ION DEPOSITION IN WASATCH MOUNTAIN SNOW:

INFLUENCE OF GREAT SALT LAKE

AND SALT LAKE CITY

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

The Wasatch Mountains are a unique place to study deposition of ions in snow because of proximity to Salt Lake City, UT, home to 1.1 million people, and Great Salt Lake, the world' fourth largest closed-basin saline lake. Prior study at low elevations of the Wasatch Mountains and in Salt Lake City indicates very high deposition (>1 mmol L^{-1}) of chloride nitrate, sulfate, sodium and calcium ions in snow and rime during winter temperature inversions. At peak snowpack, concentrations (μeq L^{-1}) and ecosystem loading (meq m^{-2}) of major ion species (Cl^-, NO_3^-, SO_4^{2-}, H^+, NH_4^+, Na^+, Mg^{2+}, K^+, and Ca^{2+}) were measured at five sites in 2008 and 16 sites in 2009 in the Wasatch Mountains. Concentrations and loading of these ion species in snow were up to an order of magnitude higher than previously observed and were likely derived from salts that precipitated from Great Salt Lake as its elevation decreased. Great Salt Lake has very high salinity dominated by concentrations of chloride, sulfate, sodium and magnesium. Moderately strong correlations existed between concentrations of these ions in snow and distance from Great Salt Lake, suggesting it as a major source of ion deposition in the Wasatch Mountains. Concentrations and ecosystem loading of nitrate in snow were lower than expected, but total winter inorganic nitrogen deposition (NO_3- and NH_4^+) was similar to observations at Niwot Ridge in the Rocky Mountains of Colorado. In general, concentrations of ions in snow decreased with elevation while ecosystem loading of ions increased with elevation due to greater snow accumulation.

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INTRODUCTION

Utah's Salt Lake Valley (SLV) and the Wasatch Front are prone to winter temperature inversions that trap cold air and anthropogenic pollutants near the valley floors during times of synoptic high pressure (Silva et al. 2007). The presence of winter temperature inversions combines with high emissions from fossil fuel combustion to cause episodes of poor air quality that may be both hazardous to human health and to adjacent natural ecosystems. SLV is home to over one million people (US Census Bureau 2006) and adjacent to the Wasatch Mountains, rising more than 2000 meters above the valley floor. Levels of particulate matter (PM 2.5 μm), rich in ammonium, nitrate and sulfate ions (Long et al. 2003), often exceed EPA standards during winter (EPA 2007). Air-borne particulate matter represents a significant hazard to human health during periods of winter valley temperature inversions (Pope 1989) and particulate matter dispersal may deposit a significant amount of natural and anthropogenic pollutants to adjacent ecosystems. A study of ion chemistry in snow and rime during a severe temperature inversion event in Salt Lake City, UT during the winter of 1985-86 found exceptionally high concentrations of nitrate, sulfate, chloride and sodium in snow (Cerling and Alexander 1987). Due to air pollution problems in SLV, and perhaps proximity Great Salt Lake (GSL), the Wasatch Mountains may experience high levels of atmospheric ion deposition in snow.

GSL is the fourth largest closed-basin lake in the world and may be a source of ion deposition in the Wasatch Mountains. It has varied in size and elevation over the last 150 years from a historic low elevation of 1,277 m in 1963 to a historic high of 1,283 m in 1987 when it covered approximately 6,200 km^2 (Stephens 1987). GSL is the remnant of Lake Bonnevile, a much larger and deeper freshwater lake, which formed during the Miocene Epoch of the Tertiary Period, 5 to 23 million years ago. Due to millennia of evaporation, modern GSL is a saline lake with very high concentrations of chloride, sulfate, sodium, magnesium and calcium (Jones et al. 2009). The shallow nature of the basin, and fluctuations in lake height on annual to decadal scales, create large areas of salt flats surrounding the lake. These salt flats likely have high soil salt concentrations, including ions of sodium, chloride, magnesium and sulfate. Extremely high concentrations (> 1 mequivalent L^{-1}) of sodium, calcium, chloride and sulfate ions observed in snow and rime during a Salt Lake City temperature inversion, suggest an influence of GSL on precipitation chemistry in SLV and the Wasatch Mountains (Cerling and Alexander 1987).

Deposition of ions in snow occurs either through wet deposition, where ions are incorporated into precipitation, or through dry deposition, where ions are deposited on as dust particles or aerosols (Williams et al. 2009). Winter snowpack provides a unique opportunity to study ion deposition because ions deposited through both wet and dry processes are conserved in snow throughout the winter (Bowman et al. 1992; Sickman et al. 2001; Hiltbrunner et al. 2005). Measurements of ions in snow at peak snow depth represent total atmospheric deposition over the snow-covered period. Commonly occurring ions in snow include chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}), hydrogen

(H^+), ammonium (NH_4^+), sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+) and calcium (Ca^{2+}). Sodium and chloride are typically derived from sea salt. Potassium, calcium and magnesium are 'crustal elements' that often come from dust storm events. Ammonium, nitrate and sulfate most commonly originate from the combustion of fossil fuels (Hidy 2003) and are common in particulate matter pollution (Long et al. 2003). Ion deposition can vary with geographic location, proximity to regional or local sources, aspect, elevation, season, and year (Bowman 1992; Baron and Denning 1993; Kuhn et al. 1998; Hiltbrunner et al. 2005). Deposition of ions in snow is important because high snow ion concentrations can affect ecosystems by altering plant function, ecosystem processes and elemental cycling (e.g., Aber et al. 1989; Fenn et al. 2003).

Ion deposition in North American snowpacks has been studied most intensively at Niwot Ridge on the Front Range of the Colorado Rocky Mountains. Niwot Ridge receives moderate amounts of ion deposition and is located in a subalpine forest near alpine tree line at 3340 m (Williams et al. 2009). Remote regions of the world, such as Greenland, Antarctica and the Himalaya Mountains receive significantly less atmospheric ion deposition than Niwot Ridge (Hidy 2003), while mountains down wind of Los Angeles and eastern Europe receive significantly greater ion deposition (Fenn and Bytnerowicz 1997; Emmet et al. 1998). Barbaris and Betterton (1996) found that snow on the Mongollon Rim of northern Arizona had relatively high concentrations of ammonium and sulfate compared to results found at Niwot Ridge (Williams et al. 2009). Snow ion concentrations of sodium and chloride in northern Arizona were also higher than Niwot Ridge perhaps due to salts derived from deserts in central and southern Arizona (Barbaris and Betterton 1996; Williams et al. 2009). Few differences in snow ion concentration were found between the eastern and western slopes of the Rocky Mountains in Colorado in a multiyear study, suggesting little winter time influence of pollutants originating from the Front Range cities of Colorado (Heuer et al. 2000). Lack of snow ion data in the Inter Mountain West, except from the Front Range of Colorado, underscores the importance of further study, especially in regions downwind from major cities.

