Measured Black Carbon Deposition on the Sierra Nevada Snow Pack and Implication for Snow Pack Retreat

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Abstract

Modeling studies show that the darkening of snow and ice by black carbon deposition is a major factor for the rapid disappearance of arctic sea ice, mountain glaciers and snow packs. This study provides one of the first direct measurements for the efficient removal of black carbon from the atmosphere by snow and its subsequent deposition on the snow packs of California. The early melting of the snow packs in the Sierras is one of the contributing factors to the severe water problems in California. BC concentrations in falling snow were measured at two mountain locations and in rain at a coastal site. All three stations reveal large BC concentrations in precipitation, ranging from 1.7 ng/g to 12.9 ng/g. The BC concentrations in the air after the snow fall were negligible suggesting an extremely efficient removal of BC by snow. The data suggest that below cloud scavenging, rather than ice nuclei, was the dominant source of BC in the snow. A five-year comparison of BC, dust, and total fine aerosol mass concentrations at multiple sites reveals that the measurements made at the sampling sites were representative of large scale deposition in the Sierra Nevada. The relative concentration of iron and calcium in the mountain aerosol indicates that one-quarter to one-third of the BC may have been transported from Asia.

Introduction

The effect that black carbon (BC) aerosols have on snow and ice reflectivity, and the subsequent impact on global ice extent and climate, has been a topic of research since the late seventies and early eighties(Chylek et al., 1983, 1984;Clarke and Noone, 1985;Warren and Wiscombe, 1980, 1985;Wiscombe and Warren, 1980). Studies showed

25 that trace amounts of aerosol impurities in the snow can noticeably reduce the amount of
26 sunlight reflected by snow and ice (Clarke and Noone, 1985;Warren and Wiscombe,
27 1980, 1985;Wiscombe and Warren, 1980). Reductions in snow and ice reflectivity and
28 extent may substantially affect the global climate and exacerbate the warming effect due
29 to greenhouse gases. For example, changes in global snow and ice cover account for
30 over 50% of the observed fluctuations in the planetary albedo (Qu and Hall, 2005), an
31 important variable in the global radiation budget (Ramanathan et al., 1989).
32 BC directly impacts snow albedo by absorbing solar radiation that would
33 otherwise be reflected back to the atmosphere by the ice grains. Both the concentration
34 of BC in snow and the size, or "age" of the snow crystals determines the degree of albedo
35 reduction (Flanner et al., 2007;Grenfell et al., 1981;Hansen and Nazarenko, 2004;Qu and
36 Hall, 2007;Wiscombe and Warren, 1980). Other factors include solar angle incident on
37 the snow pack, surface cover (forest vs. meadow or rock), and snow depth. For BC
38 concentration in snow of 10 ng/g and snow grains with an effective radius of 100 μm,
39 models predict an albedo reduction of roughly 1% in the visible spectrum (Clarke and
40 Noone, 1985;Flanner et al., 2007;Grenfell et al., 2002;Hansen and Nazarenko,
41 2004;Jacobson, 2007). As the snow pack ages the ice crystals undergo metamorphosis
42 and grow. Bigger ice crystals amplify the light-absorbing effect of the BC inclusions by
43 more than a factor of three (Flanner et al., 2007). This strong positive feedback leads to
44 ever larger albedo reduction and further accelerates BC induced snow melt in the spring.
45 Several field campaigns were dedicated to measuring the concentration of BC in
46 snow and ice in the arctic (Clarke and Noone, 1985), Antarctica (Chylek et al.,
47 1987;Warren and Clarke, 1990), and various locations in North America and

48 Europe(Chylek et al., 1987;Grenfell et al., 1981;Sergent et al., 1987). Measurements of
49 BC in glacial ice cores in the Himalayas have provided a historical record of BC
50 deposition to the high altitude glaciers during the last fifty years (Ming et al., 2008).
51 These results showed an increasing trend in BC deposition in the Himalayas and
52 suggested that BC may play a role in the observed shrinking of the Himalayan glaciers
53 and ice fields.

54 In addition to the impacts that BC may have on the radiation budget and thus,
55 climate, the results of the Himalayan study point to a more immediate concern. In many
56 regions of the planet, large population centers and agricultural economies rely on glacial
57 and snow pack run off for fresh water during the dry season. One of these regions is
58 California. Snow packs in the Sierra Nevada and the Southern Cascade mountain ranges
59 are a crucial source of fresh water for California's agricultural production, as well as for
60 densely populated urban and sub-urban centers. Increases in the snow pack melt rate are
61 of major concern, as they contain the primary reservoir of water used to water Central
62 Valley crops during the dry summer months (Painter et al., 2007).

