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# The Influence of an Extensive Dust Event on Snow Chemistry in the Southern Rocky Mountains

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## Abstract

In mid-February 2006, windstorms in Arizona, Utah, and western Colorado generated a dust cloud that distributed a layer of dust across the surface of the snowpack throughout much of the Colorado Rockies; it remained visible throughout the winter. We compared the chemical composition of snowfall and snowpack collected during and after the dust deposition event with pre-event snow at 17 sites extending from central Colorado into southern Wyoming. The chemistry of dust-event snowfall and the post-event snowpack were compared to long-term wetfall precipitation and snowpack chemistry at the Fraser Experimental Forest (FEF). The pH of the snowpack formed during the dust event was 1.5 units higher, calcium was 10-fold higher, and acid neutralizing capacity (ANC) was 100-fold higher than levels measured in either early or late-season snow. Elevated ANC was attributable to dust-derived increase in carbonate/bicarbonate ions, likely from soluble calcium carbonate inclusions in dust material. The single dust event contributed carbonate/bicarbonate-derived ANC equivalent to the sum of strong acids deposited during the entire winter at FEF. Effects appeared more pronounced at upper elevations and in the sparse forest near treeline, compared to densely forested lower elevation sites. Monthly snowpack solute analysis at FEF has not documented an event of similar magnitude during its 17-year period of record. The solute composition of post-event snow is similar to average Fraser streamwater, however. To assess the effect of dust on the timing and composition of water exported from high-elevation ecosystems, future work should consider both the contributions of eolian deposition on soil development, plant communities, and nutrient and water relations plus the impact of individual deposition events on snowpack chemistry and duration.

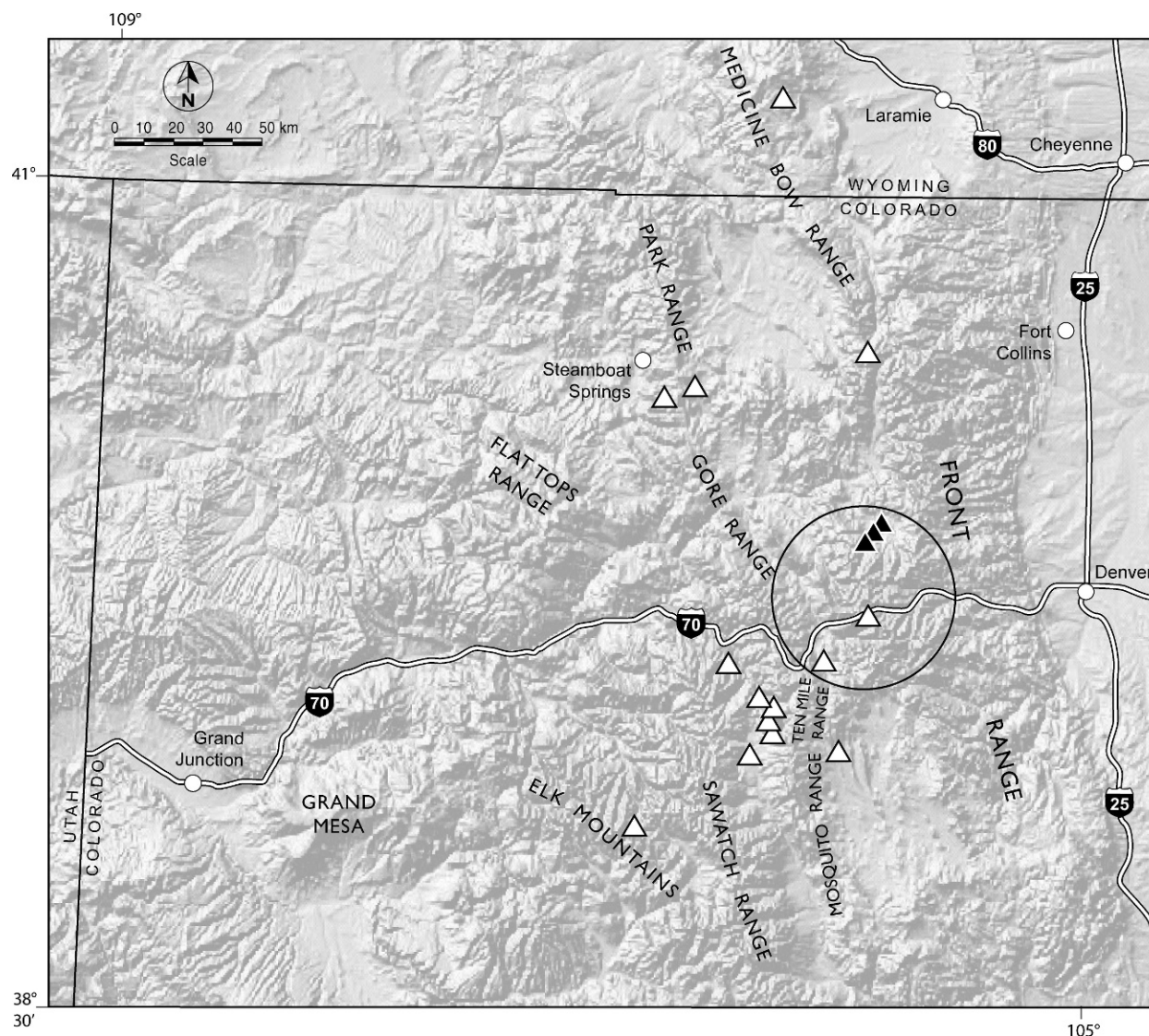
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## Introduction