Ion deposition in snow has also been thoroughly studied in the Alps. An 11-year examination of snowpack chemistry at peak snow accumulation in the Austrian Alps found typically acidic snow dominated by the deposition of sulfate and nitrate ions (>10 $\mu eq\ L^{-1}$). Ammonium, chloride and magnesium ions were also significant components of the annual snow (5-10 $\mu eq\ L^{-1}$), while sodium, potassium and magnesium were present in very low concentrations (<5 $\mu eq\ L^{-1}$) (Winiwarter et al. 1998). Two types of events dominated ion deposition in Austrian Alps snow: Saharan dust storms and anthropogenic pollution. Due to high elevation and separation from the atmospheric boundary layer during much of the winter, dust storm and pollution events were infrequent, but accounted for a significant portion of total ion deposition. Strong correlations between concentrations of sulfate, nitrate and ammonium suggested a common source, potentially representing deposition due to fossil fuel combustion (Winiwarter et al. 1998). Concentrations of sulfate and ammonium in snow loosely correlated to higher sulfate and ammonium emissions from Western Europe. In the Italian Alps at 3000 m and 4000 m ion deposition was generally low, but also dominated by Saharan dust events with high calcium, or by urban sources containing ammonium, nitrate and sulfate. Snow deposition from one "anthropogenic event" accounted for 30-40% of the total annual deposition of nitrate and sulfate (Novo and Rossi 1998). Similarly, in the Colorado Rockies, the highest concentrations of sulfate and nitrate in snow were found at a site downwind from two coal-fired power plants and a small city (Hidy 2003). While snow chemistry may not directly correlate with regional emissions, deposition of nitrate and sulfate in many mountainous regions appears to be influenced by regional transport of anthropogenic emissions.

The absence of a strong correlation between anthropogenic emissions in Western Europe and snow ion concentrations is partly explained by differences in seasonality of deposition at high elevations. Studies in both the Alps and the Rocky Mountains report seasonal changes in the ion concentration of precipitation. On an Austrian glacier, peak ion concentration in snow occurred in April. Nitrate, ammonium and sulfate concentrations were 3-10 times higher in late spring snow compared to early winter snow (Kuhn et al. 1998). Similarly, at 2500 m in the Swiss Alps, winter N deposition in snow reached a peak in March, but was much higher in summer rain. In a review of snow chemistry in the Rocky Mountains, Hidy (2003) also reported that nitrate and sulfate deposition were at their lowest in early winter and increased through winter to a peak in late spring. Mountains such as the Alps and Rockies have such large vertical relief from the surrounding lowlands that deposition at high elevations is often representative of general background levels of ions in the troposphere (Baltensperger et al. 1998). Cold temperatures during mid-winter typically create a shallower planetary boundary layer and air from lowlands near the Alps or Rocky Mountains does not often mix with air at high elevations. As temperatures warm in the spring, convection increases and the planetary boundary layer deepens, causing air at low elevations to mix with air at high elevations.

In regions where significant industry exists at low elevations, transport of valley air masses to high elevations brings higher aerosol concentrations, which typically causes higher ion concentrations in snow (Baron and Denning 1993; Kuhn et al. 1998; Schwikowski et al. 1998; Hidy 2003). Winter separation of high elevation and lowland air masses followed by greater air mass mixing in spring is the likely cause of seasonal changes in ion deposition.

Dry deposition of atmospheric pollutants can be significant in arid regions, but ions in snow is typically originate from wet deposition (Fenn et al. 2003). The National Atmospheric Deposition Program (NADP) monitors the wet deposition of ions at hundreds of sites across the United States. To examine the potential importance of dry deposition of ions in winter, Clow et al. (2002) compared NADP deposition data (wet deposition only) to total snow deposition measured at peak snowpack (wet and dry deposition). No difference between concentrations of nitrate and sulfate in snow compared to NADP deposition data were observed, suggesting that dry deposition is not significant. Differences between NADP data and snow chemistry data were found in calcium, magnesium and potassium, suggesting an increased importance of winter dry deposition for these species. Deposition of calcium, magnesium and potassium increased from north to south in the Rocky Mountains and likely represents the dry deposition of eolian carbonate dust from deserts of the Great Basin, especially from the Colorado Plateau (Clow et al. 2002; Painter et al. 2007).

Ions present in precipitation, ultimately reaching ecosystems through wet or dry deposition, transform in the atmosphere, while falling, and on the ground. Pollutants in the atmosphere, dust particles, aerosols and soluble gases, are incorporated into liquid or solid precipitation through scavenging processes. There is no simple relationship between atmospheric chemistry and snow chemistry, but several processes lead to deposition of atmospheric pollutants in snow. Ice crystal growth, and incorporation of dust and aerosols in clouds can occur one of three ways: diffusion, aggregation or accretion (Baltensperger et al. 1998; Poulida et al. 1998). Ice crystal growth through diffusion leads to large dendritic snowflakes, with typically very low ion concentration. In aggregation, individual ice crystals contact one another and clump together. Ice crystals can also grow through accretion, or riming, where supercooled liquid cloud droplets contact and freeze onto the surface of the ice crystal. The highest concentration of ions in snow, especially nitrate, sulfate and ammonium, occurs through riming. The scavenging ratio, or ratio of aerosols in precipitation to atmospheric aerosol concentration, is three times higher in the winter than in summer (Baltensperger et al. 1998). Schwikowski et al. (1998) found that aerosol scavenging efficiencies were generally low and ranged from 13% for chloride to 43% for nitrate. Events with high precipitation rates tended to produce snow with relatively low ion concentrations. The low observed scavenging efficiencies suggest that the majority of atmospheric aerosols remain in an air mass for long-range transport, even when the air mass encounters a formidable barrier like the Alps.

Transformations of ions in snow can also occur while snow is on the ground, contradicting the dogma that ions in snow are conserved in cold environments during winter. In the late 1990s anomalously high levels of NO_x gases near the snow surface were reported at the summit of Greenland (Dibb et al. 1998). Flux measurements of nitrogenous gas showed a strong correlation between the vertical flux of gases and sunlight intensity suggesting nitrate photolysis within the snowpack (Honrath et al. 2002). Research appears to indicate that photolysis of snow nitrate caused elevated concentrations of NO_x gases near the snow surface, suggesting release of deposited nitrogen from snow. Similar fluxes of nitrogenous gases from snow have also been reported in the High Arctic of Svalbard and at the South Pole (Beine et al. 2003; Davis et al. 2004; Jacobi and Hilker 2007), but has not been observed at temperate latitudes. Understanding of nitrogen transformations within the snow is imperative to accurately interpret snow chemistry, especially when concentrations of ions in snow are used as a measure of total winter deposition of nitrogen.