63 The current study was conducted to examine the concentration of BC aerosols in
64 snow in California and the potential of these aerosols to reduce albedo and increase melt.
65 Samples of falling snow and rain were collected at three locations in California (Figure
66 1): Central Sierra Snow Laboratory (CSSL) in the Sierra Nevada, Lassen Volcano
67 National Park (LAVO) in the Southern Cascades, and at Trindidad Head (THD) on the
68 Northern California coast. LAVO and THD are remote sites with few regional or local,
69 large BC emission sources. CSSL, located downwind of Sacramento and San Francisco,
70 is a much more polluted site. Air samples were collected and analyzed to quantify the

mass concentration of BC and several elements. The amount of BC measured in Sierra Nevada snowfall during this field study was placed in context with the results from several modeling studies previously conducted to determine potential impact of BC on snow albedo and melt rate. Analysis of the elemental composition of the particulate matter in precipitation and air provided information about the sources of the BC. 5-year time series of BC and aerosol elemental composition at three separate locations in mountainous Central and Northern CA were used to estimate the spatial and temporal variability in BC, dust, and total PM2.5 (mass of particles of diameter less than 2.5 microns) concentrations. Size resolved atmospheric particulate measurements were made at both CSSL and LAVO, and atmospheric concentrations of BC were tracked at LAVO.

Adding to local and regional BC emissions in California, transport of pollution from Asia to North America over the Pacific Ocean is well documented as being greatest in the late winter and early spring (Bertschi and Jaffe, 2005;Bey et al., 2001;de Gouw et al., 2004;Goldstein et al., 2004;Hadley et al., 2007;Heald et al., 2006;Park et al., 2005;Parrish et al., 2004). The contribution of transported pollution to total observed pollution on the west coast of the United States is greater in the mountains than in low lying valleys and coastal regions (Hadley et al., 2007;VanCuren et al., 2005). The spring transport of Asian pollutants coincides with the onset of spring snow melt in west coast mountain ranges, which raises the possibility that black carbon (BC), the main light-absorbing component of soot, transported from Asia and deposited in the mountains, may also contribute to BC contamination of the snow pack. The ambient aerosol measurements, coincident with the precipitation collection, were used to estimate the relative influence of regional vs. long-range transport of BC.

Methods

Precipitation samples were collected between late February and mid-April 2006 using EcoTech, automated rain water samplers (RWS) modified for both rain and snow collection. An external gauge signaled the RWS lid to open and begin collecting when a precipitation event began and to close when it was over. The RWS collected one sample for each day of precipitation. In the event of extreme precipitation events, excess water was diverted to an external drainage tube. To collect snow, the external tipping bucket and collection funnels were heated, melting the snow as it fell on the surface. The temperature inside the collectors was kept at 10ºC or ambient temperature, whichever was higher. Collections tubes were rinsed weekly with methanol and distilled water. Although there may have been some loss of BC particles to the tube walls, field blanks showed insignificant contamination of subsequent samples by BC. Manufacturer states that all parts coming in contact with the sample are selected to be chemically inert.

After collection, the precipitation samples were kept frozen until they could be filtered and analyzed. The largest volumes of collected snow and rain water were filtered through Pallflex-Tissuequartz fiber filters and analyzed for BC content using a modified version of thermo-optical analysis (TOA)(Hadley et al., 2008). Using laboratory standards of pure water and BC, filtration efficiency of a single filter was found to be only 30%; however use of three filters in series, increased the BC capture efficiency to 95% (+/-4 %) and was therefore used in this analysis. Lower volume samples were analyzed for Fe (iron) and Ca (calcium) concentration using x-ray fluorescence spectroscopy (XRF)(VanCuren et al., 2005).

116 In addition to the collection of precipitation, several aerosol measurements were
117 made at LAVO and CSSL. A Magee Scientific 7-wavelength aethalometer, measuring
118 BC concentration, and a 3-wavelength EcoTech M9003 nephelometer, measuring the
119 light scattering coefficient, were operated at LAVO for the duration of the experiment.
120 The nephelometer data were used primarily to correct the aethalometer data for scattering
121 artifacts (Arnott et al., 2005). The corrected, daily averaged, aethalometer BC
122 concentration compared favorably with the IMPROVE (Interagency Monitoring for
123 Protected Visual Environments) EC data (Chow et al., 2001) at LAVO. The linear
124 regression slope was 0.9 with a correlation of R^2=0.64. The average BC concentrations
125 used in this regression were all below 300 ng/m^3 where the uncertainties associated with
126 both measurement methods are relatively large (+/-100 ng). Ambient aerosol
127 measurements also included size resolved mass concentrations for over 26 elements at
128 LAVO and CSSL (VanCuren et al., 2005). Elemental mass concentration was measured
129 continuously in 3 hour time increments for both fine and coarse mode particles. Fe and
130 Ca were used in this study as markers for Western United States vs. Asian dust to
131 estimate how much of the BC was of Asian origin (VanCuren et al., 2005).

