Project Title: Characterizing Particulate Matter Emissions by Wildland Fires Relevant to Visibility Impairment and PM Non-Attainment

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I. Abstract

Carbonaceous aerosols, which include contributions from industrial and mobile source emissions and biomass combustion, exert a significant impact on regional air quality. Some preliminary semi-quantitative analyses suggest that smoke from fire-related activity may contribute significantly to observed organic mass concentrations. Further, these emissions have resulted in increased conflicts with the need to attain air quality standards, especially for particulate matter (PM) and visibility, as mandated by the Clean Air Act. However, federal land managers and policy makers currently lack several important tools needed for air quality assessments: composition profiles and analytical techniques necessary to differentiate carbonaceous aerosols originating from industrial and mobile source activity and those from fire emissions; measurement-based PM mass emissions rates for relevant fuels and combustion conditions; and reasonable optical properties and optical property emission rates to attach to fire emissions.

In this project, we addressed these needs via a comprehensive, multi-investigator approach that included both laboratory studies and validation of findings via field measurements. Specific elements included: (1) development and validation of promising new, inexpensive methods suitable for quantitative measurement of smoke marker (levoglucosan and K+) concentrations from aerosol filter samples, such as those routinely collected by the IMPROVE or EPA STN networks; (2) laboratory measurements of smoke emission composition profiles for several important fuel types burned under a variety of conditions to provide urgently-needed source profiles for classes of fires believed to severely impact air quality in the western and southeastern U.S.; (3) concurrent with smoke emission profile measurements, measurement of key physical and optical properties and emission rates in the laboratory; and (4) field measurements of fresh smoke plumes to validate whether laboratory smoke studies, conducted under well controlled conditions, can simulate PM2.5 mass, composition, and optical property emissions characteristics of more complex, actual prescribed and wild fires. Further, the field study was to be complemented by lidar measurements to demonstrate the feasibility of using remote sensing methods for continuous monitoring of smoke-polluted atmospheres adjacent to severe wildfires, providing diurnal and spatial variation of aerosol properties, plume heights and dynamics, and direction and rate of smoke plume movement in near real-time.

Our project resulted in the generation of a large database of emissions data, and numerous refereed publications describing the methods, findings and implications. Together, the results and methods developed during this study "support the needs of wildland fire managers and policy makers in determining the contribution of biomass burning to PM2.5 and visibility on a regional basis," as requested in the Call for Proposals, with our work specifically focusing on the western and southeastern U.S. regions.

II. Background and Purpose

Carbonaceous aerosols, which include contributions from industrial and mobile source emissions and biomass combustion, exert a significant impact on regional air quality. Some preliminary semi-quantitative analyses suggest that smoke from fire-related activity may contribute significantly to observed organic mass concentrations. Further, these emissions have resulted in increased conflicts with the need to attain air quality standards, especially for particulate matter (PM) and visibility, as mandated by the Clean Air Act. However, federal land managers and policy makers currently lack several important tools needed for air quality assessments: composition profiles and analytical techniques necessary to differentiate carbonaceous aerosols originating from industrial and mobile source activity and those from fire emissions; measurement-based PM mass emissions rates for relevant fuels and combustion conditions; and reasonable optical properties and optical property emission rates to attach to fire emissions. This three-year project has characterized wildland fire particulate matter (PM) emissions from laboratory fires during years 1 and 2 and from wildland fires during the third year of the study. We have specifically focused on fuels commonly burned in the southeastern and western U.S., two regions that experience significant annual air quality impacts from open biomass burning.

Specific project objectives listed in our proposal are as follows:

1. Develop an unambiguous, routine, and cost effective methodology for IMPROVE and other monitoring networks to characterize carbonaceous and other compounds in $PM_{2.5}$ aerosol as originating with prescribed and wildfire burn activities, to include:
    i. Development and validation of an inexpensive, robust method for routine measurement of smoke marker concentrations in aerosol filter samples
    ii. Generation of smoke marker source profiles through a series of laboratory burns utilizing important, relevant fuel types and burn conditions
2. Test this method by:
    i. Making measurements in fresh smoke plumes from wild and prescribed fires in order to validate laboratory testing results
    i. Analyzing sets of filters from several IMPROVE sites in a pilot study to document the suitability of the developed methodology for routine application
3. Deliver a proven composition source profile for fire apportionment to federal land managers, air quality regulators, and policymakers
4. Demonstrate a methodology for a high-time-resolution measurement of elemental and organic carbon concentrations, potentially superior to thermal methods
5. Determine the physical properties of emitted PM, including particle size distribution and particle morphology
6. Determine fuel-based optical and mass emission factors that are connected by optical (extinction, scattering and absorption) mass efficiencies, and assess the connection of physical and optical properties with optical properties using the commonly-applied Mie theory

7. Determine the dependence of scattering coefficients on relative humidity

In addition, we invited other separately-funded groups to participate in our laboratory studies. They benefited from our emissions characterization work and in turn, provided additional interesting aerosol characterizations, as follows:

8. Study the activity of combustion particles as seeds for warm and cold cloud formation, and link these characteristics to impacts in pyrocumulus clouds

9. Study the behavior of combustion particles under thermal processing

10. Determine emissions of mercury from burning of selected fuels

III. Study Description

Our study design had the following elements:

1. Laboratory-based development of inexpensive and accurate smoke marker measurement techniques

This work was primarily conducted at Colorado State University by CSU PIs and collaborators.

2. Laboratory-based open biomass burning experiments (two phases, Summer 2006 and Summer 2007)

This work was conducted at the USFS / USDA Fire Sciences Laboratory in Missoula, Montana, with all project co-PIs participating. The studies were comprehensive in design and addressed objectives 1-10. We conducted both "stack" burns to generate source profiles, and "chamber" burns which were used in the detailed characterization of aerosol physical and optical properties.

3. Field studies to validate our emissions dataset

The third element of the study was planned for Spring 2008, when we coordinated with the Forest Service in Missoula to obtain permission to sample during planned prescribed burns. Investigators from CSU, DRI, and FSL conducted the project planning and siting and deployed to Missoula for over 2 weeks in 2008. Ultimately, the burns could not be conducted because of the wet weather that season. Instead, the project PIs sampled in burns of opportunity, as described further below, and were able to complete partial validations.

IV. Key Findings

The key findings section provides a brief summary of the results for many of the project elements discussed above, and provides one key citation for each; additional publications are in the listings in the next section. More detailed descriptions of the findings, as well as the data obtained in our studies, are available from the project website and in the numerous publications resulting from this work.

IV.I. Laboratory-based emission factors for commonly burned species frequently consumed by fires near populated regions and protected scenic areas

We characterized the gas- and speciated aerosol-phase emissions from the open combustion of 33 different plant species during a series of 255 controlled laboratory burns. The plant species we tested were chosen to improve the existing database for U.S. domestic fuels: laboratory-based emission factors have not previously been reported for many commonly burned species that are frequently consumed by fires near populated regions and protected scenic areas. The plants we tested included the chaparral species chamise, manzanita, and ceanothus, and species common to the southeastern United States (common reed, hickory, kudzu, needlegrass rush, rhododendron, cord grass, sawgrass, titi, and wax myrtle). Burns were also conducted using components from several tree species including Ponderosa pine, lodgepole pine, Douglas fir, white spruce, black spruce, and oak. Fire-integrated emission factors for gas-phase CO_2, CO, CH_4, C2–4 hydrocarbons, NH_3, SO_2, NO, NO_2, HNO_3, and particle-phase organic carbon (OC), elemental carbon (EC), SO_4^{2-}, NO_3^-, Cl^-, Na^+, K^+, and NH_4^+ generally varied both with fuel type (Figure 1) and with the fire-integrated modified combustion efficiency (MCE), a measure of the relative importance of flaming- and smoldering-phase combustion to the total emissions during the burn. Chaparral fuels tended to emit less particulate OC per unit mass of dry fuel than did other fuel types, whereas southeastern species had some of the largest observed emission factors for total fine particulate matter. Our measurements spanned a larger range of MCE than prior studies, and thus help to improve estimates of the variation of emissions with combustion conditions for individual fuels.

Key publication:

McMeeking, G. R., Kreidenweis, S.M., Baker, S., Carrico, C.M., Chow, J.C., Collett, Jr., J.L., Hao, W.M., Holden, A., Kirchstetter, T.W., Malm, W.C., Moosmüller, H., Sullivan, A.P., and Wold, C.E., Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory. *J. Geophys. Res*., 114, D19210, doi:10.1029/2009JD011836, 2009.