In forested regions, forest canopy interception of snow and rain can cause further ion transformation. Ion concentrations of throughfall precipitation, collected beneath a forest canopy, can be many times greater than precipitation collected away from trees. Concentrations of ions in throughfall precipitation at high elevations forest sites in Italy were 20-110% greater than precipitation collected in open areas (Balestrini et al. 2001). While concentrations of ions in throughfall precipitation can be very high, Hansen et al. (1996) found sharp decreases in throughfall ion concentrations 1.5 m away from tree trunks as compared to samples collected at the base of tree trunks, suggesting that canopy influence on precipitation chemistry is strongest directly underneath tree canopies. During winter, forest canopy interception of snow can cause further changes in ion concentrations due to a variety of processes, including sublimation, volatilization and dry deposition of aerosols. In boreal forests of northern Canada, concentrations of chloride and sulfate were five to six times greater in snow intercepted by forest canopies and two to three times greater 0.5 m away from trees when compared to snow in open areas

(Pomeroy et al. 1999). Conversely, nitrate concentrations of intercepted snow was up to 25% lower than in snow in open areas of subarctic boreal forests and up to 20% less in intercepted snow in Pacific Northwest forests, suggesting volatilization of nitrate in intercepted snow (Pomeroy et al. 1999; Klopatek et al. 2006). A snow chemistry study in a *Picea englemannii* and *Abies lasiocarpa* dominated forest of Colorado showed that concentrations of hydrogen, ammonium and potassium ions were greater near forest canopies than in adjacent clear-cut areas. Similar to results in boreal forests, snow nitrate concentrations were higher in clear-cuts than near forest canopies (Stottlemyer and Troendle 2001).

Nitrogen (N) deposition in snow is particularly important because ecosystem production in many snow covered systems, such as subalpine forests or alpine tundra, is limited by the availability of N but, N can become detrimental at high levels (Aber et al. 1998; Aber et al. 2001). Over the past 100 years, human-induced changes have approximately doubled rates of N inputs to terrestrial ecosystems, much of that occurring in the form of atmospheric N deposition (Vitousek et al. 1997**.** N deposition is heterogeneously distributed with the highest rates occurring downwind of urban and industrial sources. Annual rates of ecosystem N deposition vary from high rates outside Los Angeles and in northwestern Europe (15-60 kg N ha^{-1} yr^{-1}) to moderate rates in forests of New England (8-10 kg N ha^{-1} yr^{-1}), to lower rates in subalpine forests of Colorado (4-5 kg N ha^{-1} yr^{1}) (Fenn et al. 2003; Emmett et al. 1998; Aber et al. 1997; Baron et al. 2000). N deposition can also significantly alter carbon cycling, an interaction studied in temperate deciduous forests of eastern North America (Magill et al. 2000; Magill et al. 2004; Pregitzer et al. 2008) and coniferous forests of Europe (Emmett et al. 1998; Vetter et al. 2005), but less is known about how subalpine forests of western North America will respond to increases in N deposition. Understanding effects of N deposition in western forests is important because these forests are among the most significant CO_2 sinks in North America (Schimel et al. 2002) and increased rates of urbanization will likely to lead to greater N deposition (Fenn et al. 2003). Although many forests in the West may be impacted by N deposition, which forests are impacted and how they will respond is not known. Further research examining the magnitude and spatial distribution of ion atmospheric deposition in snow will help determine areas that are heavily impacted by deposition of N and other ion species.

Climate change and anthropogenic pollution are impacting ecosystems globally. Combustion of fossil fuels over the past two centuries has led to dramatic rises in atmospheric concentrations of carbon dioxide and ions such as nitrate, ammonium and sulfate. Although it is understood how many ecosystems will respond to increasing levels of atmospheric deposition of ions, it is imperative to continue snow chemistry research to better understand the magnitude, spatial scale and distribution of ion deposition. Locally high atmospheric deposition of ions in snow is more prevalent in areas downwind of major metropolitan areas like the San Bernardino Mountains of California, outside of Los Angeles (Fenn and Bytnerowicz 1997). Mountainous regions near cities of the Inter Mountain West, such as Bozeman, MT or Salt Lake City, UT may be subject to high ecosystem ion loads of due to atmospheric deposition (Fenn et al. 2003b). The Wasatch Mountains of Utah may experience unique deposition of ions in snow due to significant air pollution problems (Long et al. 2003) and their proximity to GSL. The following study investigates the extent and geographic distribution of ion deposition in snow of the central Wasatch Mountains adjacent to SLV, UT. The study was designed to build upon previous work by Cerling and Alexander (1987), which suggests that very high concentrations of chloride, nitrate, sulfate, sodium, and calcium may be found in snow of the Wasatch Mountains.

METHODS

Site Description and Snow Sampling

Snow samples were collected near the time of peak snow depth (late March to early April) from five sites in 2008 and 16 sites 2009 in the Wasatch Mountains adjacent to Salt Lake City, Utah (Figure 1). Sites were chosen to characterize the geographic distribution of ion deposition in the Wasatch Mountains. All sites had a northeasterly to northwesterly aspect and were between 2000 m and 3000 m a.s.l. (Table 1). Sites were located adjacent to a forest dominated by coniferous tree species, except for the highest elevation site in Little Cottonwood Canyon. Snow study sites were located in five canyons of the Wasatch Mountains: City Creek Canyon (CCC), Red Butte Canyon (RBC), Neffs Canyon (Neffs), Big Cottonwood Canyon (BCC) and Little Cottonwood Canyon (LCC). Sites are named with a canyon abbreviation and elevation, i.e. LCC 2950, is a site in Little Cottonwood Canyon at 2950 m. At each site, three snow pits were dug to the ground and one sample was collected from each pit. Specific snow pit locations at a site were chosen randomly within the following two criteria. Every snow pit location was NE to NW in aspect, adjacent to a coniferous forest, or in a clearing within the forest approximately 2 m outside of the tree canopy drip-line. Forests were dominated by coniferous tree species including *Abies concolor*, *A. lasiocarpa*, *Picea engelmannii* and *Pseudotsuga menziesii* and the deciduous tree *Populus tremuloides*.

