

Supplement of

**Overview of the Manitou Experimental Forest Observatory:
site description and selected science results from 2008 to 2013**

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Table S1: Summary of gas-phase, aerosol, meteorological and hydrological measurements at the Manitou Experimental Forest Observatory.

Chemistry tower				
Measurement		Instrumentation	Institution	Time coverage
Wind speed and direction, temperature, humidity and pressure	2D sonic anemometer	Vaisala, Model WXT520 deployed at 4 heights (1.8, 7.0, 14.1, and 27.8 m)	NCAR	Aug 2009 - present
Wind speed and direction, turbulence		Campbell Scientific model CSAT-3 at 25.1 m	NCAR	September 2008 – present
CO ₂ , water, latent heat, sensible heat fluxes	Eddy Covariance and by using canopy gradients	Campbell Sonic Anemometer, Li-COR 7000 and 6262 CO ₂ /H ₂ O EC inlet at 25.1 m. Gradient at 6 measurement heights (1.6, 5.0, 8.5, 12.0, 17.7 and 25.1 m)*.	NCAR	September 2008-June 2012
Photosynthetically-active radiation (PAR)	Quantum sensor	Licor model LI190SA at 2 m and 28 m; Apogee LQS Sensors (2, 4, 8 m)	NCAR	August 2009 – present
Direct and diffuse beam PAR	Quantum sensor	Delta T Instruments, model BF3 (28 m)	NCAR	November 2009 – present
NO, NO ₂ , NO _x	NO by O ₃ -induced chemiluminescence, NO ₂ converted to NO using heated Molybdenum catalyst	Ecophysics, Model 88Y at 6 sampling heights (*see heights above)	NCAR	June 2009 – June 2012

at 380 °C				
CO	Non-dispersive infrared absorption	Thermo Environmental model 48 at 3 m	NCAR	Summer of 2010, July 2011-June 2012
SO ₂	UV-fluorescence	Thermo-Environmental, Model 43C-TLE (*see heights above)	NCAR	June 2009-June 2012
Ozone	UV absorption	2B technologies model 205 (*see heights above)	NCAR	June 2009-June 2012
Volatile organic compounds (Methyl methyl-3-buten-2-ol, isoprene, monoterpenes, other Alkenes, aromatics, alcohols, ketones, aldehydes)	Proton transfer reaction mass spectrometry (PTR-MS, PTR-TOF-MS)	Ionicon Quadrupole, Univ. Innsbruck Time of Flight (TOF). Above canopy concentrations, eddy covariance fluxes and gradient measurements	NCAR, University of Innsbruck,	2008 (DOY 240-284), 2009 (DOY 121-246), 2010 (DOY 220-312), 2011 (DOY 201-238)
Size-Resolved Particle Number Fluxes (6.04-523.3 nm)	Fast size distributions coupled with eddy covariance	TSI Fast Mobility Particle sizer (FMPS, model 3091)	Indiana University	July - August 2011
Size Distributions of PBAP 0.6-20 µm, 1-100 µm. Total aerosol size distribution and in-canopy aerosol fluxes, 0.055-1.0 µm	Ultraviolet (for primary biological particles) and optical (bulk) particle sizers profiling canopy using tower winch	WIBS-4 & UHSAS	University of Manchester, UK	July - August 2011
Micrometeorology Tower				
Measurement	Technique	Instrumentation	Institution	Time coverage
Wind speed, direction, sonic temperature	3D sonic anemometer	Campbell Scientific, model CSAT-3. 5 levels: 2, 8, 16, 29 and 43 m sampled at 20 Hz	NCAR	July 2009 – July 2012
CO ₂ , H ₂ O	Infrared gas analysis	LI-COR 7500. 4 levels: 2, 8, 16, 43 m sampled at 10 Hz	NCAR	Nov 2009 – July 2012
Atmospheric pressure	Barometer	Vaisala PTB220 sampling at 1 Hz	NCAR	Nov 2009 – July 2012
Temperature, Relative humidity	Radiation shielded and aspirated humitter and resistive temperature	NCAR–Vaisala 50Y Humitter. 5 levels: 2, 8, 16, 29 and 43 m sampled at 1 Hz	NCAR	July 2009 – July 2012