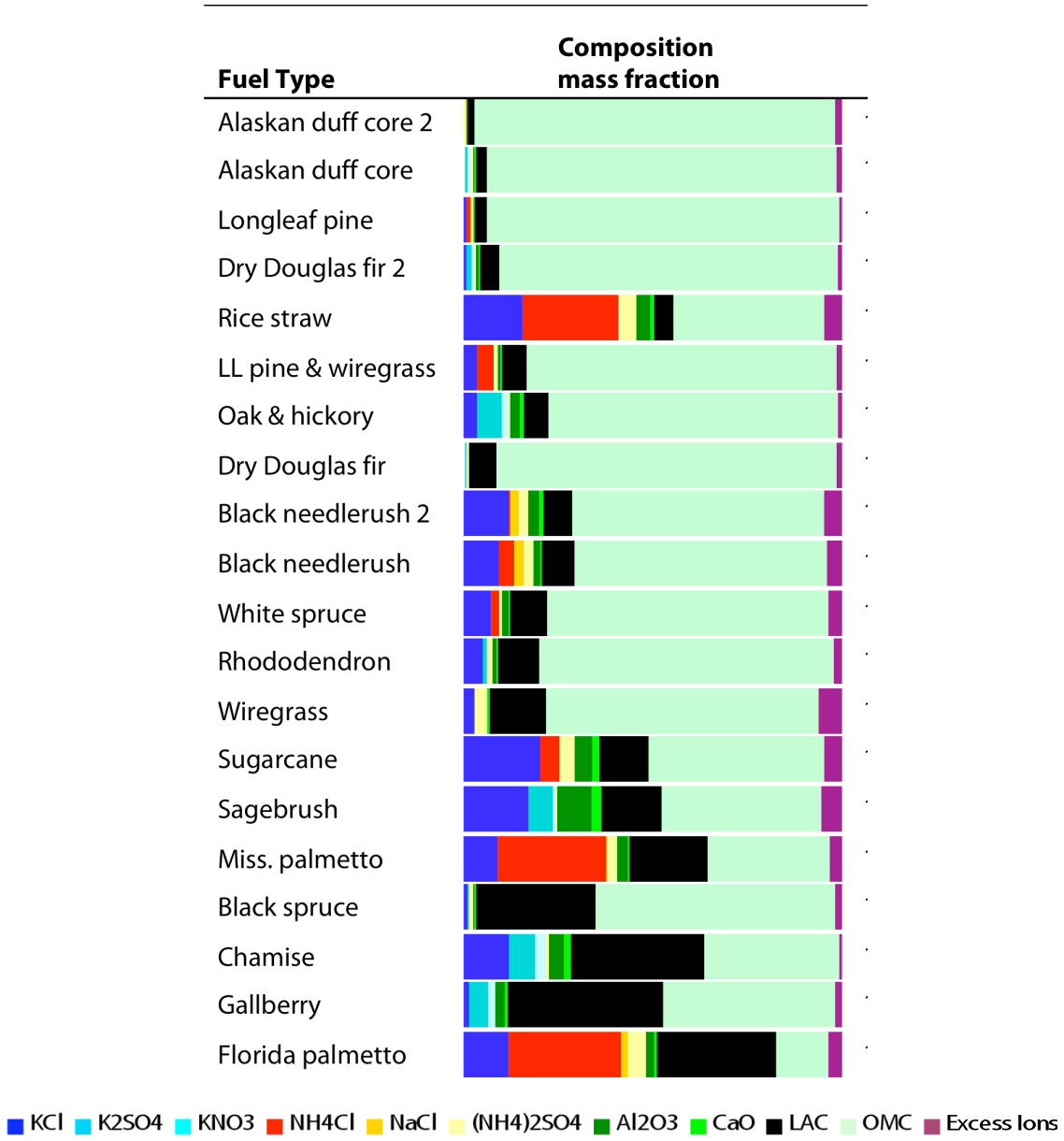

Figure 1: Aerosol composition for each FLAME 2 burn. Burns are ranked from least to most light absorbing.

IV.II Source profiles for biomass burning applicable to the western and southeastern U.S.

Hi-Volume filter source samples were collected during our studies at the Fire Science Laboratory in Missoula, MT in 2006 and 2007. Levoglucosan (and other carbohydrates) were measured in these samples using high-performance anion-exchange chromatography with pulsed amperometric detection. Results of this analysis along with water-soluble potassium, OC, and elemental carbon are presented. The results show that emissions of levoglucosan are fairly correlated with OC with an average ratio of 0.031 µg C/ µg C. Further, there was a definite

pattern that emerged based on fuel component burned with the typical levoglucosan/OC ratio of branches > straw > needles > leaves. Additionally, this carbohydrate measurement method appears to provide fingerprint information about the type of fuel burned that could help constrain profiles chosen for aerosol source apportionment and lead to a better determination of source contributions from biomass burning.

Key publication:

Sullivan, A. P., A. S. Holden, L. A. Patterson, G. R. McMeeking, S. M. Kreidenweis, W. C. Malm, W. M. Hao, C. E. Wold, and J. L.. Collett Jr., A method for smoke marker measurements and its potential application for determining the contribution of biomass burning from wildfires and prescribed fires to ambient PM2.5 organic carbon, *J. Geophys. Res.,* doi:10.1029/2008JD010216, 2008.

IV.III Optical properties of PM emissions from open biomass burning of common U.S. wild- and prescribed-fire fuels

A dual-wavelength photoacoustic instrument operating at 405 and 870 nm was used during the 2006 study to measure light scattering and absorption by smoke from the combustion of a variety of biomass fuels. Simultaneous measurements of aerosol light scattering by reciprocal nephelometry within the instrument's acoustic resonator accompany photoacoustic aerosol light absorption measurements. Single scattering albedo values at 405 nm ranging from 0.37 to 0.95 were measured for different fuel types, and the spectral dependence of absorption was quantified using the Angstrom exponent of absorption. An absorption Angstrom exponent near unity is commonly observed for motor vehicle emission-generated black carbon aerosol. For biomass smoke, absorption Angstrom exponents as high as 3.5 were found in association with smoke having single scattering albedo near unity. The measurements strongly suggest that light-absorbing organic material is present in wood smoke. A second single-wavelength photoacoustic instrument with reciprocal nephelometry was used to quantify aerosol scattering and absorption at 532 nm. Absorption Angstrom exponents calculated using 532 and 870 nm data were as large as 2.5 for smoke with single scattering albedos near unity. The spectral variation in optical properties provides insight into the differentiation of aerosols from mobile or industrial sources versus those from biomass burning. Optical properties of biomass smokes could be classified by general fuel type such as flowering shrubs versus pine needle litter.

Key publication:

Lewis, K., Arnott, W.P., Moosmüller, H., and Wold, C.E., Strong spectral variation of biomass smoke light absorption and single scattering albedo observed with a novel dual-wavelength photoacoustic instrument, *J. Geophys. Res.*, **113**, doi:10.1029/2007JD009699, 2008.

IV.IV New analytical method for determination of marker species concentrations in smoke samples

Levoglucosan, mannosan, galactosan, and other organic marker species have been shown to exhibit important characteristics for apportionment modeling. Specifically, they are relatively unique to biomass burning and stable in the atmosphere. However, existing methods for their quantification are time consuming and expensive. We developed an inexpensive method for measuring these species from a particulate sample was developed that is suitable for use in a

routine monitoring network.

Key publication:

Engling, Guenter, Christian M. Carrico, Sonia M. Kreidenweis, Jeffrey L. Collett, Jr., Derek E. Day, William C. Malm, Emily Lincoln, Wei Min Hao, Yoshiteru Iinuma and Hartmut Herrmann, Determination of levoglucosan in biomass combustion aerosol by high-performance anion-exchange chromatography with pulsed amperometric detection, *Atmos. Environ*., 40(2), 299-311, 2006.

IV.V Aerosol light scattering as a function of relative humidity

Two nephelometers simultaneously measured dry and humidified light scattering coefficients (b(sp(dry)) and b(sp(RH)), respectively), providing the first observations of the temporal evolution of the humidification factor (f(RH) = b(sp(RH))/b(sp(dry))) for fresh (minutes-old) smoke. Hygroscopic characteristics of the smoke aerosols varied with fuel type and fire conditions, with the mean f(RH) ranging from 1.01 to 1.95 for fresh minutes-old smoke for the relative humidity (RH) range of 70 - 94%. These f(RH) values exhibited temporal variability, with some fuels alternating from hygroscopic to nonhygroscopic within minutes. Humidograms were also obtained, demonstrating that smoke from different fuels begins to take up water at different RH values. Humidification factors for hour-old smoke ranged from 1.10 to 1.51 for RH > 90%. Finally, light-absorbing carbon mass measured with a multiwavelength aethalometer demonstrated different spectral responses as a function of fuel type. These laboratory experiments demonstrate the complexity of smoke hygroscopicity from young fires and are essential for understanding the radiative effects of biomass burning in the ambient atmosphere.

Key publication:

Day, D.E., J. L. Hand, C.M. Carrico, G. Engling, and W.C. Malm, Humidification factors from laboratory studies of fresh smoke from biomass fuels, *J. Geophys. Res.*, 111 (D22): Art. No. D22202, 2006.