Dust deposited on high-elevation and high-latitude snowpack gives visual evidence of long- and short-distance eolian transport of soil-derived aerosols (Pye, 1987; Franzén et al., 1994; Schwikowski et al., 1995). Saharan and West African wind storms, for example, commonly entrain dust that creates red snow layers in the European Alps (Tschiersch et al., 1990; Sodemann et al., 2006). Storms formed in Africa also deliver dust to more distant Northern Europe (Franzén et al., 1994), the Caribbean, and North America (Gatz and Prospero, 1996). Dust and agrochemicals found in the Canadian Arctic snowpack have been traced to Asian agricultural regions (Welch et al., 1991; Zdanowicz et al., 1998; Macdonald et al., 2005). The bulk of the global atmospheric dust load originates from soils disturbed either by climatic events (i.e., drought, flooding) or anthropogenic activities (i.e., tillage, deforestation, vehicle traffic, biomass and fossil fuel combustion; Orgill and Sehmel, 1976; Tegen et al., 1996). Drought and changes in grazing and other land-use practices have increased dust emissions in western North America (Schlesinger et al., 1990; Neff et al., 2005; Fernandez et al., 2008) and elsewhere (McConnell et al., 2007) and have drawn attention to the role of dust deposition on high-elevation ecosystems (Painter et al., 2007; Steltzer et al., 2009).

Dust inputs alter the elemental composition of both precipitation and the snowpack, and they influence surface water chemistry (Landers et al., 1987; Turk and Spahr, 1991; Turk et al., 2001). Atmospheric dust often contains soil-derived calcite and other carbonate bases that dissociate and neutralize acidic atmospheric inputs. Carbonates deposited during a three-day dust episode in the Swiss Alps, for example, neutralized half the total load of acidic inputs deposited in winter and spring precipitation (Schwikowski et al., 1995). Similarly, dissolution of calcite originating from Saharan dust neutralized sufficient acidity to raise the pH of Corsican precipitation from 4.1 to 7.0 (Loye-Pilot and Morelli, 1988). In California's Sierra Nevada, dissolution of dust-derived carbonate increased the acid neutralizing capacity and reduced the H<sup>+</sup> concentration of snowpack meltwater compared to dust-free snowpack (Williams and Melack, 1991). At high-elevation sites across the Rocky Mountains, spatial and inter-annual variation in snowpack and lake chemistry has been attributed to calcite and dolomite dust deposited throughout the winter (Reddy and Claassen, 1985; Turk and Spahr, 1991; Clow and Ingersoll, 1994; Stottlemyer, 2001; Rohrbough et al., 2003), though the biogeochemical consequences of individual deposition events are unknown.

In addition to immediate influences on precipitation, snowpack, and surface water chemistry, dust inputs also contribute to pedogenic development and biogeochemical processes in terrestrial ecosystems worldwide (McTainsh and Strong,



**FIGURE 1.** Location of Colorado and southern Wyoming snowpack sampling sites. Dust layer solute concentration at sites within the circle exceeded those sampled at sites located farther north or south. Black triangles denote sites sampled at the Fraser Experimental Forest.

2007). The global scope of eolian dust transport and its role in sustaining soil nutrients and ecosystem productivity was demonstrated by research that described the >6000 km link between dust sources in central Asian and the Hawaiian Islands (Chadwick et al., 1999; Kurtz et al., 2001). In West Africa, Harmattan winds delivered dust to a forest in Côte d'Ivoire over a three-week period and provided 85, 35, 42, and 31% of the total annual inputs of P, Ca, K, and Mg, respectively (Stoorvogel et al., 1997). Dust inputs double the P content of surface soils and enrich levels of carbonate, Ca, Mg, K, Na, and various micronutrients of Colorado Plateau ecosystems (Reynolds et al., 2001, 2006). Additionally, base cations deposited in eolian dust are retained on soil exchange sites, where they can replace acids in soil solution and buffer changes in soil pH (Litaor, 1987; Hedin and Likens, 1996). For example, cation inputs from Harmattan winds maintain the base saturation of highly weathered Ghanaian soils in excess of 80% (Tiessen et al., 1991). The fine-texture particles introduced by dust events also increase soil water-holding capacity and nutrient exchange capacity and contribute clay particles that promote formation of argillic horizons in areas overlying weathering-resistant parent materials (Dahms and Rawlins, 1996; Birkeland et al., 2003).