132 **BC concentration in California precipitation**

133 The average BC concentration in rain at THD, and in snow water equivalent
134 (SWE) at LAVO and CSSL, respectively, were 5.7, 5.3, and 6.9 ng/g (see Table 1 for
135 daily measurements by location). Similar measurements made by (Chylek et al., 1999)
136 near Halifax, Nova Scotia showed that BC concentration in snow in rural Nova Scotia
137 averaged 1.7 $\pm$ 0.83 ng/g, while snow falling near Halifax averaged 11 $\pm$ 7.7 ng/g of BC,
138 illustrating that even in remote locales, the BC concentrations found in the Sierra Nevada

139 snow were often similar to snow falling in an urban environment. These results also
140 support previous model predictions for BC concentration in snow and rain in California.
141 The GATOR-GCMOM (Gas, Aerosol, Transport, Radiation, General Circulation,
142 Mesoscale, and Ocean Model) predicted concentrations of BC at 3 to 6 ng/g of
143 precipitation over California in February. Other model studies predict BC concentrations
144 in snow in California mountains between 10 and 22 ng/g (Flanner et al., 2007;Qian et al.,
145 2009).

146 Significantly heavier precipitation events at CSSL removed nearly 2.5 times more
147 BC at CSSL than at either LAVO or THD (Table 1). Thus, although CSSL was a more
148 locally polluted site, the heavier precipitation diluted the BC concentration measured at
149 CSSL. The mass of BC removed each day (M_d) in ng/cm^2 was calculated as

150 $$M_d = M_c * P \quad (1)$$

151 where M_c is the measured mass concentration in ng/cm^3 (kg) of snow or rain water and P
152 is the total measured precipitation (cm) for a given sample day(s). The average BC
153 masses removed by individual precipitation events at THD, LAVO, and CSSL,
154 respectively, were 10.0, 11.5, and 24.3 ng/cm^2. Due to the size of sample required for
155 analysis (>100 mL), only BC mass in rain and snow from heavy (>10 mm/day)
156 precipitation events when sufficient snow could be collected was measured. Thus these
157 samples were likely more diluted than the average concentration of BC in falling snow
158 and therefore may underestimate the average BC mass concentration in snow.
159
160 **Impact of BC on solar heating and snow melt**

Models of radiation transfer in and above snow were used (Clarke and Noone, 1985;Flanner et al., 2007;Grenfell et al., 2002;Hansen and Nazarenko, 2004;Jacobson, 2004, 2007), along with the NCAR CCM3_CRM (Community Climate Model 3_ Column Radiation Model), to estimate the potential impact of the BC concentrations found in the snow pack of the Southern Cascades and Sierra Nevada mountains on surface radiative forcing. Models predict that the visible (400 to 700 nm) albedo of snow is reduced by roughly 1% for every 10 ng BC per gram of fresh snow, assuming a snow grain effective radius of 100 +/- 50 μm and internally mixed BC and snow (Figure 2). As BC concentrations approach and exceed 100 ng/g, the impact on albedo begins to drop off. In older snow packs containing larger ice grains, albedo reduction from the same amount of BC would be much greater (Flanner et al., 2007;Qu and Hall, 2007;Wiscombe and Warren, 1980). Using the NCAR_CCM3 CRM and the modeled albedo reduction corresponding to the BC concentrations found in the Sierra Nevada, an estimate of the subsequent surface radiative forcing at the snow pack surface was determined. The following inputs were used in the CCM3 CRM. Latitude was set at 38°N and the day of year was set at 90.3333 GMT corresponding to March 31st at 16:00 PST and a solar zenith angle of 64° to represent a diurnal average. Control albedo for pure snow was set at 0.98 in the visible with subsequent albedo reductions of 0.3% (-0.003) and 1.2% (-0.012) respectively. BC does not appreciably lower the albedo in the near-IR (Warren and Wiscombe, 1980), although larger snow grains absorb significantly more radiation between 800 and 3000 nm (Wiscombe and Warren, 1980), which presents potential for a strong positive feedback from BC induced melt. For the range of concentrations of BC measured in snow at LAVO and CSSL, 2.5 to 13 ng/g, the CCM3-CRM predicted surface

184 forcing above the snow pack is between 0.7 and 2.8 Wm^{-2}. The forcing predicted here by
185 the observed BC concentration in snow is comparable with the pre-industrial to present
186 CO_2 radiative forcing of 1.6 Wm^{-2} (Forster et al., 2007), although only regionally
187 applicable and subject to large variability over said region.

