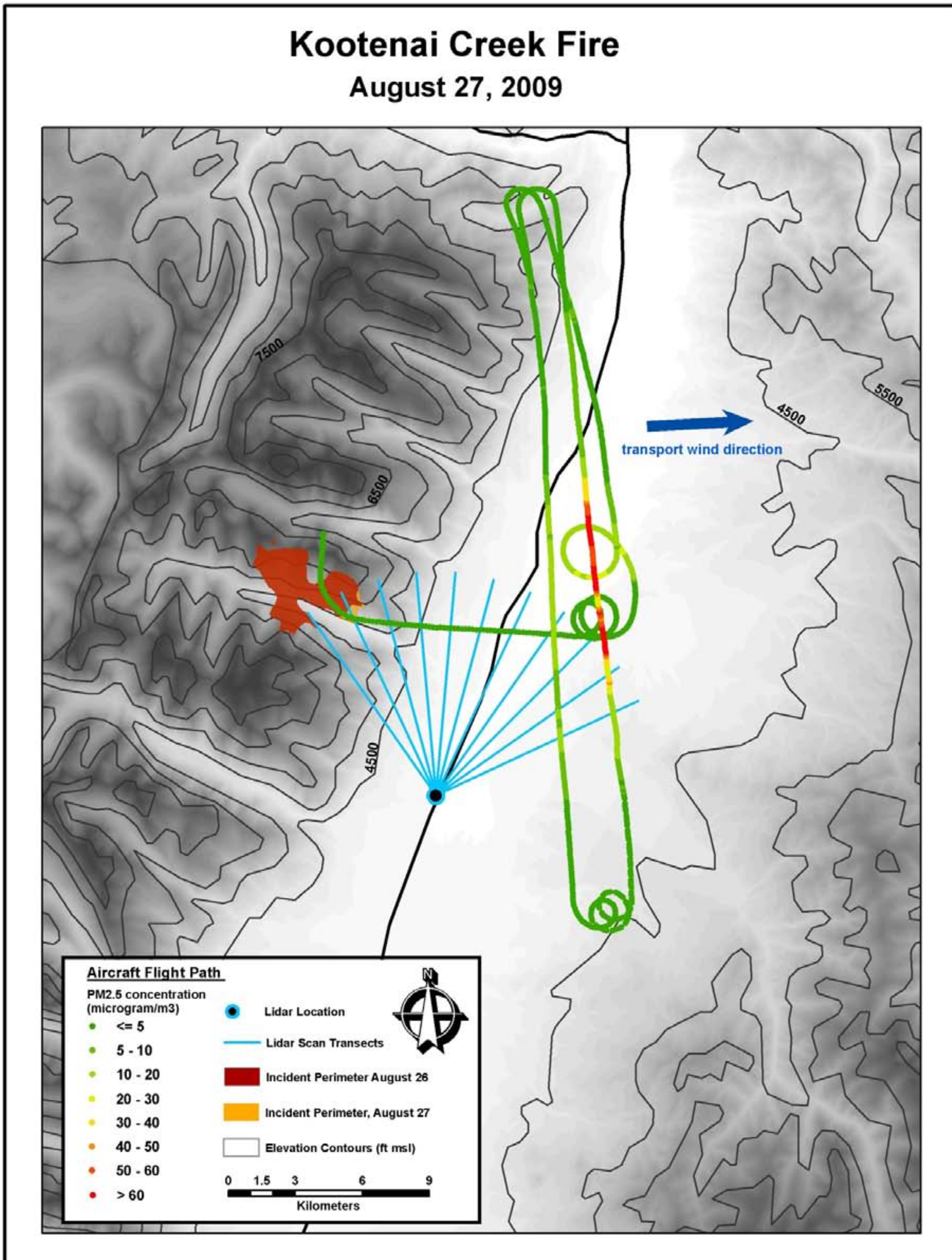


Figure 7. Flight path with measured aerosol concentration, LiDAR deployment location, LiDAR scan transects, and incident fire perimeter.