On 14 and 15 February 2006, strong winds transported dust from drought-affected parts of northern Arizona and southern Utah and deposited it upon the snowpack in an area that extended from the San Juan Mountains in southern Colorado to the Medicine Bow Mountains in southern Wyoming (Fig. 1; Toepfer et al., 2006; Painter et al., 2007). In conjunction with the dust event, the polar air mass delivered 5–10 cm of snow across the Colorado Rockies (NRCS, 2006). A 0.5 to 2.0 cm layer of red snow remained visible throughout the winter and snowmelt seasons. Following the February 2006 dust event, the radiation-absorbing discolored band created a weakly bonded snow layer that was credited with accelerating the loss of snowpack by 18 to 35 days (Painter et al., 2007) and increasing the occurrence of late-season avalanches in the Colorado high country (Toepfer et al., 2006).

The biogeochemical effects of individual dust events have not been assessed in the Rocky Mountain region. Though it is impossible to generalize from a single event, such knowledge will help characterize possible surface water implications of more frequent dust events from climate, land use, and population change in the western U.S.A. (Tegen et al., 1996; Reynolds et al., 2001). Our objective was to characterize the influence of the February 2006 dust event on snow chemistry at sites throughout



the deposition area. To assess the temporal significance of this single event, we compared dust-affected snowfall and snowpack with long-term precipitation and stream chemical records at the U.S. Forest Service, Fraser Experimental Forest, located near the center of the deposition zone in the Colorado Front Range.

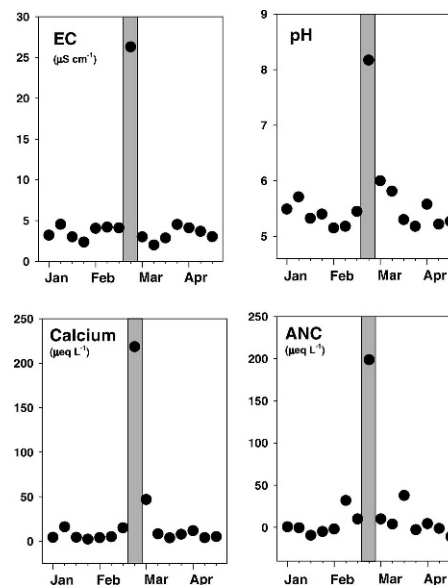
## Methods

Our study examined the influence of the February 2006 dust event on the chemistry of Snowfall from the event, Snowpack Layers, and composite Snowpack Cores. Dust and snow deposited during the event was collected in wetfall precipitation samplers (Aerochem Metrics Inc, Bushnell, Florida) located at 2750 and 3230 m elevation at the Fraser Experimental Forest (FEF). The chemistry of dust event snowfall was compared with weekly Aerochem wetfall samples from the 2005–2006 winter season prior to the event and to previous years. Samples of the dust layer were extracted using a stainless steel snow cutter (Snowmetrics, Fort Collins, Colorado) from snow pit walls at 17 locations extending from the San Juan Mountains in south-central Colorado to the Medicine Bow Mountains in southern Wyoming (Fig. 1). At each site, dust event chemistry was compared with snow collected 25–35 cm above and below the dust layer; samples were collected between mid-February and mid-March 2006, within one month of the dust event. Solute concentrations have been analyzed on integrated snowpack cores at FEF since 1990. Monthly cores are collected across an elevation gradient (2750 m, 3050 m, and 3350 m) using a stainless steel auger attached to a PVC sample tube. To characterize the dust event, we compared solute concentrations of cores collected preceding the dust deposition (1990–2005) with cores collected following the 2006 dust event.

All snow samples were thawed gradually after collection then filtered (0.45 $\mu$ ) prior to analysis by ion chromatography (Waters Ion Chromatographs with a Dionex AS12 A Separator Anion Column and Waters IC Pak Cation M/D Column; APHA, 1998). Cations were analyzed in a 0.1 mM EDTA + 3 mM HNO<sub>3</sub> eluent at 1 mL min<sup>-1</sup> flow rate. Anions were analyzed in a 2.7 mM Na<sub>2</sub>CO<sub>3</sub> + 0.3 mM NaHCO<sub>3</sub> eluent at 1.5 mL min<sup>-1</sup> flow rate. Both anions and cations used a 18 min isocratic method. Suppressed conductivity detection was used to quantify anions concentrations. Detection limits were  $\leq 0.5$   $\mu$ eq L<sup>-1</sup> for K<sup>+</sup>, Na<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, and Cl<sup>-</sup>, 1.0  $\mu$ eq L<sup>-1</sup> for Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>, and 1.6  $\mu$ eq L<sup>-1</sup> for Mg<sup>2+</sup>.