188 (Qian et al., 2009) predicted comparable mixing ratios for BC in snow water
189 equivalent (SWE) and a similar change in net shortwave radiation flux of 1 to 3 Wm^{-2} in
190 the Sierra Nevada during March. Subsequent simulations of the effect on snow melt and
191 water in the Sacramento - San Joaquin river basins showed significant decreases in SWE
192 throughout the spring and early summer, as well as an increase in surface temperatures.
193 (Flanner et al., 2009) also found that similar mixing ratios of BC in SWE could account
194 for 20 to 30% of the simulated negative perturbation in March – May snow cover in the
195 Western United States. This study provides observational support for recent modeling
196 studies suggesting significant impacts of BC to the decrease of snow packs in California.

197 **Sources of BC in snow**

198 The potential impact that the measured BC/SWE mixing ratio may have on
199 California snowpack compels us to examine the probable sources of the BC found in the
200 snow. We first investigate the relationship between the particulate in the atmosphere and
201 in the snow to determine how BC is transported to the snowpack. Secondly, we look at
202 relative contributions from local and regional sources of BC vs. long range transport from
203 global emissions.

204 At LAVO, the average ambient concentration of BC during the six hours just
205 prior to the onset of precipitation was highly correlated ($R^2 = 0.56$) to the total amount of
206 BC removed during the subsequent event (Figure 3a & b), which suggested that below-

cloud scavenging of BC from the atmosphere was the primary source of BC in the snow. Ambient BC concentration during the heavy precipitation events (>10mm) decreased to levels near or below the aethalometer's lower limit of detection (roughly 15 ng/m^3), indicating that nearly all of the BC in the air was removed by the snow prior to the accumulation of 10 mm. Thus the scavenging of BC in the atmospheric boundary layer by falling snow likely accounts for most of the BC found in the snow at LAVO. Similar analyses for CSSL and THD were not possible because ambient BC concentrations were not continuously measured at these sites.

Mass concentrations of Ca and Fe in the air and snow measured at both LAVO and CSSL were used to infer the source region of the BC observed in California's mountains. The mass ratio of Fe to Ca in PM2.5 observed on the west coast of North America is an indicator of North American vs. Asian dust (VanCuren et al., 2005). Van Curen et al., (2005) found that dust samples in which the PM2.5 Ca mass was equal to or exceeded the Fe mass characterized Asian dust well. In North American dust, the Fe mass fraction of the PM2.5 tended to be twice that of Ca or higher. Results from several elemental Asian dust characterization studies showed that the mass ratio of Fe to Ca ranges from 0.5 to 1 in Asian dust and pollution aerosols measured in China, Korea, and Hawaii (Holmes and Zoller, 1996;Krueger et al., 2004;Park et al., 2007;Shen et al., 2007;Sun et al., 2005). A dust characterization study for California's San Joaquin Valley revealed that the Fe to Ca ratio is around 2 for agricultural dust, the dominant source of dust during the Northern California wet spring. Although south and east of LAVO there are several large dry lake beds and deserts that produce dust aerosol with a Ca content about 4 times greater than Fe (Chow et al., 2003;Labban et al., 2004); predominant

surface winds and calculated back trajectories show that dust from the east rarely impacts the western slopes of the Sierra Nevada in the spring months.