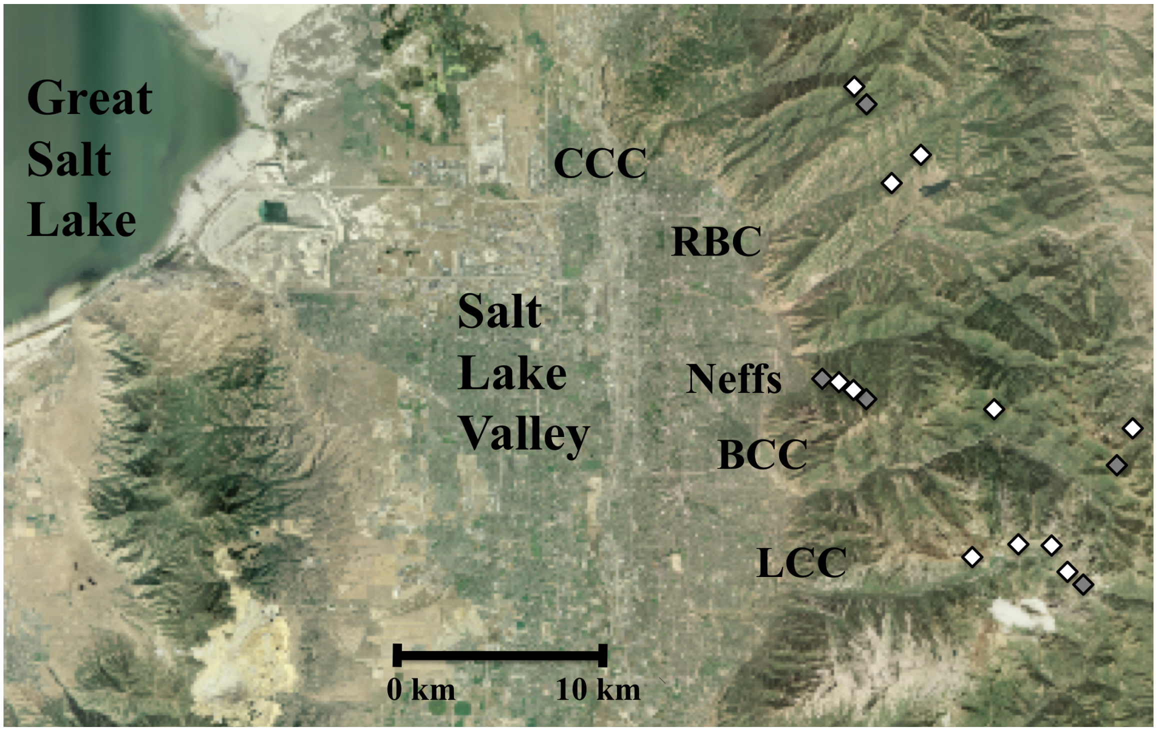

Figure 1. Snow sampling sites visited in 2008 and 2009. Snow collection occurred at all sites in 2009 (◆ and ◇) and 5 sites in 2008 (◆). Sites were located in City Creek Canyon (CCC), Red Butte Canyon (RBC), Neffs Canyon (Neffs), Big Cottonwood Canyon (BCC) and Little Cottonwood Canyon (LCC).

A continuous column of snow from the snow surface to the ground was collected in 50 cm increments using a 50 cm long PVC tube with an inner diameter of 4 cm (Sickman and Leydecker 1993). Snow depth of each sample was recorded. The PVC tube was serially washed in de-ionized water prior to each sample date but not between samples on a given date. The entire column of snow from each snow pit was stored in polyethylene bags that were also serially washed with de-ionized water prior to collection. Polethylene gloves and non-fibrous clothing were worn during all snow

Table 1. Description of sites where snow was sampled in 2008 and 2009. All sites were visited in 2009; data from 2008 are in parentheses. Sites are named with a canyon abbreviation and an elevation, i.e., BCC 2050, is a site from Big Cottonwood Canyon at 2050 m.

Sites	Elevation (m)	Aspect (°)	Snow density (g/L)	Date sampled	# snow samples	Location
BCC 2050	2051	325	296	4/3/09	3	N 40° 38.185’ W 111° 41.714’
BCC 2670	2667	350	302 (325)	4/1/09 (4/2/08)	4 (3)	N 40° 35.950’ W 111° 34.961’
BCC 2950	2947	315	324	4/1/09	3	N 40° 36.211’ W 111° 33.827’
CCC 2340	2343	320	331	3/28/09	3	N 40° 50.468’ W 111° 43.701’
CCC 2700	2689	310	317 (318)	3/28/09 (3/5/08)	3 (3)	N 40° 50.181’ W 111° 43.721’
LCC 2130	2134	315	372	3/19/09	3	N 40° 34.179’ W 111° 42.047’
LCC 2370	2370	305	368	3/19/09	3	N 40° 34.435’ W 111° 40.686’
LCC 2600	2609	315	383	3/21/09	3	N 40° 35.338’ W 111° 37.698’
LCC 2950	2945	0	314 (319)	3/23/09 (3/9/08)	3 (2)	N 40° 34.350’ W 111° 36.920’
LCC 3050	3054	60	429	3/21/09	6	N 40° 34.322’ W 111° 37.818’
Neffs 2130	2133	350	352 (285)	3/18/09	5 (3)	N 40° 40.476’ W 111° 45.403’
Neffs 2370	2374	340	345	3/18/09	3	N 40° 40.338’ W 111° 44.741’
Neffs 2560	2556	330	344	3/16/09	6	N 40° 40.109’ W 111° 43.905’
Neffs 2740	2737	325	334 (309)	3/16/09	3 (2)	N 40° 40.179’ W 111° 44.168’
RBC 2070	2069	15	377	3/17/09	3	N 40° 48.058’ W 111° 45.582’
RBC 2170	2172	340	341	3/17/09	3	N 40° 47.475’ W 111° 46.418’

sampling to minimize contamination of snow samples. Upon returning from the field, snow samples were stored in a freezer at -15° C. Snow density measurements were taken in one snow pit at each site by collecting samples in 10 cm intervals from the snow surface to the ground using a stainless steel RIP 1-L density cutter (Snowmetrics, Fort Collins, CO). One-liter snow density samples were weighed using a 500 g spring scale and snow density was calculated as the average density of all 10 cm depths for each snow pit. Snow density and snow depth were used to scale snow ion concentrations to amount of ions per ground area for each site. Ecosystem loading of ions, or amount of ions deposited to an ecosystem, was measured in mequilvalents (meq) L^{-1}.