The alkalinity of snow samples was measured on unfiltered subsamples by titration to a 3.2 pH endpoint using 0.01 N HCl (Gran, 1952). Titratable alkalinity, comprised predominantly of HCO<sub>3</sub><sup>-</sup> and CO<sub>3</sub><sup>2-</sup>, represents the acid neutralizing capacity (ANC) of natural surface waters (Stumm and Morgan, 1996; Neal et al., 1999). From a charge balance perspective, ANC is commonly approximated by the difference in sums of strong base cations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, NH<sub>4</sub><sup>+</sup>) and strong acid anions (NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>) (Reuss and Johnson, 1986; Stumm and Morgan, 1996). Ion charge balances were calculated by dividing the difference between the sums of major cation and major anion charge by the sum of total ion charge. Electrical conductivity (EC) and pH were analyzed automatically with PC Titrate sensors (Man-Tech Co.).

The chemistry of snow layers influenced by the dust event was compared to layers containing pre-event and post-event snow using analysis of variance (SAS V. 9.13; Cary, North Carolina). Levene's statistic was used as a test of homogeneity of variance, and data were log-transformed when needed. Log transformation



**FIGURE 2.** Weekly snow chemistry sampled with an Aerochem wetfall collector at the Fraser Experimental Forest (3230 m elevation), Colorado, during winter 2006. Sample points within the shaded area were collected the week of the 14–15 February dust event.

succeeded in reconciling violations of the assumption of homogeneity of variance. Non-parametric Kruskal-Wallis means comparisons were made on non-normal dust layer analytes. Statistical significance is reported at the  $\alpha = 0.05$  critical value unless noted otherwise.

## Results

### SNOWFALL CHEMISTRY

The February 2006 dust event dramatically altered the chemical composition and ionic concentration of snowfall at FEF. Electrical conductivity (EC) averaged 3.6  $\mu$ S cm<sup>-1</sup> in pre-event weekly Aerochem wetfall samples (January until mid-February 2006) compared to 26.3  $\mu$ S cm<sup>-1</sup> in dust event snowfall (Fig. 2). Snowfall pH increased 2.8 units, from 5.4 prior to the event to 8.2. Pre-event snowfall had no ANC (e.g., mean of  $-4.7$   $\mu$ eq L<sup>-1</sup>); ANC was 198.7  $\mu$ eq L<sup>-1</sup> in dust event snowfall. The Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, and K<sup>+</sup> concentrations of dust event snowfall were 35, 9, 16, and 5-fold higher, respectively, than pre-event January and February 2006 snow. Dust event snowfall pH, EC, and ANC (Fig. 2) exceeded the maximum values measured during the previous five years at FEF (6.9, 17.1  $\mu$ S cm<sup>-1</sup>, and 89.9  $\mu$ eq L<sup>-1</sup>, respectively).

In clean (e.g., non-dust-event) Aerochem wetfall snow at FEF (2001 through 2005), Ca<sup>2+</sup> and the sum of NH<sub>4</sub><sup>+</sup> and H<sup>+</sup> each contributed 40% to the total cation charge, and the sum of Mg<sup>2+</sup>, K<sup>+</sup>, and Na<sup>+</sup> represented the remaining 20% (Fig. 3). During snow-free summer months, the contribution of Ca<sup>2+</sup> increased to 48% of total cation charge. Nitrate and sulfate were the dominant anions in clean FEF precipitation, representing roughly 60 and 40%, respectively, of the total anion charge. Bicarbonate, carbonate, and Cl<sup>-</sup> typically contributed little to the total anion charge (<5%) to FEF precipitation. In contrast, during the dust event calcium was the predominant cation (85%), and bicarbonate and carbonate were the predominant anions (82%). These dust-derived changes in the ion budget generated the observed increases in snowpack ANC (Fig. 3).

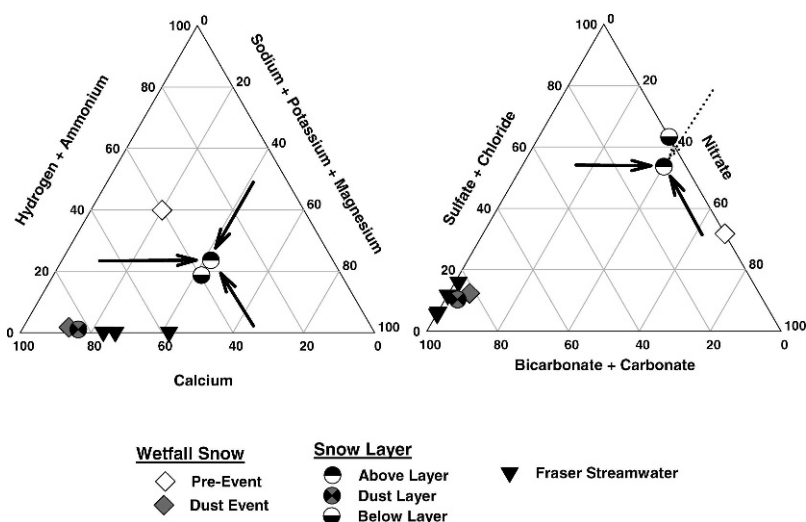


FIGURE 3. The proportional contribution of major anion and cation constituents to wetfall snow, snowpack layers, and streamwater at the Fraser Experimental Forest, Colorado. Symbol locations are plotted in a clockwise direction, as indicated by the arrows and values for each axis sum to 100.