Using the observed Fe/Ca ratio in the fine atmospheric particulate matter at LAVO and CSSL, an estimate of the relative contribution of Asian PM2.5 soil dust to the observed PM2.5 soil dust was established. When the Fe/Ca ratio was greater than or equal to 2, the fractional contribution was assumed to be zero, when the Fe/Ca ratio was less than or equal to 1, the fractional contribution was assumed to be 1, and finally for Fe/Ca ratios between 1 and 2, the fractional contribution was scaled linearly (VanCuren et al., 2005). The total soil mass concentration was calculated using the XRF elemental data and equation 2(Eldred et al., 1997;Malm et al., 1994).

$$\text{Soil} = 2.2\,\text{Al} + 2.49\,\text{Si} + 1.63\,\text{Ca} + 2.42\,\text{Fe} + 1.94\,\text{Ti} \qquad (2)$$

With the exception of three instances, the Fe/Ca ratio found in the snow samples at both LAVO and CSSL compare well with the PM2.5 Fe/Ca ratios in the surface air (Figure 4). Therefore we conclude that these surface aerosols were generally representative of the ambient aerosols in the boundary layer and subject to scavenging by the snow. Thus the sources of BC and other aerosols in the atmosphere can be applied to that in the snow.

The average Asian BC contribution to BC mass observed at LAVO was estimated using the Asian dust fraction. Previous analysis of aerosol composition exported from Asia in the spring showed that the average BC, or EC, mass was approximately equal to 7% (+/- 1%) of the PM2.5 soil dust mass(Bates et al., 2004;Moon et al., 2008;Shen et al., 2007). In North Eastern China, the average ratio of BC mass to soil dust mass in spring 2005 was 7.5% (Shen et al., 2007). The average springtime PM2.5 BC/dust ratio

253 measured at a background site in Korea between 2001 and 2003 was 8% (Moon et al.,
254 2008). In March and April 2001, PM10 aerosol measurements, taken between Hawaii and
255 Japan on NOAA's R/V Ronald Brown, presented a BC to soil dust ratio of 6.2% (Bates et
256 al., 2004). Assuming that a proportionate amount of Asian BC is transported along with
257 the dust to North America, estimates of the relative contribution of Asian BC to the total
258 observed BC at LAVO can be made for spring 2006. Given that dust particles tend to be
259 more massive than BC particles and may settle out more quickly during intercontinental
260 transit, the following estimate of the fractional contribution of Asian BC to total BC in
261 the Sierra Nevada may be biased low.

262 This estimate is valid only for dust and BC concentration measured during March,
263 April, and May, as the field studies upon which it is based also reported only seasonal
264 averages. BC to dust ratio at greater temporal resolution is likely to be significantly more
265 variable. The estimated average Asian BC contribution to total average observed BC
266 during the spring of 2006 was 27 to 36%, about 13% lower than the CFORS model
267 estimated contribution (40 to 50%) at this altitude and location in the spring of 2004
268 (Hadley et al., 2007); it is however, in close agreement with simulations of Asian BC
269 transport to the Western United States made during the TRACE-P (Transport and
270 Chemical Evolution over the Pacific) experiment (Verma et al., 2008), which showed that
271 25% of the BC over the Western United States in the spring was from Asian origin. The
272 average contribution of Asian dust to the total dust in the Sierra Nevada during this same
273 time period was 87%.

274 Although these measurements were made at only two locations, one in the
275 Southern Cascades and one in the Sierra Nevada range, an inter-comparison of five years

of aerosol data taken at three different IMPROVE (Interagency Monitoring of Protected Visual Environments) sites (Figure 1) showed that the aerosol measurements at these locations are spatially and temporally representative of mountains in Northern California (Figure 5). At all three locations, there is a clear annual signal in the Fe/Ca ratio with a minimum value at or below 1 in the late winter and early spring, coinciding with the observed peak in trans-Pacific transport, and a late summertime high around 2, when local emissions dominate. Concentrations of EC, PM2.5 soil and PM2.5 are highly correlated and similar in magnitude at all three sites. These data provide justification that the measurements made at LAVO in spring of 2006 may be generally applicable to mountain conditions in Northern and Central California and moreover that 2006 was not an unusual year compared with the previous five.

Implications for Future Trends

The data reveal that BC concentrations in the Sierra Nevada snowpack are sufficient to perturb both snow melt and surface temperatures. The concentration of BC measured in the snow is consistent with recent model predictions for BC concentration in California mountain snow. The associated reduction in snow albedo and reduced snow packs in early spring snowpack has been shown by regional climate models to be significant. A five year time series of BC, fine dust, and PM2.5 elemental composition from LAVO and two other sites in the IMPROVE data network indicate that the results presented in this study are spatially and temporally representative of conditions in the Southern Cascades and Sierra Nevada Mountains in Central and Northern California.