Ion Analysis

Prior to snow water ion analysis, snow stored in polyethylene bags was melted at room temperature and transferred to 0.5L polyethylene bottles. Approximately 30 mL of melted snow–water was filtered using a 0.45 μm syringe filter. All melted snow samples were re-frozen at approximately -15°C. Snow water samples were analyzed for concentrations of Cl^-, NO_3^-, SO_4^{2-}, H^+, NH_4^+, Na, Mg^{2+}, K^+ and$^+$ Ca^{2+}. Concentrations of Cl^-, NO_3^-, and SO_4^{2-} ions were analyzed using a Dionex 4100 ion chromatograph at the Brigham Young University (BYU) water chemistry laboratory. General methods used for ion chromatography followed Anderson et al. (2006). For each batch of samples analyzed for anions, a five-point calibration curve was collected using dilute solutions of ions mixed from 99.99% pure NaCl, $NaNO_3$ and Na_2SO_4 at concentrations ranging from 3.1 to 83.5 μeq L^{-1} for chloride, 1.7 to 47.3 μeq L^{-1} for nitrate and 1.2 to 30.4 μeq L^{-1} for sulfate. All calibration curves used were determined using a quadratic regression with coefficients of determination (r^2) > 0.99. One snow sample from LCC 2370 was analyzed twice during each of three batches (n = 6) with mean ion values of 41.1 μeq L^{-1} (s.d. = 1.12) for chloride, 7.7 μeq L^{-1} (s.d. = 0.28) for nitrate and 7.8 μeq L^{-1} (s.d. = 0.29) for sulfate.

Hydrogen ions were measured as pH on unfiltered snow water samples using an Oakton 1100 series pH meter (Oakton Instruments, Vernon Hills, IL) and converted to ion concentrations. A three-point calibration curve was employed, using NIST standard buffer solutions with a pH of 4.00, 7.00 and 10.00. One sample from Neffs 2370 was analyzed ten times to yield a mean of H^+ concentration of 0.41 μeq L^{-1} (s.d. = 0.03). Concentrations of Na^+, Mg^{2+} and Ca^{2+} ions were measured at the BYU water chemistry laboratory in Provo, UT using a Perkin Elmer 5100C Atomic Absorption Spectrometer. General methods used for cation analysis followed Anderson et al. (2006). Samples were analyzed in small batches that contained a five-point calibration curve and a quality control sample analyzed in replicates of six. The five-point calibration curve was constructed using dilute solutions mixed from 99.99% pure NaCl, $MgCl_2$ and $CaCl_2$ and ranged in concentration from 4.3 to 131.1 μeq L^{-1} for sodium, 4.1 to 125.1 μeq L^{-1} for magnesium and 2.5 to 75.7 μeq L^{-1} for calcium. All calibration curves had significant correlations with coefficients of determination (r^2) > 0.99. For all batches, quality control samples had a standard deviation of <5% of the sample's value. K^+ and NH_4^+ ions were measured at the Kiowa wet chemistry laboratory at the University of Colorado in Boulder, CO following the protocols used in Williams et al. (2009). Potassium ions were measured using a Perkin Elmer Analyst 100 Atomic Absorption Spectrometer. NH_4^+ ions were measured on an OI Analytical Spectrophotometer Flow System IV Analyzer.

To assess the potential for contamination of snow samples due to sampling techniques, 1-L samples of ultra-pure de-ionized water were poured through a serially washed PVC sampling tube and stored in polyethylene bags at -15°C for 60 days prior to analysis. Analysis of these samples (n = 3) resulted in mean ion concentrations of 4.75 μeq L^{-1} (s.d.=1.06) for chloride, 0.18 μeq L^{-1} (s.d.=0.001) for nitrate, 0.77 μeq L^{-1} (s.d.=0.36) for sulfate, 1.6 μeq L^{-1} (s.d.=0.32) for ammonium, 4.3 μeq L^{-1} (s.d=1.56) for sodium, 0.35 μeq L^{-1} (s.d.=0.40) for magnesium and 0.6 μeq L^{-1} (s.d.=0.32) for potassium.

Data Analysis

To compare concentrations and ecosystem loading of ions at different elevations in 2009, sites were grouped into three elevation categories, low (2,000-2,200 m), middle (2,200-2,600 m) and high (2,600-2,950m) comprised of four, five and seven sites respectively. Data from LCC 3050 was excluded from these analyses due its high elevation and lack of forest. Comparisons of ion concentrations and ecosystem loading between years and between different elevation groups were made using a Student's t-test with a two-tailed distribution and heteroscedastic variance (Microsoft Excel:Mac, 2008). To assess the effects of a site's location relative to potential ion sources, the distance of a site from the nearest point of GSL, downtown Salt Lake City and the oil refineries in North Salt Lake was measured using topographical mapping software (TOPO! Utah, 2004). The relationship between elevation or distance from a source and ion concentration or ecosystem loading was assessed using linear regression (Microsoft Excel:Mac, 2008). Significant correlation between distance and ion deposition were only found for distance from GSL. Results from linear regressions using distance from downtown Salt Lake City and the oil refineries in North Salt Lake are not presented.

RESULTS

Snow samples from five sites in 2008 and 16 sites in 2009 were analyzed for concentrations (μeq L^{-1}) and ecosystem loading (meq m^{-2}) of dominant ion species. Data reported include concentrations and ecosystem loading of chloride, nitrate, sulfate, hydrogen, ammonium, sodium, magnesium, potassium and calcium (Cl^-, NO_3^-, SO_4^{2-}, H^+, NH_4^+, Na^+, Mg^{2+}, K^+ and Ca^{2+}). In 2008, ion concentrations ranged from 16 to 22 μeq L^{-1} for chloride, 9 to 16 μeq L^{-1} for nitrate, 8 to 16 μeq L^{-1} for sulfate, 1.1 to 1.4 μeq L^{-1} for hydrogen, 10 to 23 μeq L^{-1} for ammonium, 14 to 70 μeq L^{-1} 13 to 30 μeq L^{-1} for sodium, 4 to 7 μeq L^{-1} for magnesium and 6 to 12 μeq L^{-1} for potassium (Table 2). Due to problems with the atomic absorption spectrometer, only one 2008 sample was measured for calcium. In 2009, concentrations of ions ranged from 14 to 60 μeq L^{-1} for chloride, 6 to 10 μeq L^{-1} for nitrate, 9 to 31 μeq L^{-1} for sulfate, 0.2 to 1.5 μeq L^{-1} for hydrogen, 6 to 16 μeq L^{-1} for ammonium 14 to 70 μeq L^{-1} for sodium, 5 to 15 μeq L^{-1} for magnesium, 3 to 10 μeq L^{-1} for potassium and 9 to 102 μeq L^{-1} for calcium (Table 3).