Solute deposition at FEF during the 2006 dust event surpassed average monthly inputs for most constituents. Calcium input during the event ( $55 \text{ eq ha}^{-1}$ ) was more than 10-fold greater than the average February load ( $3.6 \text{ eq ha}^{-1}$ ) and 2.4-fold more than the highest average monthly load (May; Fig. 4) for the period from 2001 to 2005 ( $n = 20$ ). Dust event calcium inputs were 2.7-fold more than the sum of winter inputs ( $20 \text{ eq ha}^{-1}$ ) and equivalent to 49% of the average annual  $\text{Ca}^{2+}$  load received at FEF. Dust event  $\text{K}^+$ ,  $\text{Na}^+$ , and  $\text{Mg}^{2+}$  deposition was comparable to the monthly total deposited during snow-free months when deposition of soil-derived cations is highest. Dust-derived bicarbonate and carbonate ANC was equivalent to the sum of strong acid inputs deposited during the 6-month winter season at FEF and 30% of total annual strong acid inputs (Fig. 4).

#### SNOWPACK LAYERS

Mean solute concentrations measured in the dust layer significantly exceeded mean, and in most cases the maximum concentrations of snow collected above and below the dust layer (Table 1). Dust layer  $\text{Ca}^{2+}$  and ANC concentrations were two orders of magnitude greater than in snow deposited before or after the event. Magnesium concentrations were 7-fold higher on average in dust layer snow, and concentrations of most other ions doubled. Snow pH was 1.5 units higher in the dust layer, equivalent to a 16-fold decline in hydrogen ion concentration. Electrical conductivity and the total equivalents of ionic charge of dust snow were 10-fold and 16-fold higher than the other layers, respectively. Only the mean  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations did not differ between the dust and other layers, though values at some sites were double the maximum values measured in earlier or later snow. The chemical composition of snow collected beneath and above the dust layer were similar ( $P > 0.05$ ), indicating that ion elution from the dust layer had not altered the chemistry of snow at lower depths.

The chemical composition of snow deposited with the dust event varied among sample sites. Dust layer EC,  $\text{Ca}^{2+}$ , ANC, and  $\text{SO}_4^{2-}$  concentrations and the sums of cations and anions were significantly higher in the central portion of the dust deposition region (Fig. 1) compared to either the northern or southern extent of the area receiving dust ( $p < 0.05$ ). However, at even the most

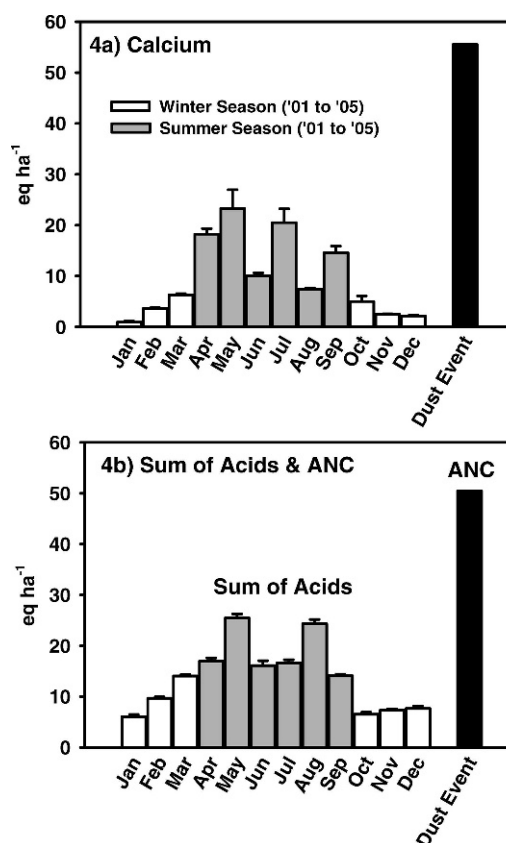


FIGURE 4. (a) Mean monthly  $\text{Ca}^{2+}$  deposition at 3230 m at the Fraser Experimental Forest, Colorado (2001 through 2005), compared to  $\text{Ca}^{2+}$  deposition during the February 2006 dust event. Shaded and open bars correspond to summer and winter season means and SE. The black bar corresponds to the  $\text{Ca}^{2+}$  deposition during February 2006. (b) Mean monthly deposition of sum of acids ( $\text{SO}_4^{2-} + \text{NO}_3^- + \text{Cl}^-$ ) at 3230 m at the Fraser Experimental Forest, Colorado (2001 through 2005), compared to the deposition of bicarbonate/carbonate-ANC during the February 2006 dust event. Shaded and open bars correspond to summer and winter season means and SE. The black bar corresponds to the bicarbonate/carbonate-ANC deposition during February 2006. ANC—acid neutralizing capacity.