Radiation	4-component net radiometer	Kipp and Zonen, model CNR-1. Above-canopy measurement at 22m. Upwelling and downwelling shortwave and longwave radiation measured at 1 Hz	NCAR	Nov 2009 – July 2012
Peripheral measurements-1 (gas-phase)				
Measurement	Technique	Instrumentation	Institution	Time coverage
Volatile Organic Compounds (concentrations)	Total Organic Gas Analyzer (TOGA); Fast GCMS method	Custom cryo-trapping and desorption GC system with quadrupole MS detection (60 seconds per GC run); Apel et al., 2010	NCAR	August 2010
NO ₃ , N ₂ O ₅	Cavity Ringdown Spectroscopy	NOAA custom-built system (Dube et al., 2006; Wagner et al., 2011)	Reed college and NOAA	July - August 2011
HO _x (OH, HO ₂ , and RO ₂)	Chemical ionization mass spectrometry	Extrel quadrupole system with a Custom made ionization system (Eisele and Tanner, 1991)	NCAR	August 2010, August 2011
H ₂ SO ₄	Chemical ionization mass spectrometry	Extrel quadrupole system with a Custom made ionization system (Eisele and Tanner, 1993)	NCAR	August 2010, August 2011
OH reactivity	Laser pump-probe Laser induced fluorescence (LIF)	Tokyo Metropolitan University LIF (Sadanaga et al., 2004)	Tokyo Metropolitan University	Summer 2010
Formaldehyde (HCHO) concentration and flux	Fiber Laser-induced fluorescence (FILIF)	Madison FILIF instrument (Hottle et al., 2012)	University of Wisconsin Madison	August 2010 (DOY 224-237; 241-243 flux, 217-237; 241-243 conc.)
Glyoxal (CHOCHO)	Laser-Induced Phosphorescence (LIP)	Madison LIP instrument (Huisman et al., 2008)	University of Wisconsin Madison	August 2010 (DOY 227-243)
Intermediate and semi-volatile gas-phase organic compounds	Cryotrapping followed by temperature programmed desorption into electron impact mass	Instrument described in Cross et al., 2013	Massachusetts Institute of Technology	July - August 2011

spectrometry (EI-MS)				
Peripheral measurements-2 (particle-phase)				
Chemical composition of nano-particles	Thermal Desorption Chemical Ionization Mass Spectrometry (TDCIMS)	TDCIMS with quadrupole (2008) and HRTOF (2011) mass spectrometers (Smith et al., 2004)	NCAR	July 2008, August 2011
Particle size distributions	1. nano-Scanning Mobility Particle Sizer (SMPS, 3-50 nm); 2. regular SMPS (40-350 nm); 3. optical particle counter (200 nm – 2.5 µm)	1-TSI model 3085 nano-DMA with model 3025 CPC; 2-TSI model 3081 Long-DMA with model 3760 CPC; 3-Particle Measurement Systems Lasair (model 1002)	NCAR	February 2010 – Jan 2012
Particle size distributions (5 nm - 32 µm)	Wide Range Aerosol Spectrometer (WRAS)	Grimm Model EDM 665	Max Planck Institute for Chemistry	July - August 2011
Particle size distributions	Scanning mobility particle sizer (10-600 nm)	TSI model 3080 classifier using TSI model 3081 long column DMA and TSI model 3010 CPC.	University of Colorado, Boulder	July 2011 – June 2012
Particle size distributions of total particles and fluorescent biological particles (0.5 – 20 µm)	Ultraviolet aerodynamic particle sizer (UV-APS)	TSI model 3014	Max Planck Institute for Chemistry	July 2011 – June 2012
Ice nuclei (IN) and bioaerosol characterization	Multiple Orifice Uniform Deposition Impactor (MOUDI) analyzed via droplet freezing technique (UBC) and fluorescence microscopy (MPIC)	MSP Model 110-R	Max Planck Institute for Chemistry and University of British Columbia	July - August 2011
Particle elemental composition, characterization, and imaging	Low-volume filters (gold-coated Nuclepore) analyzed via scanning electron microscopy (SEM)	Scanning electron microscopy	Max Planck Institute for Chemistry	July - August 2011
Particle elemental composition and characterization	Low-volume impactors (silicon nitride windows) analyzed via scanning transmission x-ray microscopy with near-	X-ray microscopy and near-edge x-ray absorption	Max Planck Institute for Chemistry	July - August 2011