IV.V Field studies

In field sampling during burns of opportunity, we conducted filter-based sampling in CA and in the southeastern U.S. and evaluated smoke marker concentrations in those samples. We also sampled optical properties of smoke plumes in Reno, as discussed below:

Hundreds of wildfires in Northern California were sparked by lightning during the summer of 2008, resulting in downwind smoke for the months of June and July. Comparisons were reported for aerosol optics measurements in Reno, Nevada made during the very smoky month of July and the relatively clean month of August. Photoacoustic instruments equipped with integrating nephelometers were used to measure aerosol light scattering and absorption coefficients at wavelengths of 405 nm and 870 nm, revealing a strong variation of aerosol light absorption with wavelength. Insight on fuels burned is gleaned from comparison of Ångström exponents of absorption (AEA) versus single scattering albedo (SSA) of the ambient measurements with laboratory biomass smoke measurements for many fuels. Measurements

during the month of August, which were largely unaffected by fire smoke, exhibit surprisingly low AEA for aerosol light absorption when the SSA is highest, again likely as a consequence of the underappreciated wavelength dependence of aerosol light absorption by particles coated with non-absorbing organic and inorganic matter. Coated sphere calculations were used to show that AEA as large as 1.6 are possible for wood smoke even with non-absorbing organic coatings on black carbon cores, suggesting care be exercised when diagnosing AEA.

Key publication:

Gyawali, M., W. P. Arnott, K. Lewis, and H. Moosmüller, *In situ* aerosol optics in Reno, NV, USA during and after the summer 2008 California wildfires and the influence of absorbing and non-absorbing organic coatings on spectral light absorption. *Atmos. Chem. Phys.,* 9, 8007–8015, 2009.

As another example of field sampling during burns of opportunity, we discuss here the application of lidar to studies of fire emissions.

A mobile two-wavelength lidar developed in the Forest Service Missoula Fire Sciences Laboratory (FSL) was used. The FSL scanning lidar measures the elastically backscattered signals as a function of range and height at two wavelengths, the infrared (1064 nm) and the ultraviolet (355 nm) regions of spectra, simultaneously. The backscattered signals at 1064 nm are used for monitoring smoke plume dynamics and propagation; the signals at 355 nm are used for the calculation of smoke particulate optical properties. The operating range of the lidar is up to 5 - 12 km, depending on atmospheric conditions and information required. The scanning capabilities of the lidar allow changing the searching direction rapidly through 180° horizontal and 90° vertical ranges. When making measurements in the vicinity of wildfires, the FSL lidar operates as part of a mobile laboratory, which is equipped with auxiliary instrumentation operating simultaneously with lidar. The auxiliary data obtained with such in situ instrumentation provide reference data for lidar signal processing. The combination of the remote sensing and in situ instrumentation significantly enhances the quality of measurement data and their value.

During our investigation, the FSL lidar provided the following basic types of measurements in smoke-polluted atmospheres from a wildfire in Yellowstone National Park, August 6, 2008.

(1) Vertical scans of smoke plumes, which provided information about the plume heights (Fig. 2).

(2) Multiangle measurements of stable smoke layering in the vicinity of wildfires. Such measurements allow monitoring of the spatial-temporal evolution of extended horizontal layers. An example of measured vertical profiles of optical characteristics in such a horizontal layering, which is typical in smoke-polluted atmospheres in conditions of the morning inversion, is shown in Fig. 3. The profiles were measured on August 6, 2008, for a measurement period from 11:30 AM to 11:45 AM.

The FSL lidar team is continuously improving the measurement capabilities of the mobile lidar, by modifying its hardware and data-processing algorithms on the base of recent experimental results obtained from lidar remote sensing of prescribed and wildfire smokes. In

the coming year, we plan to investigate multiple wildland fires in the northwestern United States and measure plume rise and transport over a wide range of meteorological, fire activity, fuel, and terrain conditions.

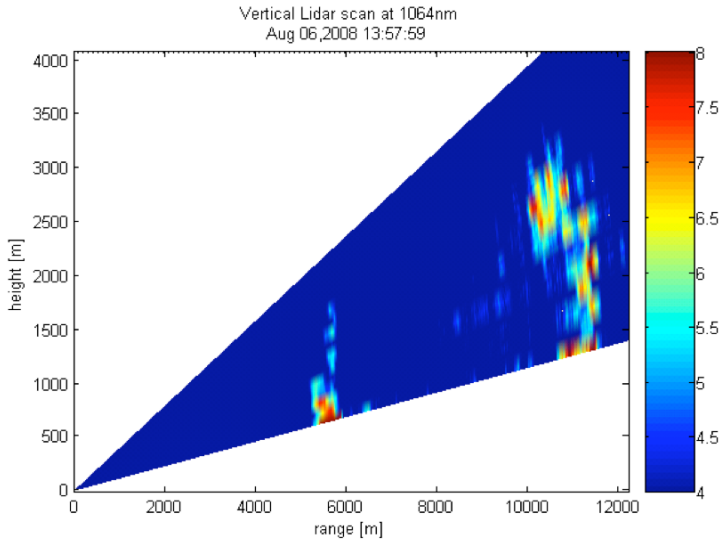

Fig. 2. Vertical scan of two distant smoke plumes during Lehardy Fire in the Yellowstone National Park. The colored scale shows relative intensity of backscattering in arbitrary units.

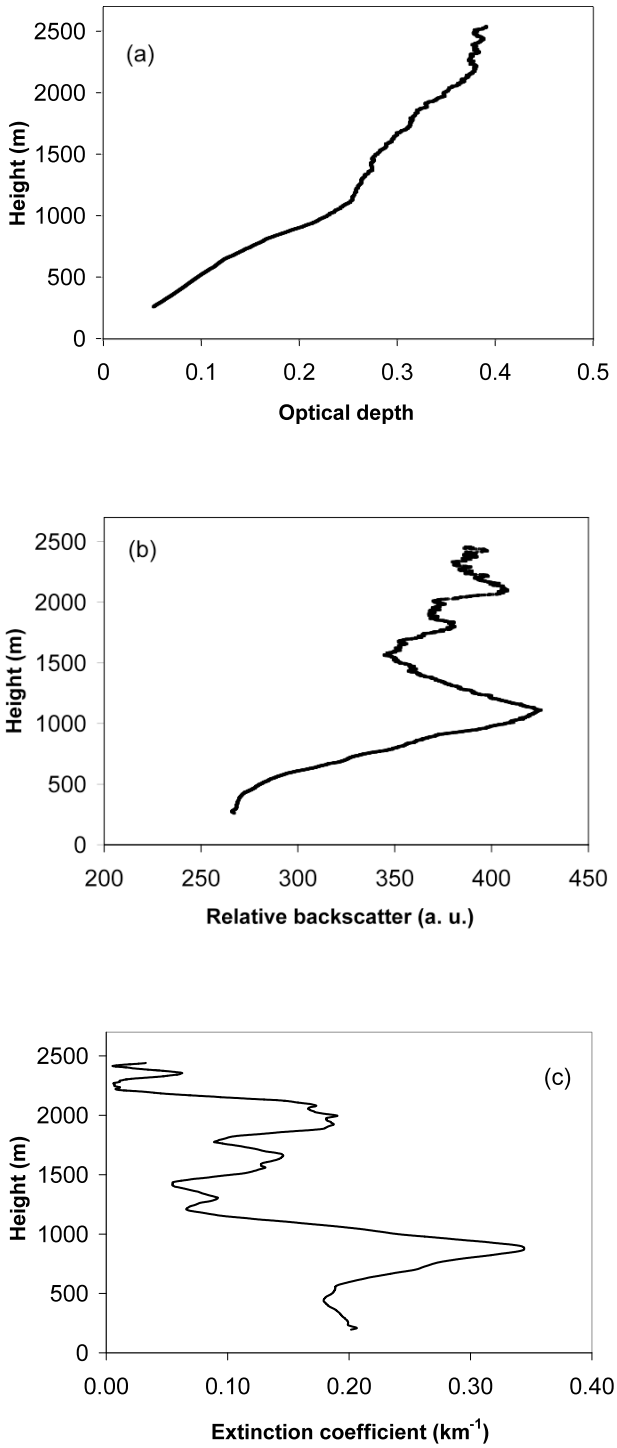

Fig. 3. Vertical profiles of (a) the optical depth, (b) the relative backscatter coefficient, and (c) the smoke particle extinction coefficient, measured at 355 nm in well-defined smoke horizontal layering conditions.

IV.V Additional findings

As one example of additional findings, we report on the observed activity of smoke particles as warm-cloud condensation nuclei.