TABLE 1

Chemical composition of snow layers sampled at 17 sites across the Colorado and southern Wyoming Rocky Mountains. Constituent concentrations ( $\mu\text{eq L}^{-1}$ , excepted where noted) were analyzed for the dust layer and samples collected  $>20$  cm above and below the layer. EC—electrical conductivity, ANC—acid neutralizing capacity.

	Layer	Mean	Median	Std Dev	Min	Max
EC ( $\mu\text{S cm}^{-1}$ )	Above	4.39	4.61	1.67	0.97	7.17
	Dust	43.37	26.80	39.12	4.29	139.20
	Below	4.43	4.31	0.82	2.88	5.82
pH	Above	5.65	5.67	0.37	5.06	6.39
	Dust	7.14	7.18	0.60	5.88	7.91
	Below	5.56	5.60	0.37	5.00	6.41
ANC	Above	1.30	-0.25	12.41	-33.23	21.06
	Dust	346.51	204.21	339.25	4.12	1176.22
	Below	-0.85	-3.26	12.08	-15.05	38.27
$\text{Ca}^{2+}$	Above	0.18	0.12	0.15	0.04	0.60
	Dust	7.32	6.47	6.51	0.06	22.81
	Below	0.30	0.16	0.51	0.03	2.34
$\text{Mg}^{2+}$	Above	0.02	0.02	0.02	0.01	0.08
	Dust	0.37	0.27	0.32	0.02	1.45
	Below	0.04	0.02	0.06	0.01	0.27
$\text{Na}^+$	Above	0.15	0.09	0.13	0.02	0.41
	Dust	0.75	0.73	0.60	0.08	3.20
	Below	0.25	0.13	0.30	0.03	1.10
$\text{K}^+$	Above	0.10	0.06	0.09	0.00	0.28
	Dust	0.28	0.24	0.24	0.02	0.95
	Below	0.08	0.06	0.06	0.02	0.29
$\text{NH}_4^+$	Above	0.06	0.06	0.03	0.00	0.10
	Dust	0.07	0.05	0.07	0.00	0.27
	Below	0.05	0.05	0.03	0.00	0.13
$\text{SO}_4^{2-}$	Above	0.20	0.21	0.14	0.00	0.58
	Dust	1.45	1.28	1.25	0.03	4.14
	Below	0.23	0.19	0.17	0.04	0.83
$\text{NO}_3^-$	Above	0.46	0.38	0.28	0.01	1.06
	Dust	0.90	1.00	0.62	0.03	1.89
	Below	0.47	0.48	0.23	0.06	0.95
$\text{Cl}^-$	Above	0.20	0.20	0.15	0.00	0.62
	Dust	0.42	0.28	0.41	0.08	1.67
	Below	0.29	0.16	0.38	0.04	1.48

northerly sites where the dust event formed a faint,  $<1$  cm thick band, dust layer pH exceeded that of earlier or later snow by 1.4 units and EC was 5-fold higher. At a pair of sites at FEF, dense forest canopy reduced concentrations of most ions relative to an adjacent open forest. Dust layer snow collected in open-canopy forest had significantly higher ANC,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{SO}_4^{2-}$ , and  $\text{NO}_3^-$  concentrations ( $\alpha = 0.05$ ), and higher total anion and cations compared to adjacent closed-canopy forest ( $n = 3$  subsamples per site).

#### SNOWPACK CORES

Seasonal fluctuations in FEF snowpack chemistry mirror those of snowfall chemistry. Snowpack cores collected in late winter have the highest mean and greatest variability in ion concentrations (Fig. 5). Solute concentrations and variability were typically at their lowest in January or February, though mid-winter outliers occur. Snow cores collected shortly after the February dust event exceeded any outlier measured during the past 15 years. Snowpack pH and ANC remained elevated above