In 2008, the highest ion concentrations generally occurred at 2,130 m in Neffs canyon while the lowest ion concentrations were found at high elevations of Neffs or Little Cottonwood Canyon (LCC). The lowest concentrations of ions measured in 2009 occurred at the highest elevations sampled in LCC (2,950 m or 3,050 m), while the highest ion concentrations were found near 2,000 m in Big Cottonwood Canyon (BCC) or Red Butte Canyon (RBC). When compared to 2007 snow chemistry data at Niwot

Table 2. Mean ion concentrations in μequivalent L^{-1} for 2008 snow samples. Number inside parentheses denotes 1 s.d., lack of s.d. means only one sample was analyzed. Missing samples are labeled n.d. for not determined. ^{a}denotes ion concentrations in snow from Niwot Ridge, CO in 2007 (Williams et al. 2009).

Sites	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**pH**	**H^+**	**NH_4^+**	**K^+**	**Na^+**	**Mg^{2+}**	**Ca^{2+}**
BCC 2670	16.4(2.3)	9.7(0.6)	10.4(0.7)	5.9	1.3	10.3	10.3	13.7(5.9)	4.1(2.2)	n.d.
CCC 2700	22.1(6.0)	12.3(0.7)	13.3(2.4)	5.9(0.2)	1.3(0.1)	12.8(1.0)	5.9(1.5)	16.89(2.6)	4.5(0.1)	n.d.
LCC 2950	16.23(6.1)	7.5(0.7)	11.2(2.2)	6.0	1.1	11.3	11.3	29.9(6.3)	5.7(0.43	6.0
Neffs 2130	27.1(4.2)	16.1(2.6)	16.0(4.5)	5.9	1.4(0.8)	22.7(2.1)	6.2(1.8)	21.9(1.8)	7.2(1.4)	n.d.
Neffs 2740	16.4(2.4)	9.1(1.0)	7.8(0.7)	5.9	1.3	12.5	12.5	13.2	3.7	n.d.
Niwot Ridge[a]	1.8	12.1	7.7	5.3	5.50	5.6	6.5	1.9	1.8	10.2

Table 3. Mean ion concentrations in µequivalent L^{-1} for 2009 snow samples. Number inside parentheses denotes 1 s.d., lack f s.d. means only one sample was analyzed. Missing samples are labeled n.d. for not determined. [a]denotes ion concentrations in snow from Niwot Ridge, CO in 2007 (Williams et al. 2009).

Site	**Cl$^-$**	**NO$_3^-$**	**SO$_4^{2-}$**	**pH**	**H$^+$**	**NH$_4^+$**	**K$^+$**	**Na$^+$**	**Mg^{2+}**	**Ca^{2+}**
BCC 2050	60.4(1.6)	6.1(0.4)	30.6(1.6)	6.6(0.3)	0.3(0.2)	9.0(0.7)	5.1(0.5)	70.4(2.0)	14.4(1.3)	102(19.9)
BCC 2670	34.2(2.7)	7.6(0.4)	21.8(2.8)	6.8(0.2)	0.2(0.1)	9.7(0.2)	6.3(1.0)	42.4(4.4)	10.5(0.9)	72.2(0.5)
BCC 2950	25.7(1.3)	7.6(0.5)	19.2(0.6)	6.0(0.2)	1.0(0.5)	8.8(0.8)	7.3(0.8)	33.6(1.7)	5.4(0.5)	61.3(9.5)
CCC 2340	39.2(9.2)	9.1(0.9)	20.4(1.5)	6.5(0.1)	0.3(0.1)	13.5(0.2)	9.2(2.7)	44.7(9.2)	13.5(2.2)	73.3(22.1)
CCC 2700	40.8(2.8)	8.1(0.4)	23.7(1.6)	6.3(0.4)	0.7(0.7)	16.0(0.8)	6.7(1.4)	40.8(2.0)	9.4(1.5)	n.d.
LCC 2130	45.1(8.4)	6.9(1.1)	22.7(2.6)	6.2(0.2)	0.6(0.3)	6.0(1.4)	6.0(0.6)	53.2(10.8)	12.3(0.1)	57.4
LCC 2370	33.4(5.2)	7.6(0.3)	18.67(2.4)	6.3(0.3)	0.5(0.3)	14.4(4.6)	4.2(0.9)	36.7(0.2)	8.5(0.8)	50.2
LCC 2600	35.9(8.8)	7.0(0.4)	13.6(1.8)	6.2(0.4)	0.8(0.6)	10.3(1.6)	2.6(0.4)	37.4(8.8)	9.4(2.0)	34.6
LCC 2950	20.8(2.4)	7.89(0.1)	15.1(0.4)	6.6(0.1)	0.3(0.0)	12.6(2.3)	8.2(2.1)	13.7(1.6)	4.7(0.3)	41.2
LCC 3050	13.5(3.3)	5.7(0.3)	9.0(0.9)	6.0(0.4)	1.5(1.1)	10.1(1.4)	4.4(2.4)	14.0(3.23)	5.1(0.6)	9.3(0.2)
Neffs 2130	52.8(8.9)	7.1(0.2)	24.9(3.3)	6.4(0.3)	0.5(0.3)	11.4(3.5)	23.5(2.5)	58.5(8.3)	13.3(1.4)	66.9(8.0)
Neffs 2370	49.1(5.0)	8.1(0.4)	20.2(1.2)	6.3(0.1)	0.6(0.2)	13.1(2.9)	6.4(0.6)	53.7(5.3)	11.6(0.6)	65.7
Neffs 2560	44.2(3.4)	7.4(0.2)	19.9(0.5)	6.3(0.3)	0.4(0.2)	10.3(1.0)	6.5(1.4)	48.2(6.1)	10.2(1.4)	66.1(5.6)
Neffs 2740	50.3(6.1)	7.4(0.3)	21.1(1.5)	6.7(0.1)	0.2(0.1)	13.7(0.9)	6.5(1.4)	45.2(5.8)	8.7(0.7)	47.3(5.2)
RBC 2070	41.4(6.6)	7.5(0.3)	19.3(1.7)	6.1(0.2)	0.8(0.4)	13.6(1.6)	3.2(0.2)	44.6(6.0)	11.9(1.7)	48.6(5.2)
RBC 2170	58.9(7.26)	9.6(1.1)	27.5(2.8)	6.1(0.2)	1.0(0.4)	12.8(5.1)	7.4(3.1)	60.1(5.7)	15.5(3.0)	72.9(21.1)
Niwot Ridge[a]	1.8	12.1	7.7	5.3	5.5	5.6	6.5	1.87	1.8	10.2

Ridge in Colorado, 2009 Wasatch Mountain snow samples had higher concentrations of chloride, sulfate, ammonium, sodium, magnesium and calcium. Concentrations of chloride, magnesium and calcium were approximately an order of magnitude higher than those found at Niwot Ridge. Contrasting the other ion species, 2009 concentrations of nitrate and hydrogen in the Wasatch Mountains were generally lower than those measured at Niwot Ridge.