	edge x-ray absorption fine structure analysis (STXM-NEXAFS)			
Particle imaging	Low volume impactors (TEM grids) analyzed via transmission electron microscopy (TEM)	Transmission electron microscopy	Max Planck Institute for Chemistry	July - August 2011
Biological organism DNA speciation	High-volume filters (glass fiber) analyzed via polymerase chain reaction (PCR) technique	Digitel DHA-80	Max Planck Institute for Chemistry	July - August 2011
Culturable biological particle identification and ice activity	Direct-to-agar impactor samplers (time-resolved/slit and size-resolved/6-stage) analyzed via PCR and drop freezing	Andersen Bioaerosol Sampler	Max Planck Institute for Chemistry	July - August 2011
Cloud condensation nuclei (CCN)	Continuous-flow streamwise thermal- gradient CCN chamber sampling bulk (2008) and size selected particles	Droplet Measurement Technologies model CCN-100 with TSI DMA and particle counter	Colorado State University (2010-2011); Washington State University (2008);	July 2008, March 2010- May 2011
Ice Nuclei (IN)	Continuous Flow Diffusion Chamber (CFDC)	Manufactured at CSU following Rogers et al., 2001	Colorado State University (CSU)	July 2008, July – August 2011
Primary biological aerosol particle (PBAP) speciation	Sampling with offline analysis	Biosampler with PCR/sequencing	Colorado State University	July - August 2011
Black carbon mass, size distribution and mixing state	Single Particle soot spectrometer	Droplet Measurement Technologies, model SP2	Los Alamos National Laboratory	July - August 2011
3-wavelength aerosol absorption and scattering	3-Wavelength Photo- acoustic Sensors, 2- Vis/IR, 1-UV	Droplet Measurement Technologies, model PASS-3	Los Alamos National Laboratory	July - August 2011
Aerosol volatility- resolved 3-wavelength aerosol absorption and scattering	Thermal denuder with 3-Wavelength Photo- acoustic Sensors, 2- Vis/IR, 1-UV	Droplet Measurement Technologies, model PASS-3	Los Alamos National Laboratory	July - August 2011
Sub-micron non- refractory bulk and size-resolved aerosol composition	Aerosol mass spectrometry	HR-TOF-AMS (DeCarlo et al., 2006)	University of Colorado, Boulder;	July - August 2011
Aerosol volatility- resolved aerosol composition	Thermal denuder (Huffman et al., 2009) with aerosol mass	Aerodyne thermal denuder with HR- TOF-AMS	University of Colorado, Boulder	July - August 2011

	spectrometry	(DeCarlo et al., 2006)		
Aerosol volatility-resolved 3-wavelength aerosol absorption and scattering	Thermal denuder with 3-Wavelength Photo-acoustic Sensors, 2-Vis/IR, 1-UV	Droplet Measurement Technologies, model PASS-3	Los Alamos National Laboratory	July - August 2011
Sub-micron non-refractory bulk and size-resolved aerosol composition	Aerosol mass spectrometry	HR-TOF-AMS (DeCarlo et al., 2006)	University of Colorado, Boulder;	July - August 2011
Aerosol volatility-resolved aerosol composition	Thermal denuder (Huffman et al., 2009) with aerosol mass spectrometry	Aerodyne thermal denuder with HR-TOF-AMS (DeCarlo et al., 2006)	University of Colorado, Boulder	July - August 2011
MBO-derived epoxides	High volume filter samples	Filter sampler and offline GC/MS and LC/MS analysis	University of North Carolina	July - August 2011
Organic speciation, biomarkers including precursor-specific SOA tracers, EC/OC and ¹⁴ C of EC/OC for PM _{2.5}	High volume filter samples	Filter sampler and offline analysis	United States EPA	July - August 2011
Lipids, carbohydrates, proteins constituents of aerosol	High volume filter samples	Quartz filters with offline analysis	University of Colorado, Boulder	Summers of 2008, 2009, 2011
Particulate elemental carbon and organic carbon	Thermal-optical method	Sunset EC/OC	University of Colorado, Boulder	July - August 2011
Peripheral measurements-3 (mixed gas + aerosol-phase)				
Aerosol- and gas-phase chemistry of ambient air in a highly oxidizing environment	Ambient sampling via oxidant flow reactor with addition of OH, NO ₃ , O ₃	2 x Potential Aerosol Mass (PAM) oxidant flow reactors (Kang et al., 2007, Ortega et al., 2013); Oxidants: OH, O ₃ , NO ₃ ; analysis by Aerodyne AMS, PTR-TOF-MS and SMPS	University of Colorado, Boulder; University of Innsbruck	July - August 2011
NO ₂ , PANs, HNO ₃ , Alkyl nitrates (gas & aerosol using denuder)	Thermal Desorption - Laser induced fluorescence	Custom-built system (Day et al., 2002, Rollins et al., 2010)	Reed College and University of California, Berkeley	July - August 2011
Gas- and particle-phase organic acids composition and partitioning-1	Micro-Orifice Volatilization Impactor High-Resolution Time-of-Flight Chemical	Aerodyne Research Inc. MOVI-HRToF-CIMS (Yatavelli et al. 2012, Yatavelli et	University of Colorado, Boulder	July - August 2011