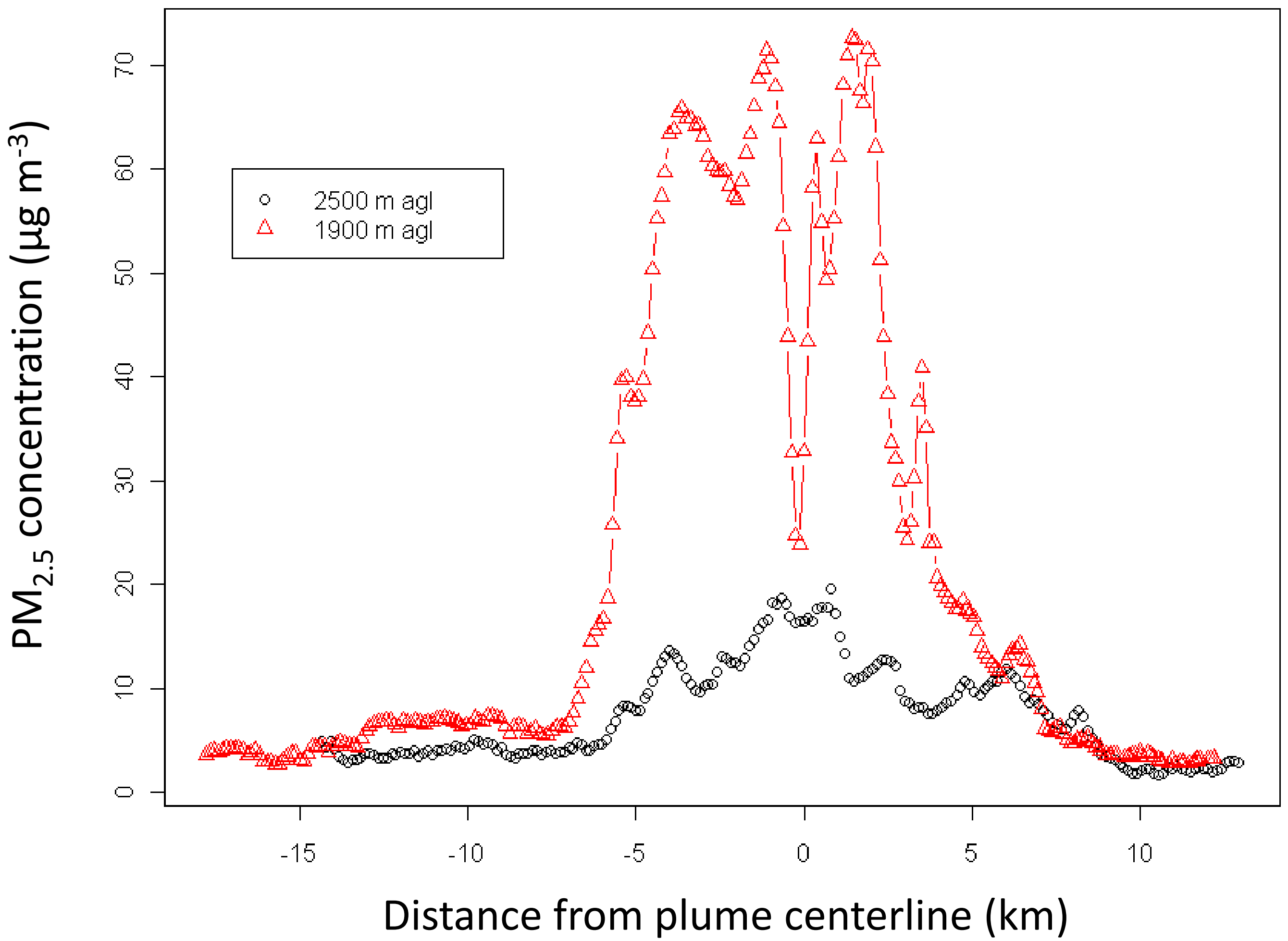


Figure 8. Airborne measurements of aerosol concentration downwind of the Kootenai Creek Fire on August 27, 2009. The aircraft flight path consisted of two 30 km segments, oriented perpendicular to the transport winds (i.e. the direction of the plume flow) and located ≈ 10 km downwind of the active fire. The flight segments were obtained at elevations of 1900 m and 2500 m above ground level.

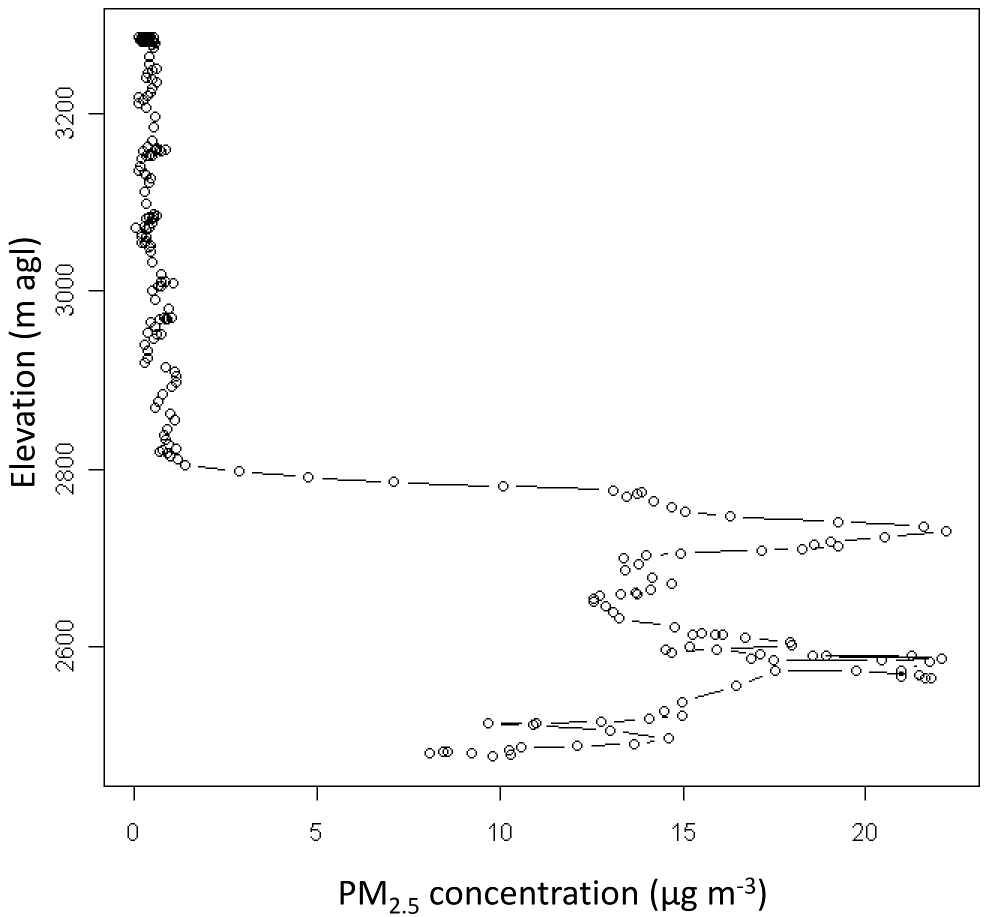


Figure 9. Vertical profile of aerosol concentration 10 km downwind from the Kootenai Creek Fire. The vertical profile clearly identifies the top of the plume located at 2790 m.