Ecosystem loading of ions to sites in 2008 and 2009 was measured in milliequivalents m^{-2} (meq m^{-2}) and represents the total deposition of ions over a period of four to five months. In 2008, ecosystem loading of ions in the Wasatch Mountains varied from 10 to 18 meq m^{-2} for chloride, 5 to 11 meq m^{-2} for nitrate, 5 to 13 meq m^{-2} for sulfate, 0.7 to 1.2 meq m^{-2} for hydrogen, 7 to 12 meq m^{-2} for ammonium, 8 to 16 meq m^{-2} for sodium, 2 to 5 meq m^{-2} for magnesium and 2 to 4 meq m^{-2} for potassium (Table 4). In 2009, ecosystem loading of ions varied from 12 to 36 meq m^{-2} for chloride, 2 to 6 meq m^{-2} for nitrate, 6 to 19 meq m^{-2} for sulfate, 0.1 to 1.2 meq $m^{-2}$for hydrogen, 2 to 13 meq m^{-2} for ammonium, 1 to 38 meq m^{-2} for sodium, 4 to 10 meq m^{-2} for magnesium, 1 to 7 meq m^{-2} for potassium and 6 to 56 meq m^{-2} for calcium (Table 5).

In 2008, the highest levels of ecosystem ion loading occurred at 2,950 m in LCC, while the lowest levels were found at 2,740 m in Neffs Canyon. In 2009, the lowest values for ecosystem loading of ions in snow occurred either at low elevations of Red Butte Canyon (2,070 m) or high elevations of LCC (2,950 m). High levels of ecosystem ion loading occurred at many sites and elevations, but high elevations of City Creek Canyon (CCC) tended to have greater ecosystem loading for all ions in 2009. Lower

Table 4. Mean ecosystem loading on ions in snow at peak snowpack of 2008 measured in mequivalents L^{-1}. Number inside parentheses denotes 1 s.d., lack of s.d. means only one sample was analyzed. Missing samples are labeled n.d. for not determined. [a]denotes ecosystem loading on ions in snow from Niwot Ridge, CO in 2007 (Williams et al. 2009).

Sites	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**H^+**	**NH_4^+**	**K^+**	**Na^+**	**Mg^{2+}**	**Ca^{2+}**
BCC 2670	10.4(1.7)	6.1(0.5)	6.5(0.4)	0.9	6.7	4.0	12.1 (2.6)	3.9(1.0)	n.d.
CCC 2700	14.6(3.7)	8.2(0.3)	8.9(1.9)	0.9(0.2)	8.6(0.3)	4.1(1.8)	11.2(1.6)	3.0(0.1)	n.d.
LCC 2950	18.4(4.9)	8.7(0.3)	12.8(1.6)	1.2	12.4	2.9	15.7(1.2)	5.4(0.6)	7.3
Neffs 2130	11.5(1.9)	11.1(5.3)	7.8(2.3)	0.6(0.5)	8.5(2.8)	2.2(1.0)	8.8(1.0)	2.8(0.4)	n.d.
Neffs 2740	9.8(1.4)	5.5(0.6)	4.7(0.4)	0.7	7.9	2.3	8.0	2.2	n.d.
Niwot[a]	2.0	12.9	8.2	5.9	6.0	2.8	1.6	2.8	10.9

Table 5. Mean ecosystem loading on ions in snow at peak snowpack of 2009 measured in mequivalents L^{-1}. Number inside parentheses denotes 1 s.d., lack of s.d. means only one sample was analyzed. Missing samples are labeled n.d. for not determined. [a]denotes ecosystem loading on ions in snow from Niwot Ridge, CO in 2007 (Williams et al. 2009).

Site	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**H^+**	**NH_4^+**	**K^+**	**Na^+**	**Mg^{2+}**	**Ca^{2+}**
BCC 2050	32.3(1.8)	3.3(0.1)	16.3(1.0)	0.2(0.1)	4.8(0.5)	2.7(0.3)	37.5(1.6)	7.7(0.5)	54.0(5.7)
BCC 2670	19.3(1.2)	4.3(0.2)	12.2(1.5)	0.1(0.0)	5.4(0.2)	3.5(0.5)	23.8(2.2)	5.9(0.4)	41.1(0.2)
BCC 2950	20.8(1.9)	5.9(0.2)	15.1(0.6)	0.8(0.3)	6.9(1.2)	5.6(0.2)	26.0(1.9)	8.3(0.6)	45.0(7.5)
CCC 2340	30.4(7.3)	7.0(0.6)	15.7(1.0)	0.2(0.0)	10.4(0.2)	7.0(2.0)	34.5(7.0)	10.4(1.5)	53.6(14.6)
CCC 2700	32.6(2.7)	6.5(0.5)	18.9(1.0)	0.3(0.1)	12.7(0.7)	5.2(1.0)	32.7(2.9)	7.5(1.1)	n.d.
LCC 2130	15.6(2.5)	2.5(0.5)	7.9(1.0)	0.2(0.1)	1.8(0.8)	1.9(0.0)	18.3(2.8)	4.3(0.3)	17.2
LCC 2370	17.7(1.4)	4.0(0.1)	9.9(0.8)	0.3(0.2)	5.0(0.8)	2.1(0.4)	19.4(2.4)	4.5(0.3))	23.3
LCC 2600	31.1(7.7)	6.1(0.6)	12.0(2.0)	0.7(0.6)	9.1(1.9)	2.3(0.5)	32.6(8.1)	8.4(2.1)	33.2
LCC 2950	24.6(2.5)	6.2(0.1)	14.4(0.3)	0.3(0.0)	12.7(3.7)	8.3(2.2)	30.4(5.3)	5.7(0.3)	41.8
LCC 3050	12.1(3.9)	4.7(0.6)	7.5(1.3)	1.2(0.9)	7.4(0.7)	1.9(0.3)	12.3(4.9)	4.2(0.9)	6.1(2.1)
Neffs 2130	15.8(1.6)	2.6(0.2)	7.8(0.7)	0.2(0.1)	3.9(0.8)	4.8(1.8)	20.3(2.5)	4.6(0.4)	22.6(2.6)
Neffs 2370	32.2(4.2)	5.2(0.1)	13.2(1.2)	0.4(0.1)	8.5(1.9)	4.2(0.5)	35.3(4.7)	7.5(0.1)	39.8
Neffs 2560	28.6(2.3)	4.9(0.3)	13.0(0.5)	0.3(0.2)	7.4(0.6)	4.1(1.0)	31.1(2.9)	6.9(1.2)	45.4(10.5)
Neffs 2740	35.6(4.9)	5.8(0.2)	15.0(1.2)	0.2(0.0)	10.8(0.7)	5.1(1.1)	35.7(4.7)	6.9(0.6)	37.1(4.2)
RBC 2070	12.8(1.2)	2.4(0.2)	6.1(0.2)	0.3(0.1)	4.3(0.3)	1.0(0.1)	13.9(0.9)	3.7(0.3)	16.4(2.2)
RBC 2170	18.9(2.2)	3.1(0.3)	8.8(0.8)	0.3(0.1)	5.7(1.8)	2.4(0.7)	19.4(2.0)	5.0(0.8)	18.7(5.9)
Niwot Ridge[a]	2.0	12.9	8.2	5.9	6.0	6.9	1.6	2.8	10.9

levels of ecosystem ion loading were generally found at low elevations of all canyons sampled.