It is significant that the average contribution of Asian BC accounts for roughly one quarter to one third of the BC observed in the snow pack at high elevation sites in

299 Northern and Central California. Between 1988 and 2001, the annual average
300 atmospheric BC concentration in the San Francisco Bay Area has decreased from 2 $\mu g/m^3$
301 to less than 1 $\mu g/m^3$ (Kirchstetter et al., 2008), while at the same time, BC emissions from
302 Asia have risen dramatically (Novakov et al., 2003). The fractional Asian contribution of
303 BC to snowpack contamination in Western North America can be expected to increase
304 should this trend continue.

305 **Acknowledgements**

306 We would foremost like to acknowledge Guido Franco and the California Energy
307 Commission for support of this study, as well as partial support from the National
308 Science Foundation (ATMO721142). The authors gratefully acknowledge the use of
309 beamline 10.3.1 at the Advanced Light Source-Lawrence Berkeley National Laboratory.
310 The Advanced Light Source is supported by the Director, Office of Science, Office of
311 Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-
312 05CH11231. Also we thank Nancy Nordenstern, Mike Magnuson and the National Park
313 Service for their assistance with site installation at LAVO. Lastly, we thank Randall
314 Osterhuber for his help with site installation and maintenance at CSSL and Michael Ives
315 for his assistance at the Trinidad Head site.

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Table 1 Black carbon mass concentration measured in falling snow, precipitation amount, and total BC mass removed to the snow pack by precipitation events at Trinidad Head (THD), Lassen Volcano National Park (LAVO), and Central Sierra Snow Lab (CSSL).

Site and date	**BC conc. (ng/cm^3)**	**Precip (cm)**	**Total BC (ng/cm^2) dep**
THD 2/26/2006	2.3 $\pm$ 2.3	2.2	5.1
THD 2/27/2006	4.5 $\pm$ 3.7	4.4	19.8
THD 3/2/2006	5.0 $\pm$ 1.8	2.1	10.5
THD 3/5/2006	1.2 $\pm$ 1.2	2.3	2.8
THD 3/6/2006	9.8 $\pm$ 5.9	1.3	12.7
THD 3/8/2006	12.9 $\pm$ 3.6	1.6	20.6
THD 3/9/2006	9.9 $\pm$ 3.5	2.9	28.7
THD 3/13/2006	3.6 $\pm$ 2.3	1.4	5.0
THD 3/16/2006	1.7 $\pm$ 1.2	1.5	2.6
THD 3/23/2006	8.3 $\pm$ 3.1	0.9	7.5
THD 3/25/2006	3.0 $\pm$ 2.0	2.7	8.1
THD 3/30/2006	4.1 $\pm$ 3.7	1.2	4.9
THD 3/31/2006	5.5 $\pm$ 2.5	1.2	6.6
THD 4/2/2006	7.8 $\pm$ 3.1	0.7	5.5
AVG	**5.7**	**1.9**	**10.0**
LAVO 3/2/2006	7.0 $\pm$ 2.2	1.8	12.6

LAVO 3/6/2006	3.7 ± 2.1	2.1	7.8
LAVO 3/7/2006	6.0 ± 4.7	2.4	14.4
LAVO 3/16/2006	4.0 ± 3.3	1.1	4.4
LAVO 3/23/2006	4.2 ± 1.5	3.7	15.5
LAVO 3/31/2006	9.6 ± 3.9	1.3	12.5
LAVO 4/3/2006	2.8 ± 2.3	4.7	13.2
AVG	**5.3**	**2.4**	**11.5**
CSSL 3/14/2006	7.9 ± 1.5	3.4	26.9
CSSL 3/17/2006	7.3 ± 2.5	1.7	12.4
CSSL 3/24/2006	9.8 ± 2.4	6.3	61.7
CSSL 3/25/2006	8.0 ± 1.7	2.4	19.2
CSSL 3/28/2006	11.2 ± 4.5	3.7	41.4
CSSL 3/31/2006	5.8 ± 1.6	1.9	11.0
CSSL 4/2/2006	2.9 ± 1.9	5.5	15.9
CSSL 4/3/2006	2.5 ± 2.5	2.4	6.0
AVG	**6.9**	**3.41**	**24.3**