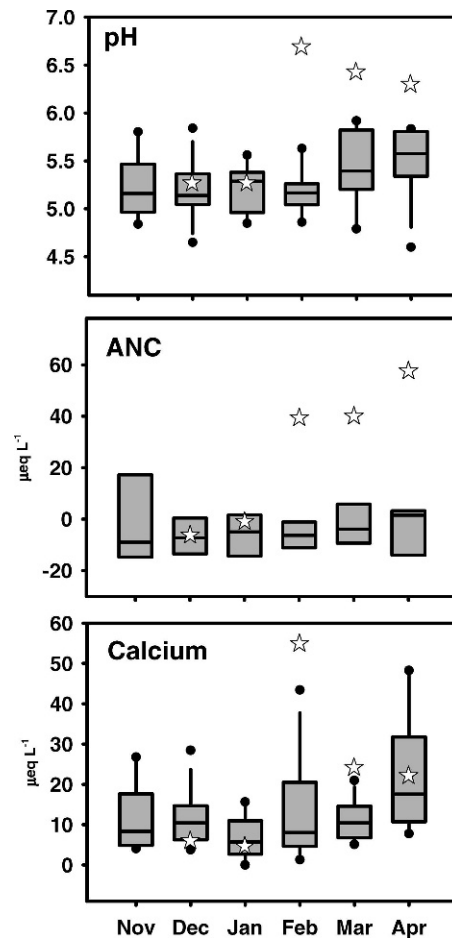


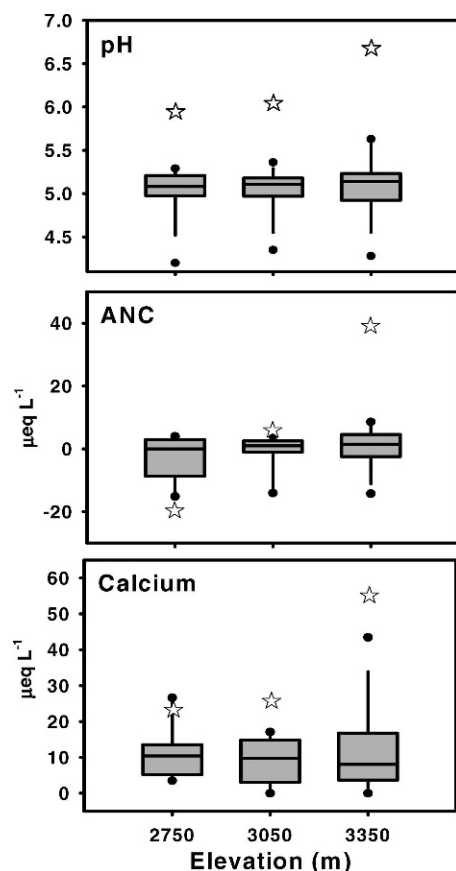
FIGURE 5. Monthly snowpack chemistry at the Fraser Experimental Forest from 1990 to 2005 and following the February 2006 dust event. Box plots show 15-year median snow core value, 25th/75th percentiles (box), 10th/90th percentiles (bars), and outliers (filled circles). Stars denote monthly composite snow cores collected during 2006.

long-term monthly mean and maximum values for the duration of the 2006 snowpack season.

February snowpack chemistry normally differs little with elevation at FEF (Fig. 6), but elevation appeared to have a pronounced effect on snowpack chemistry after the 2006 dust deposition event. The pH of the post-event snowpack collected near treeline (3350 m) was 0.6 units higher than the lowest site (2750 m), ANC was 40-fold higher, and  $\text{Ca}^{2+}$  was twice as high. Dust inputs did not significantly alter the ANC or  $\text{Ca}^{2+}$  of snowpack cored at the lowest site, though snowpack pH was nearly one unit above the long-term mean. At the upper Fraser snowfall collection site (3230 m), the loads of cations and anions received during the dust event were both more than twice the total loads received during three months of pre-event precipitation. In contrast, at the lower elevation collection site (2750 m), ion inputs did not differ between the dust event and the balance of the snowfall season.

#### Discussion

The February 2006 dust deposition event gave visible evidence of the  $>500$  km link between ecosystems of the arid Colorado Plateau in northern Arizona and southern Utah and the high-elevation areas in the southern Rockies. Earlier research



**FIGURE 6.** The influence of elevation on long-term (1990–2005) and dust-event February snowpack chemistry at the Fraser Experimental Forest. Box plots show 15-year median snow cores, 25th/75th percentiles (box), 10th/90th percentiles (bars), and outliers (filled circles). Stars denote February 2006 composite snow cores.

traced Colorado Plateau and Great Basin dust sources to the Rocky Mountain snowpack chemistry (Turk et al., 2001). The current study characterizes how an individual dust deposition event contributes to regional and local dust deposition patterns and variability in snowpack chemistry and corroborates the links between southwestern dust sources and Rocky Mountain snow chemistry established by previous research. Snowpack  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations are typically highest in southern Colorado and New Mexico near Colorado Plateau dust sources (Turk et al., 2001; Ingersoll et al., 2009) and decline northward into Wyoming and Montana. Following the February 2006 event, snowpack solute concentrations were highest at the center of the deposition zone and declined both south toward the San Juan Mountains and north into Wyoming (Fig. 1).

In addition to regional-scale patterns, the orographic conditions and sharp transition in vegetation structure near treeline created an elevation gradient in post-event snowpack solute concentrations (Fig. 6). Chemical evidence of the dust event was more pronounced at upper elevations and in sparse forests near treeline, compared to densely forested lower elevation sites. Tree canopies intercept a significant portion of the snowfall in Colorado subalpine forests (Schmidt et al., 1998; Montesi et al., 2004) and we suspect that dust inputs were similarly retained. Canopy throughfall and stemflow during spring snowmelt and summer rains likely transfers dust deposited on canopy foliage and branches to the soil surface.