We examined the hygroscopic properties of particles freshly emitted from laboratory biomass burning experiments conducted during the second Fire Lab At Missoula Experiment (FLAME- II). Values of the hygroscopicity parameter, kappa, were derived from both hygroscopic growth measurements and size-resolved (30-300 nm in diameter) cloud condensation nuclei (CCN) measurements for smokes emitted by the open combustion of 24 biomass fuels from the United States and Asia. Kappa varied between 0.02 (weakly hygroscopic) and 0.8 (highly hygroscopic). For individual smokes, kappa was a function of particle size, with 250 nm particles being generally weakly hygroscopic and sub-100 nm particles being more hygroscopic. At any given size the emissions were often externally mixed, showing more and less hygroscopic growth modes and bimodal CCN activation spectra. Comparisons between growth factor-derived and CCN-derived hygroscopicities were consistent when taking this heterogeneity into account. A conceptual model of biomass burning emissions suggests that most particles are CCN active at the point of emission and do not require conversion in the atmosphere to more hygroscopic compositions before they can participate in cloud formation and undergo wet deposition.

Key publication:

Petters, M. D., C. M. Carrico, S. M. Kreidenweis, A. J. Prenni, P. J. DeMott, J. R. Collett Jr., and H. Moosmüller, Cloud condensation nucleation activity of biomass burning aerosol, *J Geophys Res,* 114, doi:10.1029/2009JD012353, in press.

IV.VI. Outreach

As part of this project there was extensive outreach conducted to the federal, state, and private scientific and regulatory communities. This outreach was conducted by means of the participation and sharing of results at a number of conferences, workshops, and meetings; see list below.

IV.VI.I. Publications: Peer-Reviewed Journal Articles

Engling, Guenter, Christian M. Carrico, Sonia M. Kreidenweis, Jeffrey L. Collett, Jr., Derek E. Day, William C. Malm, Emily Lincoln, Wei Min Hao, Yoshiteru Iinuma and Hartmut Herrmann, Determination of levoglucosan in biomass combustion aerosol by high-performance anion-exchange chromatography with pulsed amperometric detection, *Atmos. Environ*., 40(2), 299-311, 2006.

Day, D.E., J. L. Hand, C.M. Carrico, G. Engling, and W.C. Malm, Humidification factors from laboratory studies of fresh smoke from biomass fuels, *J. Geophys. Res.*, 111 (D22): Art. No. D22202, 2006.

Chen, L.-W. Antony, Hans Moosmüller, W. Patrick Arnott, Judith C. Chow, John G. Watson, Ronald A. Susott, Ronald E. Babbitt, Cyle E. Wold, Emily N. Lincoln, and Wei Min Hao, Particle emissions from laboratory combustion of wildland fuels: In situ optical and mass measurements, *Geophys. Res. Lett.,* 33, doi:10.1029/2005GL024838, 2006.

Chakrabarty, Rajan K., Hans Moosmüller, Mark A. Garro, W. Patrick Arnott, John Walker, Ronald A. Susott, Ronald E. Babbitt, Cyle E. Wold, Emily N. Lincoln, and Wei Min Hao, Particle emissions from laboratory combustion of wildland fuels: Particle morphology and size, *J. Geophys. Res*., 111 (d7), D072404 (2006), doi:10.1029/2005JD006659, 2006.

Mazzoleni, L. R., Zielinska, B., and Moosmüller, H., Emissions of levoglucosan, methoxy phenols, and organic acids from prescribed burns, wildland fuels, and residential wood combustion, *Environ. Sci. Technol.*, **41**, 2115-2122, 2007.

Chen, L.-W. A., Moosmüller, H., Arnott, W.P., Chow, J.C., Watson, J.G., Susott, R.A., Babbitt, R.E., Wold, C.E., Lincoln, E.N., and Hao, W.M., Emissions from laboratory combustion of wildland fuels: Emission factors and source profiles, *Environ. Sci. Technol.*, **41**, 4317-4325, 2007.

Hopkins, R.J., Lewis, K., Desyaterik, Y., Wang, Z., Tivanski, A.V., Arnott, W.P, Laskin, A., and Gilles M.K., Correlations between optical, chemical and physical properties of biomass burn aerosols, *Geophys. Res. Lett.,* **34**, L18806, doi: 10.1029/2007GL030502, 20 September 2007.

Obrist, D., Moosmüller, H., Schürmann, R., Chen, L-W. A. and Kreidenweis, S.M., Particulate-phase and gaseous elemental mercury speciation during biomass combustion: controlling factors and correlation with particulate matter emissions, *Environ. Sci. Technol.,* **42**, 721-727, 2008.

Lewis, K., Arnott, W.P., Moosmüller, H., and Wold, C.E., Strong spectral variation of biomass smoke light absorption and single scattering albedo observed with a novel dual-wavelength photoacoustic instrument, *J. Geophys. Res.*, **113**, doi:10.1029/2007JD009699, 2008.

Carrico, C.M., Petters, M.D., Kreidenweis, S.M., Collett, Jr., J.L., Engling, G. and Malm, W.C., Aerosol hygroscopicity and cloud droplet activation of extracts of filters from biomass burning experiments, *J. Geophys. Res.*, **113**, D08206, doi:10.1029/ 2007JD009274, 2008.

Sullivan, A. P., A. S. Holden, L. A. Patterson, G. R. McMeeking, S. M. Kreidenweis, W. C. Malm, W. M. Hao, C. E. Wold, and J. L.. Collett Jr., A method for smoke marker measurements and its potential application for determining the contribution of biomass burning from wildfires and prescribed fires to ambient PM2.5 organic carbon, *J. Geophys. Res.,* doi:10.1029/2008JD010216, 2008.

Petters, M.D., Parsons, M.T., Prenni, A.J., DeMott, P.J., Kreidenweis, S.M., Carrico, C.M., Sullivan, A.P., McMeeking, G.R., Levin, E., Wold, C.E., Collett, Jr., J.L., Moosmüller, H., , Ice nuclei emissions from biomass burning, *J. Geophys. Res.*, **114**, D07209,

doi:10.1029/2008JD011532, 2009.

Vladimir A. Kovalev, Cyle Wold, Alexander Petkov, and Wei Min Hao, Alternative method for determining the constant offset in lidar signal, Applied Optics Vol. 48, Iss. 13, pp. 2559-2565, 2009.

McMeeking, G. R., Kreidenweis, S.M., Baker, S., Carrico, C.M., Chow, J.C., Collett, Jr., J.L., Hao, W.M., Holden, A., Kirchstetter, T.W., Malm, W.C., Moosmüller, H., Sullivan, A.P., and Wold, C.E., Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory. *J. Geophys. Res*., 114, D19210, doi:10.1029/2009JD011836, 2009.

DeMott, P.J., Petters, M.D., Prenni, A.J., Carrico, C.M., Kreidenweis, S.M., Collett, Jr., J.L., and Moosmüller, H., Ice nucleation behavior of biomass combustion particles at cirrus temperatures, *J. Geophys. Res.*, 114, D16205, doi:10.1029/2009JD012036, 2009.

Lewis, K., Arnott, W. P., Moosmüller, H., Chakrabarty, R. K., Carrico, C. M., Kreidenweis, S. M., Day, D. E., Malm, W. C., Laskin, A., Jimenez, J.-L., Huffman, J. A., Ulbrich, I. M., Onasch, T. B., Trimborn, A., Liu, L., and Mishchenko, M. I.: Reduction in biomass burning aerosol light absorption upon humidification: Roles of inorganically-induced hygroscopicity, particle collapse, and photoacoustic heat and mass transfer, *Atmos. Chem. Phys. Discussions,* 9, 15247-15294, 2009; *Atmos. Chem. Phys.,* in press.

Gyawali, M., W. P. Arnott, K. Lewis, and H. Moosmüller, *In situ* aerosol optics in Reno, NV, USA during and after the summer 2008 California wildfires and the influence of absorbing and non-absorbing organic coatings on spectral light absorption. *Atmos. Chem. Phys.,* 9, 8007–8015, 2009.

Petters, M. D., C. M. Carrico, S. M. Kreidenweis, A. J. Prenni, P. J. DeMott, J. R. Collett Jr., and H. Moosmüller, Cloud condensation nucleation ability of biomass burning aerosol, *J Geophys Res,* 114, doi:10.1029/2009JD012353, in press.

IV.VI.II. Other Articles

Moosmüller, H., Kreidenweis, S.M., Collett, Jr., J.L., Hao, W.M. and Malm, W.C., Characterization of particle emissions from laboratory combustion of wildland fuels. *iLeaps Newsletter,* 4, 22-23, 2007.

Moosmüller, H., S. M. Kreidenweis, J. L. Collett Jr., W. M. Hao, and W. C. Malm, Characterization of Particle Emissions from Laboratory Combustion of Wildland Fuels, Interagency Monitoring of Protected Visual Environments (IMPROVE) 2009 Calendar.