Figures

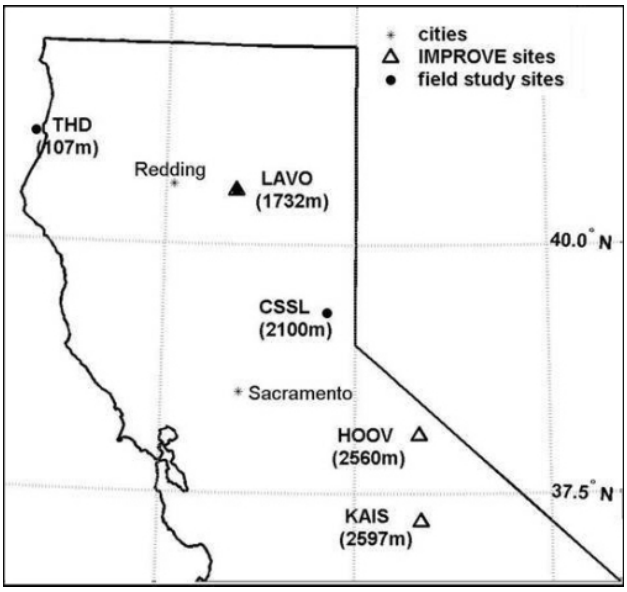

Figure 1 Field study sites (circles) and IMPROVE sites (triangles) used in this study. LAVO is both an IMPROVE and field study site. The elevation is shown in parenthesis.

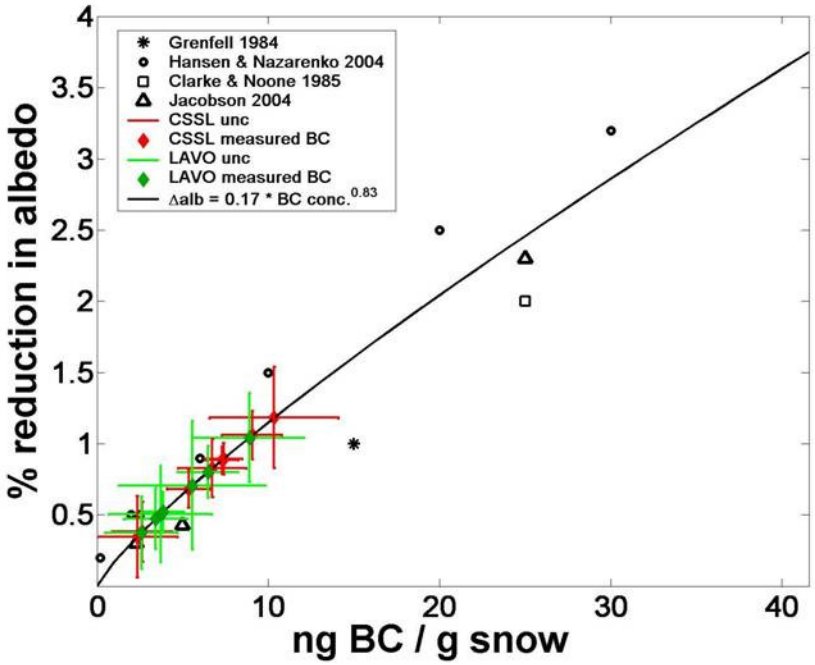

Figure 2 Model results for BC induced albedo reduction on snow and subsequent potential for measured BC concentrations in falling snow at LAVO and CSSL to reduce snow surface albedo.

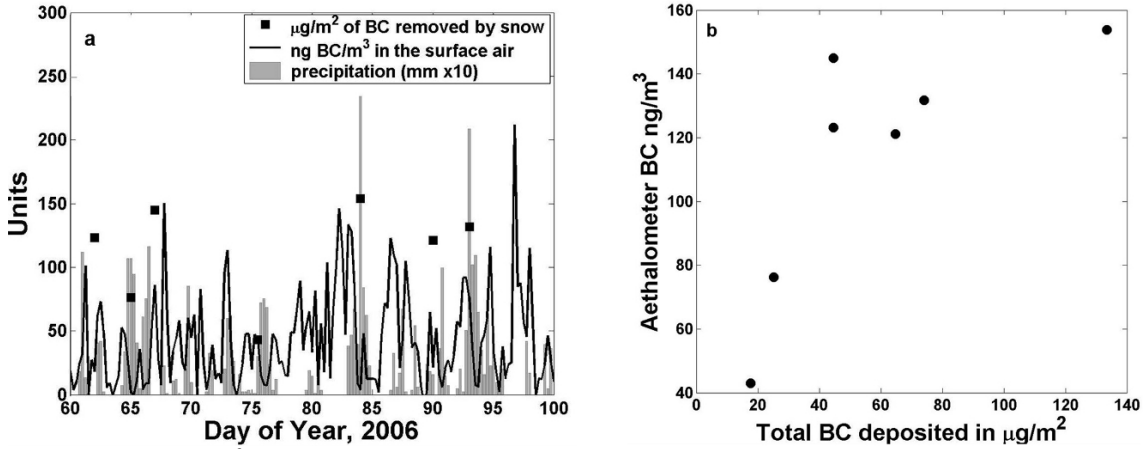

Figure 3 a.) BC/m^3 in the surface air (black line), mm of snow depth accumulated in 6 hour increments (light grey bars), total BC μg/m^2 (units converted from ng/cm^2 to fit on figure) deposited by the falling snow during a 24 to 48 hour period depending on timing of the snowfall (black squares). b.) Correlation of BC removed in a precipitation event to average ambient concentrations during the 6 hours prior to the event. $R^2 = 0.56$. Data are from LAVO.