	Ionization Mass Spectrometer (MOVI-HRToF-CIMS) using acetate reagent ion	al., 2014)		
Gas- and particle-phase organic acids composition and partitioning-2	Atmospheric Pressure Chemical Ionization Ion Trap Mass Spectrometry using O ₂ - reagent ion (APCI-IT-MS)	Custom-built instrument (as described by Hoffman et al., 2002 and Vogel et al. 2013)	University of Mainz	July - August 2011
Simultaneous bulk and speciated organics in gas and particle phases	Thermal Desorption Gas Chromatography Mass Spectrometry and Aerosol Mass Spectrometry	Semi-Volatile Thermal desorption Aerosol Gas chromatograph / Aerosol Mass Spectrometry (SV-TAG-AMS; Zhao et al., 2013)	University of California Berkeley	July - August 2011
Ambient neutral molecular clusters	Chemical ionization mass spectrometry	Cluster-Chemical Ionization Mass Spectrometer (Zhao et al., 2010)	NCAR	July 2008
Peripheral measurements-4 (hydrological)				
Precipitation (rain)	Tipping buckets	Texas Electronics model USW525. 11 tipping buckets distributed around chemistry tower	NCAR	July 2009-present
Precipitation (total)	Weighing total precipitation gauge	Environmental Technologies Inc., Noah-II (5 minute averaging)	NCAR	February 2010-present
Snow depth	Laser snow depth sensor	Jenoptik, Inc. SHM30	NCAR	2010-present.
Soil moisture	Frequency domain reflectometry	Decagon EC-5 probes (3 sites around flux tower extending 1 m into soil)	NCAR	June 2010-present
Soil temperature	Thermistor	Campbell Scientific T107 (co-located with soil moisture above).	NCAR	June 2010-present
Peripheral measurements-5 (biological)				
Sap flow	Compensation Heat Pulse Method	Made in house, following Burgess et al. 2001	NCAR	May 2010-December 2011
Soil VOC emissions	Static (University of Colorado) and dynamic (NCAR)	Custom-built chambers with automated lid	NCAR, University of Colorado	July 2008

	chamber approaches, measuring VOC abundances by PTR-MS	control. Measurements by Ionicon PTR-MS and NCAR PTR-MS	Boulder	
Leaf-level photosynthesis and respiration	2-channel infrared gas analyzer (CO ₂ + H ₂ O)	Licor Model 6262	NCAR	Campaign-style measurements each growing season (2008-2012)
Leaf-level BVOC emission measurements	VOC trapping onto solid adsorbents followed by GC-FID/MS analysis	Flow through cuvettes with light and temperature control	NCAR	Campaign-style measurements each growing season (2008-2012)
Tree branch gas exchange	Infrared gas analysis	LiCor Model 6400	University of Colorado, Boulder	July - August 2011
Tree branch VOC emissions	Proton transfer reaction mass spectrometry (PTR-MS)	Ionicon PTR-MS	University of Colorado, Boulder	July - August 2011
Peripheral measurements-6 (miscellaneous)				
Understory radiation and flux of latent heat, sensible heat water and CO ₂	Eddy covariance, radiometer	Campbell C-SAT sonic anemometer; open-path infrared gas analyzer and krytpon hygrometer	NCAR	2011-2012
NO ₂ photolysis	Actinic flux filter radiometry	Metcon jNO ₂ filter radiometers	NCAR	Outside and within canopy (August 2010, July-Aug 2011)
Actinic flux (product of photolysis frequencies)	Spectrally-resolved diode array	Metcon Spectrograph with Diode Array Detector	NCAR	Top of chemistry tower (July-August 2011).
Actinic flux and jNO ₂	Diode array actinic flux spectroradiometer (DAAFS)	Metcon with jNO ₂ filter	University of Houston	August 2011
Water isotopes	Cavity ring-down spectrometry	Picarro L2120-i	Univ. of Arizona (2010), Univ. Colorado, Boulder (2011)	August 2010, May-October 2011
Boundary layer height and atmospheric structure	Ceilometer	Vaisala CL-31 (Haman et al. 2012)	University of Houston	August 2010, July-August 2011