IV.VI.III. Theses Partially Supported by This Project

The optical, chemical, and physical properties of aerosols and gases emitted by the laboratory combustion of wildland fuels, Ph.D. Dissertation, Department of Atmospheric Science,

Colorado State University, Gavin McMeeking, Fall 2008

The retrieval of aerosol optical properties from biomass burning during FLAME2, M.S. Thesis, Department of Atmospheric Science, Colorado State University, Laurie Mack, Fall 2008

Estimating contributions of primary biomass combustion to fine particulate matter at sites in the Western United States, M.S. Thesis, Department of Atmospheric Science, Colorado State University, Amanda Holden, Fall 2008

On the morphology and optics of carbonaceous aerosols, M.S. Thesis, Department of Atmospheric Sciences, University of Nevada-Reno, Rajan Chakrabarty, August 2006

Characterization of size, morphology, and fractal properties of aerosols emitted from spark ignition engines and from the combustion of wildland fuels, Ph.D. Dissertation, Department of Chemical Physics, University of Nevada-Reno, Rajan Chakrabarty, December 2008

Development of a dual-wavelength photoacoustic instrument for measurement of light absorption and scattering by aerosol and gases, Ph.D. Dissertation, Department of Atmospheric Sciences, University of Nevada-Reno, Kristin Lewis, December 2008

IV.VI.IV. Conference Proceeding and Presentations

Rinehart, L. R., D. E. Campbell, H. Moosmüller, J. C. Chow, and B. Zielinska (2004). Semi-Volatile Organic Compound Characterization of Biomass Combustion Emission for Prescribed Burns, Wildland Fuels, and Residential Wood Combustion. *Regional and Global Perspectives on Haze: Causes, Consequences, and Controversies (Visibility Specialty Conference)*, Asheville, NC, October 25-29, 2004.

Moosmüller, H., W. P. Arnott, L. R. Rinehart, R. A. Susott, V. Kovalev, and W. M. Hao (2004). Characterization of Visibility Relevant Fire Emissions from Several Wildland Fuels. *Regional and Global Perspectives on Haze: Causes, Consequences, and Controversies (Visibility Specialty Conference)*, Asheville, NC, October 25-29, 2004.

Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, V. Kovalev, and W. M. Hao (2004). Variability of Physical and Optical Properties of Particles Emitted from Combustion of Wildland Fuels. *2004 Fall Meeting of the American Geophysical Union*, San Francisco, CA, December 13-17, 2004.

Huang, L. A. Shashkov, K. Higuchi, H. Moosmüller, D. Worthy, D. Lavoué, W. M. Hao, D. Chan, A. Chivulescu, and M. Ernst (2005). Identifying Biomass Burning in Atmospheric CO_2 via Isotope Measurements. *7th International Carbon Dioxide Conference (ICDC7)*, Boulder, CO, September 25-30, 2005.

Chakrabarty, R. K., H. Moosmüller, W. P. Arnott, J. W. Walker, V. A. Kovalev, R. A. Susott, and W. M. Hao (2005). Emissions from the Laboratory Combustion of Wildland Fuels: Characterization of Particle Morphology. *24th Annual Conference of the American*

Association for Aerosol Research, Austin, TX, October 17-21, 2005.

Chen, L.-W. A., H. Moosmüller, J. C. Chow, J. G. Watson, and W. P. Arnott (2006). Particle Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Carbon Emission Characterization and Inventory Workshop*, Reno, NV, April 18-19, 2006.

Chakrabarty, R. K., H. Moosmüller, W. P. Arnott, J. W. Walker, V. A. Kovalev, R. A. Susott, and W. M. Hao (2006). Investigation into the Morphology of Particles Emitted from the Laboratory Combustion of Wildland Fuels. *Carbon Emission Characterization and Inventory Workshop*, Reno, NV, April 18-19, 2006.

W. Patrick Arnott, Kristin Lewis, Guadalupe Paredes-Miranda, Derek Day, Rajan K. Chakrabarty, Hans Moosmüller, Jose-Luis Jimenez, Ingrid Ulbrich, Alex Huffman, Timothy Onasch, Achim Trimborn, Sonia Kreidenweis, Christian Carrico, Cyle Wold, Emily N. Lincoln, Patrick Freeborn, and Wei-Min Hao, "Observations of the REDUCTION Of Aerosol Light Absorption and INCREASE of Biomass Burning Aerosol Light Scattering for Increasing Relative Humidity," presented at the Aerosol Workshop on Climate Prediction Uncertainty, Santa Fe, New Mexico, July 20-21, 2006.

Kristin Lewis, William P. Arnott, and Hans Moosmuller, "Multiwavelength photoacoustic measurements of light absorption and scattering by wood smoke," presented at the Aerosol Workshop on Climate Prediction Uncertainty, Santa Fe, New Mexico, July 20-21, 2006.

Hans Moosmüller, W. Patrick Arnott, L.-W. Antony Chen, Rajan K. Chakrabarty, Daniel Obrist, Kristin Lewis, Claudio Mazzoleni, Cyle E. Wold, Emily N. Lincoln, and Wei Min Hao, "Particle emissions from laboratory combustion of wildland fuels: Aerosol optical properties during flaming and smoldering combustion phases," presented at the Aerosol Workshop on Climate Prediction Uncertainty, Santa Fe, New Mexico, July 20-21, 2006.

Chakrabarty, R. K., H. Moosmüller, L.-W. A. Chen, C. Mazzoleni, P. Chylek, M. Dubey, W. P. Arnott, K. Lewis, and W. M. Hao, Experimental determination of effective refractive indices of aerosols emitted from high-moisture-content biomass combustion. Presented at the Aerosol Workshop on Climate Prediction Uncertainties, Second International Conference on Global Warming and the Next Ice Age, Santa Fe, NM, July 17-21, 2006.

Moosmüller, H., W. P. Arnott, L.-W. A. Chen, R. K. Chakrabarty, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and W. M. Hao, Particle Emissions from Laboratory Combustion of Wildland Fuels: Time Evolution of Aerosol Optical Properties and the Transition from Flaming to Smoldering Combustion. Presented at the Conference on Visibility, Aerosol, and Atmospheric Optics, Vienna, Austria, September 3-6, 2006.

Chakrabarty, R. K., H. Moosmüller, M. A. Garro, and W. P. Arnott (2006). Characterization of Morphology and Structural Properties of Particles Emitted from the Laboratory Combustion of Wildland Fuels. *Conference on Visibility, Aerosol, and Atmospheric Optics*, Vienna, Austria, September 3-6, 2006.

Chen, L.-W. A., H. Moosmüller, W. P. Arnott, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and W. M. Hao (2006). Emission Factors for Carbon Monoxide, Elemental Carbon, and Light Absorption from Laboratory Combustion of Wildland Fuels. *International Aerosol Conference*, St. Paul, MN, September 10-15, 2006.

Huang, L., P. Tans, K. Higuchi, D. Worthy, T. Chan, A. Shashkov, H. Moosmüller, W. M. Hao, B. Chen (2006). Carbon Cycle and Environmental Changes on Regional Scales: What We Can Learn From High Precision Isotope Measurements in Atmospheric CO_2. *7th International Symposium on Environmental Geochemistry (7th ISEG)*, Beijing, China, September 24-27, 2006.

Arnott, W. P., K. A. Lewis, G. Parades-Miranda, S. Winter, D. E. Day, R. K. Chakrabarty, H. Moosmüller, J.-L. Jimenez, I. Ulbrich, A. Huffman, T. B. Onasch, A. Trimborn, S. M. Kreidenweis, C. M. Carrico, C. E. Wold, E. N. Lincoln, P. Freeborn, and W. M. Hao (2006). Observations of the Reduction of Aerosol Light Absorption and Increase of Aerosol Light Scattering for Biomass Burning for Increasing Relative Humidity. *Science Talk, Division of Atmospheric Sciences, Desert Research Institute, Nevada System of Higher Education*, Reno, NV, September 27, 2006.

K. Lewis, W. P. Arnott, and H. Moosmüller (2006). Multiwavelength Photoacoustic Measurements of Light Absorption and Scattering by Wood Smoke. *Science Talk, Division of Atmospheric Sciences, Desert Research Institute, Nevada System of Higher Education*, Reno, NV, September 27, 2006.

Obrist, D., H. Moosmüller, C. E. Wold, E. N. Lincoln, P. Freeborn, W. M. Hao and S. M. Kreidenweis (2006). Speciated Mercury Emissions from Laboratory Combustion of Wildland Fuel. *Tahoe Research Symposium*, Incline Village, NV, October 18-20, 2006

Carrico, C., M. Petters, S. Kreidenweis, A. Prenni, P. DeMott, J. Collett, and W. Malm, "Hygroscopic Growth and CCN Properties of Primary Smoke Emissions from Forest Fuels," presented at the Fall Meeting of the American Geophysical Union, December 2006.

P.J. DeMott, M.D. Petters, A.J. Prenni, S.M. Kreidenweis, C.M. Carrico, M.R. Bennett, R. Stanglmaier, J. Volckens, O. Popovicheva. Ice Formation by Soot-Containing Aerosol Particles, Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract A34C-03, AGU Conference, Dec. 2006.