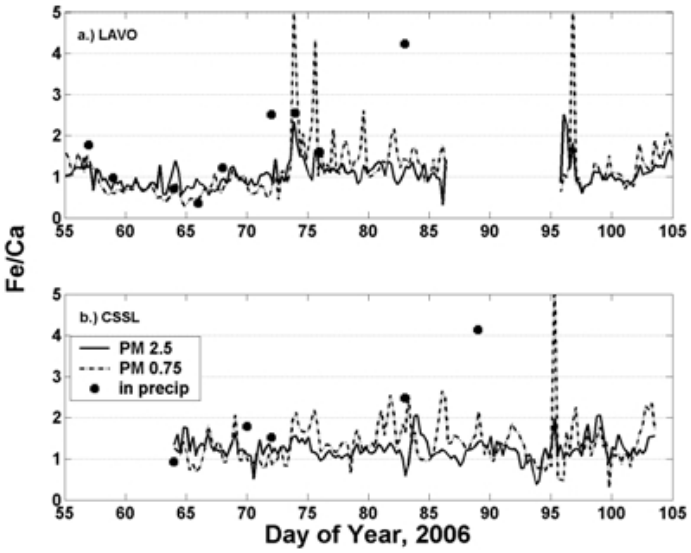

Figure4. Fe/Ca ratios for PM 2.5, PM 0.75 ambient particulate matter, as well as in the precipitation, at a.) LAVO and b.) CSSL.

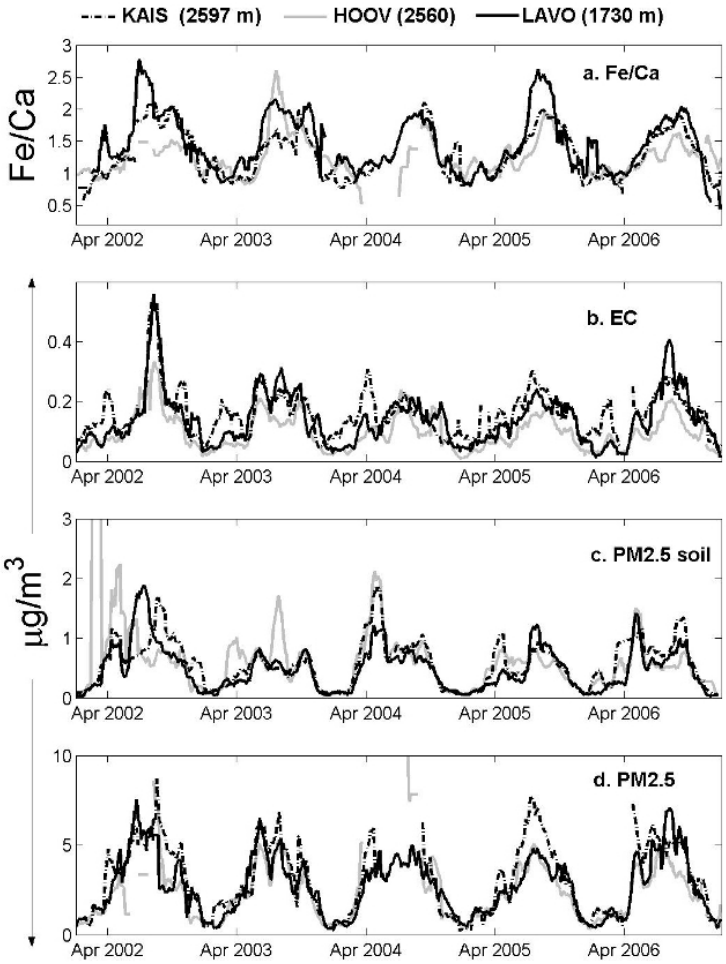

Figure 5. Aerosol data from three IMPROVE (Interagency Monitoring for Protected Visual Environments) sites in Northern CA.