This single February dust event had a dramatic effect on the 2006 snow pack of the southern Rockies; it is noteworthy that the

chemical composition and concentrations of major solutes following this event exceeded any monthly snowpack sample analyzed during the past 17 years for FEF (Figs. 5 and 6). Yet, the solute composition of post-event wetfall and dust layer snowpack are similar to average Fraser streamwater (Fig. 3). In spite of its impact on the solute composition of relatively pristine, high-elevation snowpack (Figs. 3 and 4), the direct chemical evidence of the dust event was not apparent in streamwater once it had emerged from the soil profile. Cumulative dust inputs are known to play a significant role in determining the chemical composition of Rocky Mountain streams and lakes. Dust inputs to Rocky Mountain ecosystems have been shown to elevate the  $\text{Ca}^{2+}$  concentrations of wilderness lakes relative to California lakes located at similar elevation and with similar geology, but that receive less dust (Landers et al., 1987; Turk and Spahr, 1991). In the Loch Vale watershed, a Colorado basin formed on granitic and metamorphic bedrock, weathering of dust-derived calcite contributes an equal amount of  $\text{Ca}^{2+}$  to streamwater as the weathering of plagioclase bedrock (26 and 23%, respectively); the remaining  $\text{Ca}^{2+}$  (51%) was generated by weathering of trace amounts of bedrock calcite (Clow et al., 1997). At FEF, differences in streamwater  $\text{Ca}^{2+}$  between individual basins (Fig. 3) correspond primarily to the presence of limited amounts of sedimentary bedrock or calcite. It is unknown if the relative importance of dust inputs differs among basins based on their physiographic attributes (i.e., orientation relative to predominant wind, elevation, and extent above treeline).

Dust deposition alters soil physical and chemical properties and snowmelt dynamics with consequences for both plant communities and watershed processes in Rocky Mountain ecosystems. In addition to the soluble fraction of the dust event that resulted in the snow chemistry patterns we report here, insoluble mineral and organic dust components that we did not analyze were released from the snowpack and deposited on the soil surface. Sustained eolian inputs to alpine and subalpine ecosystems create fine-textured soil horizons (fine-sand and finer) with calcium carbonate levels in excess of those typical for the coarse-textured, acidic soils derived from granitic parent material (Retzer, 1962, 1965; Litaor, 1987; Muhs and Benedict, 2006). Cations deposited with dust elevate the base saturation and pH and likely enhance nutrient availability of Front Range soils (Litaor, 1987). Cumulative dust inputs also accelerate pedogenic development and increase moisture retention of coarse-textured soils (Muhs and Benedict, 2006; Birkeland et al., 2003). Earlier snowmelt following dust deposition alters plant phenology and species interactions in southwestern Colorado alpine ecosystems (Steltzer et al., 2009). The long-term consequences of eolian deposition on soil development, plant communities, and nutrient and water relations combined with the impact of individual deposition events likely create additive effects on the processes that regulate the timing and composition of water exported from high-elevation ecosystems. It is notable that the influences of dust on soil properties were pondered in the mid-1950s by John Retzer during soil mapping at the Fraser Experimental Forest:

‘Westerly winds pick up silt as they pass over the deserts to the west and constantly deposit it in the Fraser Alpine Area. These deposits are noticeable only during winter when they are caught on the snow. The deposits are always thin, and they vary greatly from year to year. In many years they are hardly noticeable. It is not known to what degree this dust influences soil development, or to what extent it is responsible for the silt and clay measured in the soil profiles’ (Retzer, 1962).



Recent changes in climate and land-use intensity and the resulting increase in dust emissions have stimulated interest in the influence of dust inputs on North American ecosystems (Reynolds et al., 2001; Neff et al., 2005; Steltzer et al., 2009). Recognition of the importance of and uncertainty about current and future global, continental and regional dust linkages prompted including dust monitoring into the southern Rocky Mountains and other North American geographic domains participating in the National Ecological Observation Network (NEON Inc., 2009). In the Rocky Mountains, analysis of snowpack chemistry is recognized as an efficient method for characterizing spatial patterns of atmospheric deposition and for monitoring temporal changes associated with development and land use change in remote, high-elevation ecosystems (Turk et al., 2001; Ingersoll et al., 2002). Future research should aim to refine knowledge of regional and local dust deposition patterns, in conjunction with process-level studies of single and multiple deposition events to advance understanding of the consequences of current and future dust deposition scenarios on the high-elevation ecosystems.

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## ERRATA

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The Influence of an Extensive Dust Event on Snow Chemistry in the Southern Rocky Mountains. Erratum. C. Rhoades, K. Elder, and E. Greene.

This article originally appeared in *Arctic, Antarctic, and Alpine Research*, vol. 42, no. 1, February 2010. On p. 102, change wording in the caption for Table 1 from “Constituent concentrations ( $\mu\text{eq L}^{-1}$ , excepted where noted)” to “Constituent concentrations (EC:  $\mu\text{S cm}^{-1}$ ; pH: unitless; ANC:  $\mu\text{eq L}^{-1}$ ; cations and anions:  $\text{mg L}^{-1}$ ).”

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