W.P. Arnott, K. Lewis, G. Paredes-Miranda, S. Winter, D. Day, R. Chakrabarty, H. Moosmuller, J.L. Jimenez, I. Ulbrich, A. Huffman, T. Onasch, A. Trimborn, S. Kreidenweis, C.M. Carrico, C. Wold, E. Lincoln, P. Freeborn, W. Hao, G. McMeeking, Observations of Aerosol Light Scattering, Absorption, and Particle Morphology Changes as a Function of Relative Humidity, Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract A43A-0116, AGU Conference, Dec. 2006.

K. A. Lewis, W. P. Arnott, and H. Moosmüller (2006). Multiwavelength Photoacoustic Measurements of Light Absorption and Scattering by Wood Smoke. *2006 Fall Meeting of the American Geophysical Union*, San Francisco, CA, December 11-15, 2006.

Chen, L.-W. A., R. K. Chakrabarty, H. Moosmüller, W. P. Arnott, J. G. Watson, and J. C. Chow (2007). Nanoparticle Emission from Biomass Burning? *Symposium on PM Formation in Fuel Combustion, 233rd American Chemical Society National Meeting*, Chicago, IL, March 25-29, 2007.

G. Engling, Y.-T. Chen, Y.-C. Wu, L. R. Rinehart, C. M. Carrico, A. Sullivan, A. Holden, S. M. Kreidenweis, J. L. Collett, Jr., and W. M. Hao, Chemical and physical characteristics of smoke particles from laboratory combustion of biomass. To be presented at the 5th Asian Aerosol Conference, Kaohsiung, Taiwan, August 26-29, 2007.

Schichtel, B., Malm, W., Kreidenweis, S.M., Collett, Jr., J., Sullivan, A. and Holden, A., Contribution of smoke to PM2.5 and haze: Development of smoke source profiles and routine source apportionment tools. Presented at the 2007 IMPROVE Steering Committee Meeting, Durango, CO September 5 & 6, 2007.

Lee, T., Collett, Jr., J.L, Kreidenweis, S.M., Jimenez, J. L., Kimmel, J., Kroll, J.H., Onasch, T.B., Trimborn, A.M., Malm, W.C., Hao, W.M. and Wold, C., Characterizing of smoke properties from laboratory combustion of forest fuels using an aerosol mass spectrometer. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Carrico, C., Petters, M., Kreidenweis, S., Prenni, A., DeMott, P., McMeeking, G., Sullivan, A., Rinehart, L. and Collett, Jr., J., Hygroscopic growth and cloud condensation nuclei activity and chemical composition of primary biomass smoke. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Sullivan, A.P., Holden, A.S., Mazzoleni, L.R., Kreidenweis, S.M., Collett, Jr., J.L., Malm, W.C., Hao, W.M. and Wold, C.E., A method for smoke marker measurements for determining air quality impacts of biomass burning. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Holden, A.S., Sullivan, A.P., Kreidenweis, S.M., Collett Jr., J.L., Schichtel, B.A., Malm, W.C. and Bench, G., Application of anion exchange chromatography with pulsed amperometric detection for measurement of levoglucosan in ambient aerosol samples. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Mack, L., Obrist, D., Moosmuller, H., Lewis, K., Arnott, P., McMeeking, G.R., Kreidenweis, S.M., Wold, C., Hao, W.M., Collett, Jr., J.L. and Malm, W., Experimental and theoretical closure experiments for biomass smoke using extinction cells, photoacoustics and nephelometry. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

McMeeking, G.R., Sullivan, A.P., Carrico, C.M., Kreidenweis, S.M., Collett, Jr., J.L.,

Kirchstetter, T., Lunden, M., Chen, A., Obrist, D., Moosmuller, H., Chow, J., Wold, C., Hao, W.M., Day, D.E. and Malm, W.C., A comparison of thermal-optical carbon measurement methods for aerosols emitted during a series of controlled biomass burning experiments. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

McMeeking, G.R., Carrico, C.M., Levin, E., Kreidenweis, S.M., Collett, Jr., J.L., Moosmuller, H., Arnott, P., Wold, C., Hao, W.M. and Malm, W.C., Measurements of smoke aerosol size distributions and refractive indices during a series of laboratory biomass burning experiments. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Day, D., Hand, J., McMeeking, G.R., Kreidenweis, S.M., Collett, Jr., J.L., Hao, W.M. and Malm, W.C., Humidification factors (f(RH)) for fresh biomass smoke from laboratory controlled burns. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Onasch, T.B., Trimborn, A., Kroll, J., Worsnop, D., Ulbrich, I., Huffman, J. A., Jimenez, J., Kreidenweis, S. and Hao, W.M., The chemical and physical characteristics of biomass burning particulate emissions studied at the Fire Science Laboratory. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Hutchings, J., Herckes, P., McMeeking, G.R., Sullivan, A.P., Kreidenweis, S.M., Collett, Jr., J.L., Hao, W.M., Wold, C. and Malm, W.C., Investigation of biomass combustion aerosols by ^{1}H-NMR spectroscopy. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Arnott, W.P., Lewis, K., Parades-Miranda, G., Winter, S., Day, D., Chakrabarty, R.K., Chen, A., and Moosmuller, H., Relative humidity influence on aerosol light absorption and scattering by biomass burning aerosol. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Hopkins, R.J., Wang, Z., Tivanski, A.V., Gilles, M.K., Lewis, K., Arnott, W.P, Desyaterik, Y., and Laskin, A., Diversity of biomass burn aerosols based on fuel. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Lewis, K.A., Arnott, W.P., Moosmuller, H., Dual-wavelength photoacoustic measurements of light absorption and scattering by wood smoke. Presented at the 26th Annual AAAR Conference, Reno, NV, September 24-28, 2007.

Investigation of the properties of smoke from wildland fires: The relationship to visual impacts of smoke. Carrico, C.M., Kreidenweis, S.M., Collett, Jr., J.L., McMeeking, G.R., Sullivan, A.P., Holden, A. and Lee, T. Presented at the Human Dimension of Wildland Fire Conference International Association of Wildland Fire in Fort Collins, CO October 23-25, 2007.

The potential health effects of smoke from wildland fires: Acute and long-term impacts on

wildland fire fighters and the general public. Peel, J. L., Fluck, J., Lipsey, T., Carrico, C.M., Kreidenweis, S.M. and Collett, Jr., J.L. Presented at the Human Dimension of Wildland Fire Conference International Association of Wildland Fire in Fort Collins, CO October 23-25, 2007.

Particle emissions from flaming and smoldering laboratory combustion of wildland fuels. Moosmüller, H., Arnott, W.P., Chen, L-W.A., Obrist, D., Chakrabarty, R.K., Wold, C.E., Hao, W.M., and Kreidenweis, S.M., NASA Fire Science Workshop, Adelphi, MD, February 20-22, 2008.

Heterogeneous ice nuclei measurements: Results for biomass burning particles from FLAME 2 and biogenic aerosols from AMAZE. Parsons, M.T., Petters, M.D., Prenni, A.J., DeMott, P.J., and Kreidenweis, S.M. Poster presented at the 235th ACS National Meeting, New Orleans, LA, April 6-10, 2008.

The hygroscopicity of organic aerosols. Kreidenweis, S.M., Invited Seminar, Department of Chemical Engineering, Carnegie Mellon University, April 17-18, 2008.

Hygroscopic growth and cloud condensation nuclei activity of primary biomass smoke aerosol, Kreidenweis, S., Carrico, C., Petters, M., Prenni, A. DeMott, P., McMeeking, G., Sullivan, A., Rinehart, L., Collett, J., Malm, W., Wold, C., and Hao, W., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 -May 2, 2008.

Characterization of light absorbance from organic and elemental carbon emitted by biomass burning, McMeeking, G., Kreidenweis, S., Collett, J., Kirchstetter, T., Hao, W., Wold, C., W., and Malm, W., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 -May 2, 2008.

Hygroscopicity measurements and comparisons with theoretical values for fresh biomass smoke obtained during laboratory burns, Day, D., Hand, J., McMeeking, G., Kreidenweis, S., Collett, J., Wold, C., Hao, W., Laskin, A, Desyaterik, Y., and Malm, W., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 -May 2, 2008.

Repeatability of PM emissions during laboratory combustion of wildland fuels, Moosmuller, H., Chen, L, Arnott, W., and Kreidenweis, S., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 - May 2, 2008.

Cavity ring down and cavity enhanced detection measurements of extinction from smoke generated through laboratory combustion of wildland fires, Moosmuller, H., Obrist, D., Arnott, W., Mack, L., and Kreidenweis, S., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 - May 2, 2008.

A method for smoke marker measurements for determining the contribution of biomass burning to ambient PM2.5 organic carbon, Sullivan, A.P., Holden, A.S., Patterson, L.A., Kreidenweis, S.M., Malm, W.C., Hao, W.M., Wold, C.E., and Collett, Jr., J.L., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 -May 2, 2008.