Abbreviations:

NOAA – National Oceanic and Atmospheric Administration

NCAR – National Center for Atmospheric Research

EPA –Environmental Protection Agency

CPC – Condensational Particle Counter

DMA – Differential Mobility Analyzer

UHSAS – Ultra-high Sensitivity Aerosol Spectrometer

CSU – Colorado State University

PCR - Polymerase Chain Reaction

EC/OC – Elemental Carbon/Organic Carbon

GC-FID/MS – Gas chromatography with Flame Ionization Detector and Mass Spectrometer

Table S2: Selected studies of BEACHON (Bio-hydro-atmosphere interactions of Energy, Aerosols, Carbon, H₂O, Organics & Nitrogen) field campaigns at the Manitou Experimental Forest Observatory.

BEACHON SRM08 (Southern Rocky Mountain 2008)	
Emphasis	Citation
PTR-MS measurements of BVOC; interpretation of mass spectra	Kim et al. 2010
Mass spectrometer measurements of neutral sulfuric acid clusters	Zhao et al. 2010
Characterizing neutral clusters containing sulfuric acid and amines	Zhao et al. 2011
BEACHON ROCS (Rocky Mountain Organic Study). http://www.acd.ucar.edu/beachon/data/	
Emphasis	Citation
Nocturnal evapotranspiration in an open-canopy forest through isotopic analysis of H ₂ O	Berkelhammer et al., 2013
Formaldehyde flux measurements using laser-induced fluorescence (LIF)	DiGangi et al., 2011
Fast glyoxal and formaldehyde measurements and comparison to other Ponderosa Pine forest	DiGangi et al., 2012
Leaf and needle BVOC contribution to whole ecosystem fluxes	Greenberg et al., 2012
Comparison of BVOC measurement techniques	Kaser et al., 2013a
Measurements and modeling results above-canopy ponderosa pine emissions	Kaser et al., 2013b
Evaluation of HO _x sources in an ecosystem	Kim et al., 2013

dominated by MBO and MT emissions

Analysis of HO ₂ and RO ₂ budgets and chemical reactions at MEFO	Wolfe et al., 2013
BEACHON RoMBAS (Rocky Mountain Biogenic Aerosol Study). http://rap.ucar.edu/projects/beachon/data/	
Emphasis	Citation
Exposed monoterpene resin effects on ecosystem MT emissions	Eller et al., 2013
Modeling ultra-fine particle formation and growth from SO ₂ and biogenic precursors.	Cui et al., 2014
Measurements of particle and gaseous organic nitrate species.	Fry et al., 2013
Rain effects on the concentration of biological particles and ice condensation nuclei	Huffman et al., 2013
Isoprene and 232-MBO measurements using NO ⁺ ionization mass spectrometry	Karl et al., 2012
Year-long characterization of aerosol hygroscopicity	Levin et al., 2012
Aerosol hygroscopicity and aerosol chemical composition in summer	Levin et al., 2013
Rain effects on populations of ice nuclei	Prenni et al., 2013
Size- and time-dependent vertical aerosol flux measurements	Pryor et al., 2013
Cluster analysis to characterize constituents of bio-aerosol samples	Robinson et al., 2013
Seasonal cycles of fluorescent biological aerosol particles	Schumacher et al., 2013
Correlations between ice nuclei and fluorescent biological aerosol particles	Tobo et al., 2013
Gas- and particle-phase partitioning of organic acids	Yatavelli et al., 2014
Organosulfates as tracers for MBO-derived SOA formation	Zhang et al., 2013

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