Estimating the contribution of smoke to fine particulate matter using a hybrid-receptor model, Schichtel, B., Malm, W., Collett, J., Sullivan, A., Holden, A., and Patterson, L., Abstract presented at the AWMA conference on Aerosol and Atmospheric Optics: Visual Air Quality and Radiation, Moab, Utah, April 28 -May 2, 2008.

Aerosol optical properties during flaming and smoldering phases of laboratory combustion of wildland fuels. Moosmüller, H., Arnott, W.P., Chen, L-W.A., Chakrabarty, R.K., Obrist, D., Lewis, K., Mazzoleni, C., Wold, C.E., Lincoln, E.N., and Hao, W.M., Conference on "Light Scattering: Mie and More – Commemorating 100 Years Mie's 1908 Publications", Gesellschaft für Aerosol Forschung (GAeF) Annual Meeting, Karlsruhe, Germany, July 3-4, 2008.

Multiwavelength photoacoustic measurements of light absorption and scattering by biomass smoke. Lewis, K., Arnott, W.P., and Moosmüller, H., Conference on "Light Scattering: Mie and More – Commemorating 100 Years Mie's 1908 Publications", Gesellschaft für Aerosol Forschung (GAeF) Annual Meeting, Karlsruhe, Germany, July 3-4, 2008.

Determination of effective refractive indices of aerosols emitted from high-moisture-content biomass combustion using Mie theory. Chakrabarty, R.K., Moosmüller, H., Chen, L-W.A., Mazzoleni, C., Chylek, P., Dubey, M., Arnott, W.P., Lewis, K., and Hao, W.M., Conference on "Light Scattering: Mie and More – Commemorating 100 Years Mie's 1908 Publications", Gesellschaft für Aerosol Forschung (GAeF) Annual Meeting, Karlsruhe, Germany, July 3-4, 2008.

Water interactions of biomass burning aerosols. Kreidenweis, S.M., Telluride Science Research Center workshop, Organic Particles in the Atmosphere: Formation, Properties, Processing, and Impact, Telluride, CO August 4-8, 2008.

Characterization of emissions from the laboratory combustion of wildland plant species. McMeeking, G. R., Carrico, C.M., Petters, M.D., Parsons, M., Prenni, A.J., Sullivan, A.P., DeMott, P.J., Kreidenweis, S.M., Collett, Jr., J.L., Kirchstetter, T.W., Lunden, M.M., Moosmüller, H., Arnott, W.P., Lewis, K., Baker, S., Wold, C.E., Hao, W.M., and Malm, W.C., 9th International Conference on Carbonaceous Particles in the Atmosphere (ICCPA), Berkeley, CA, August 12-14, 2008.

The light attenuation spectral dependence of organic carbon emitted by biomass burning. McMeeking, G. R., Sullivan, A.P., DeMott, P.J., Kreidenweis, S.M., Collett, Jr., J.L., Kirchstetter, T.W., Lunden, M.M., Moosmüller, H., Arnott, W.P., Lewis, K., Hao, W.M., and Malm, W.C., 9th International Conference on Carbonaceous Particles in the Atmosphere (ICCPA), Berkeley, CA, August 12-14, 2008.

Photoacoustic evidence for strong spectral variation of biomass smoke light absorption and single scattering albedo. Lewis, K., Arnott, W.P., and Moosmüller, H., 9th International Conference on Carbonaceous Particles in the Atmosphere (ICCPA), Berkeley, CA, August 12-14, 2008.

Morphology and effective refractive indices of aerosols emitted from high-moisture-content biomass combustion. Chakrabarty, R.K., Moosmüller, H., Chen, L-W.A., Mazzoleni, C., Chylek, P., Dubey, M., Arnott, W.P., Lewis, K., and Hao, W.M., 9th International Conference on Carbonaceous Particles in the Atmosphere (ICCPA), Berkeley, CA, August 12-14, 2008.

Parameterization of the hygroscopicity and CCN activity of atmospheric aerosols. Kreidenweis, S.M., Petters, M., DeMott, P., Prenni, A., and Carrico, C., Presented at the IGAC 10th International Conference, Annecy, France, September 7-12, 2008.

Petters, M., Parsons, M., Prenni, A., DeMott, P., Carrico, C., and Kreidenweis, S., Do biomass burning aerosols nucleate ice? Abstract presented at the 27th Annual AAAR Conference, Orlando, Florida, October 20-24, 2008

Holden, A.S., Sullivan, A.P., Patterson, L.A., Schichtel, B., Malm, W., Kreidenweis, S., and Collett, Jr., J.L., Estimating contributions of primary biomass burning to fine particulates in ambient aerosol in the Western United States. Poster presented at the 27th Annual AAAR Conference, Orlando, Florida, October 20-24, 2008

Mack, L., Obrist, D., Moosmuller, H., Lewis, K., Arnott, P., McMeeking, G., Levin, E., Kreidenweis, S., Wold, C., Hao W-M., Collett, J.L., Jr., and Malm W., Optical closure experiments of biomass smoke aerosols. Poster presented at the 27th Annual AAAR Conference, Orlando, Florida, October 20-24, 2008

Sullivan, A.P., Kenski, D.M., and Collett, J.L., Jr., Spatial and temporal impacts of biomass burning on the Upper Midwest, Abstract presented at the 27th Annual AAAR Conference, Orlando, Florida, October 20-24, 2008

Carrico, C.M., Petters, M.D., Kreidenweis, S.M., Prenni, A.J., DeMott, P.J., McMeeking, G.R., Levin, E., Mack, L., Sullivan, A., Holden, A., Collett, J.L., Day, D., Hand, J., Malm, W.C., Wold, C., and Hao, W.-M., Physicochemical Properties of Fresh Biomass Smoke Aerosols. Invited Talk, NOAA Earth System Research Lab Chemical Sciences Division, 29 October 2008.

Patterson, L.A., Schichtel, B.A., Sullivan, A.P., Collett, Jr., J.L., Holden, A.S., Kreidenweis, S.M., and Malm, W.C., Development of a wildland fire smoke marker emissions map for the contiguous United States. Poster presented at AGU Conference, San Francisco, CA, December 15-19, 2008.

Gyawali, M., W. P. Arnott, I. Arnold, K. A. Lewis, G. Parades-Miranda, H. Moosmüller, R. K.

Chakrabarty, G. Kok, J. W. Walker, and D. Baumgardner (2009). Wavelength Dependence of Aerosol Light Absorption. *Annual Science Team Meeting of the Department of Energy Atmospheric Science Program (DOE ASP)*, Santa Fe, NM, February 25–27, 2009.

Arnott, W. P. and H. Moosmüller (2009). Multispectral Photoacoustic Analysis of Atmospheric Aerosol. *15th International Conference on Photoacoustic and Photothermal Phenomena*, Leuven, Belgium, July 19-23, 2009.

Lee, T., Collett, J.L., Kreidenweis, S.M., Sullivan, A., Mack, L., Jimenez, J.L., Kimmel, J., Onasch, T.B., Malm, W., Wold, C., and Hao, W-M., Aerosol mass spectrometer measurement of the evolution of chemical smoke markers during laboratory open burning of wildland fuels, Abstract for presentation at AAAR, 28th Annual Conference, October 26 – 30, 2009, Minneapolis, MN

Holden, A.S., Desyaterik, Y., Collett, J.L., Kreidenweis, S.M., and Malm, W., Analysis of fresh and aged aerosols produced by biomass combustion, Abstract for presentation at AAAR, 28th Annual Conference, October 26 – 30, 2009, Minneapolis, MN

Levin, E.J.T., Mack, L., Carrico, C.M., McMeeking, G.R., Kreidenweis, S.M., Wold, C.E., Moosmuller, H., Arnott, W.P., Hao, W.M., Collett, Jr., J.L., and Malm, W.C., Optical properties of biomass burning smoke aerosols, Abstract for presentation at AAAR, 28th Annual Conference, October 26 – 30, 2009, Minneapolis, MN

Mack, L., Lee, T., Jimenez, J-L., Kreidenweis, S., Collett, Jr., J., Moosmuller, H., Wold, C., Kimmel, J.R., Onasch, T., Hao W.M., and Malm, W., Elemental analysis of aerosol mass spectrometer measurements of laboratory open biomass burning aerosols, Oral presentation at AAAR, 28th Annual Conference, October 26 – 30, 2009, Minneapolis, MN

Chakrabarty, R. K., H. Moosmüller, L.-W. A. Chen, W. P. Arnott, K. A. Lewis, C. Mazzoleni, M. Dubey, C. E. Wold, W. M. Hao, and S. M. Kreidenweis (2009). Brown Carbon in Smoldering Biomass Aerosols. *28th Annual Conference of the American Association for Aerosol Research*, Minneapolis, MN, October 26-30, 2009.

Gyawali, M., W. P. Arnott, and H. Moosmüller (2009). Wavelength Dependence of Aerosol Light Absorption: Diurnal and Seasonal Variation in Reno, NV. *28th Annual Conference of the American Association for Aerosol Research*, Minneapolis, MN, October 26-30, 2009.

Malm, W. C., J. L. Collett, Jr., S. M. Kreidenweis, B. A. Schichtel, H. Moosmüller, W. M. Hao, and C. M. Carrico (2009, **invited**). Measurements Needed to Understand the Role of Biomass Burning within the Regulatory Framework of the Environmental Protection Agency and the Federal Land Managing Community. *28th Annual Conference of the American Association for Aerosol Research*, Minneapolis, MN, October 26-30, 2009.

Kreidenweis, S. M., G. R. McMeeking, W. P. Arnott, S. Baker, C. M. Carrico, J. C. Chow, J. L. Collett, Jr., W. M. Hao, A. S. Holden, T. W. Kirchstetter, E. J. T. Levin, K. A. Lewis, L. Mack, W. C. Malm, H. Moosmüller, A. P. Sullivan, and C. E. Wold (2009). The Fire Lab at

Missoula Experiment (FLAME): Measurements of Trace Gases and Aerosols during the Open Combustion of Biomass in the Laboratory. *4th International Fire Ecology and Management Congress: Fire as a Global Process*, Savannah, GA, November 30 - December 4, 2009.

Kreidenweis, S. M., P. J. DeMott, M. D. Petters, A. J. Prenni, C. M. Carrico, C. E. Wold, J. L. Collett, Jr., H. Moosmüller, W. C. Malm, and W. M. Hao (2010). Ice Nucleation Behavior of Particles Generated in Open Burning of Biomass. *90th American Meteorological Society Annual Meeting*, Atlanta, GA, January 17-21, 2010.

IV.VI.V. Workshops and Meetings

We organized the FLAME (Fire Lab at Missoula Experiment) Data Meeting held at Colorado State University, Fort Collins, February 22-23, 2007, Colorado State University. http://chem.atmos.colostate.edu/FLAME/feb_data_meeting.html

IV.VI.VI. Other Outreach

Tour of FLAME I experiment at the USDA Forest Service Fire Sciences Laboratory, Missoula, MT, June 7, 2006: guests Drs. Bill Sommers and John Qu, East Fire Laboratory, George Mason University,Fairfax, Virginia.

An open data meeting addressing Year 1 results and planning for the Year 2 field study was held in Fort Collins, CO, February 22-23, 2007, and included representation from the USEPA, National Park Service, US Forest Service, and the US Fish and Wildlife Service.

Aerosol optics measurements and survey of the current state of the science, Tutorial Workshop presented by Dr. P. Arnott at the Annual Meeting of the American Association for Aerosol Research, September 2007.

A Special Symposium on Recent Advances in Biomass Burning Emission Measurement and Modeling that included three oral seesions and one poster session with a total of 34 presentations was organized by L.-W. A. Chen and H. Moosmüller during the *Annual Meeting of the American Association for Aerosol Research (AAAR)*, Minneapolis, MN, October 26-30, 2009.

A Special Issue of “Atmospheric Chemistry and Physics” entitled "Measurement and Modeling of Aerosol Emissions from Biomass Burning" edited by H. Moosmüller, L.-W. A. Chen, and T. Kirchstetter.

V. Management Implications

This project has characterized the particulate-phase emissions from a variety of fuels relevant to U.S. prescribed and wildfires. We have reported emission factors of aerosol mass and

speciated aerosol components for use as input to air quality models, as well as reporting the optical properties of the smoke aerosols produced by the tested fuels. This information can be used in models by air quality regulators in developing regional haze and $PM_{2.5}$ State Implementation Plans (SIPs) to reduce the haze and $PM_{2.5}$ below regulated thresholds.

Ongoing work with lidar will be used to quantitatively evaluate several plume rise models (e.g. DAYSMOKE) and the high-resolution smoke dispersion and air quality forecasting capabilities of the Weather Research and Forecasting – Smoke Dispersion (WRF-SD) modeling system. Our optical property characterizations will also be used to improve the processing of lidar signals for smoke emissions, resulting in better quantification of PM levels and characteristics.

Our project element that developed new chemical tracer detection methods offers, for the first time, a low-cost alternative for filter-based determination of biomass burning marking species. The low cost and high precision measurements are suitable for use in routine aerosol monitoring networks. These data in conjunction with the biomass burning source profiles, developed as part of this project, would provide air quality regulators with the ability to estimate the contributions of primary emissions from fires to total ambient PM.

VI. Relationship to Other Recent Findings and Ongoing Work on This Topic

To our knowledge, our studies have provided the first laboratory-based emissions factors and source profiles for many fuels commonly burned in U.S. wild- and prescribed fires.

We have worked closely with Dr. Bret Schichtel on his companion JFSP-sponsored project, which was supported over the same time period and focused on the apportionment of PM to biomass burning and other sources. Specifically, source profiles for biomass burning and other sources were needed for input into his hybrid chemical mass balance model as well as for testing and evaluating the models. He compiled a database of biomass burning source profiles as well as a set of source profile biomass burning marker species that spatially vary based upon different vegetation and fuel loadings throughout the United States, using data from the literature as well as the new data generated in our Fire Lab at Missoula Experiment (FLAME) studies. The source profiles contain elemental, ionic, and organic molecular marker species, as well as fine particulate mass, EC, OC, and TC. To account for the variation due to fuel type and loading, smoke marker species source profiles for six vegetation types were constructed: softwood branches, shrub branches, hardwood leaves, shrub leaves, needles, and grasses. The spatial distribution, mixture, and loadings of these vegetation types were estimated from the Fuel Characteristic Classification System (FCCS) on a 1-km by 1-km resolution for the conterminous United States. The combustion efficiency for each vegetation type in the mix was estimated from literature values and used to estimate the fractional contribution of each vegetation type to the fuel burned, which was then used to aggregate the source profiles in a given mixture.

It was found that the levoglucosan/OC ratio can vary by about a factor of 2 over the United States and the mannosan/OC ratio can vary by a factor of 10. This variability translates to the potential variability in CMB modeling estimates of biomass burning contributions to particulate organic carbon from CMB modeling without using the proper source profiles. This work demonstrates the utility of our JFSP-supported results, and the use of these data to improve

modeling of fire effects on air quality.

VII. Future Work Needed

To improve confidence in our ability to predict the effects of biomass burning on U.S. air quality, future work that still needs to be addressed includes

- Source profiles characterizing the optical and chemical properties of the emissions were developed from laboratory data, which generally reflected a single fire-integrated modified combustion efficiency. There is an urgent need to gather more field data from actual prescribed and wildfires to evaluate and validate these profiles.
- The laboratory studies did not include effects of fuel moisture, yet PM emissions are expected to be sensitive to this parameter. Additional lab studies exploring the parameter space further, coupled with fieldwork verifying the findings, are needed.
- The optical properties of emitted aerosols varied widely. The implications of this variability for visibility and radiative forcing have not been fully explored.
- This study looked only at primary emissions. Secondary organic aerosol formed in the atmosphere from biomass emissions is likely to be an important source of PM in many regions of the U.S. The data generated in this project can be used to more accurately apportion PM to primary emissions, but additional work is needed to understand the role of biomass burning in the formation of secondary organic aerosols and its regulatory implications. A comprehensive series of laboratory and field measurements are needed to address this problem.
- It is necessary to incorporate these data into forecasting, apportionment, and other models at a variety of scales, that are simulating emissions from open biomass burning in the U.S.
- With the increasing interest in climate change, the influence of biomass burning on radiative forcing also needs to be assessed.

VIII. Deliverables Cross-Walk

Deliverable	Description	Status
Annual reports	Annual reports	Completed
Final report	Project final report, summarizing results and deliverables	Completed
Project website	http://chem.atmos.colostate.edu/FLAME/	Updated as needed
Laboratory combustion studies	Series of 2 laboratory studies as outlined in proposal	Completed
Field validation studies	One field validation study in prescribed burn	Completed, although planned venue was modified due to cancellation of prescribed burn
Development and validation of inexpensive analytical method for smoke markers	Development and validation of an inexpensive method for routine levoglucosan and K^+ measurements; demonstration of the feasibility and utility of both marker measurement methods through a pilot IMPROVE monitoring study	Completed
Training DVD and manual	DVD training session containing training presentation materials from user training workshops to be accompanied by a written manual	Incomplete. As discussed in IV.VI. Outreach we participated in a number of workshops and meetings sharing the methods and results developed in this project
Peer-reviewed journal articles	See publication list in IV.VI. Outreach	Completed
Other documents, workshops and documents	Master's theses, conference presentations and proceeding and workshops and meeting are listed in IV.VI. Outreach	Completed