Five sites sampled in 2009 were also sampled in 2008 allowing for a 2 year comparison of ion concentrations and ecosystem ion loading in four Wasatch Mountain canyons adjacent to SLV. At most sites, concentrations of chloride, sulfate, sodium and magnesium in 2009 were nearly twice that observed in 2008 (Figure 2). Nitrate concentrations, however, were generally slightly higher in 2008 when compared to those in 2009. Nitrate concentrations in 2009 were low compared to those observed at Niwot Ridge in 2007, but 2008 nitrate concentrations in the Wasatch Mountains were similar to those observed at Niwot Ridge (Williams et al. 2009).

Similar to comparisons of ion concentrations between years, mean ecosystem ion loading was generally greater in 2009, especially for chloride and sodium where values were at least twice that observed in 2008 (Figure 3). Ecosystem loading of sulfate and magnesium was significantly greater at several sites in 2009 compared to 2008. Few differences in ecosystem loading of hydrogen, ammonium and potassium were observed between 2008 and 2009. The one exception aforementioned trend was nitrate, where mean ecosystem loading was greater in 2008 and approached values observed at Niwot Ridge in 2007 (Williams et al. 2009).

Sites varied in elevation and distance from potential sources of ion deposition. The relationship between ion deposition and elevation or distance from potential sources was evaluated using linear regression analysis (Table 6). Relationships between distance from potential sources and ion deposition were evaluated as distance from the nearest point of GSL. Relatively low r^2 values were observed for all regressions between ion

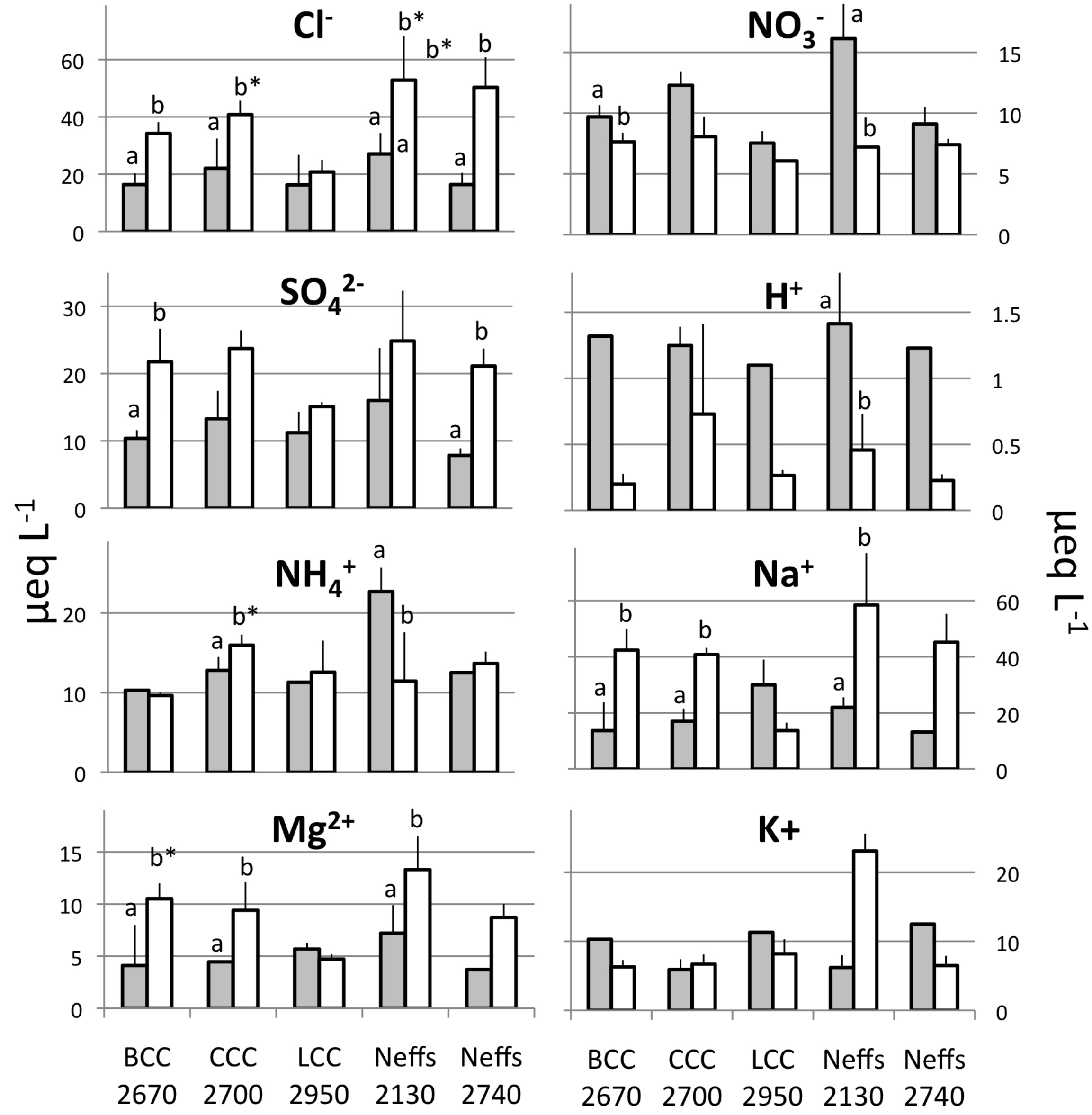

Figure 2. Mean ion concentrations of snow collected in 2008 (gray bars) and 2009 (white bars). Measurements are in µequivalents L^{-1} (µeq L^{-1}) and error bars represent 1 s.d. Paired bars with 'a' and 'b' above them represent significantly different values (t-test, $p<0.05$). Paired bars with 'a' and 'b*' also represent significantly different values (t-test, $p<0.1$). Data for Ca^{2+} was omitted because only one 2008 Ca^{2+} samples was analyzed.

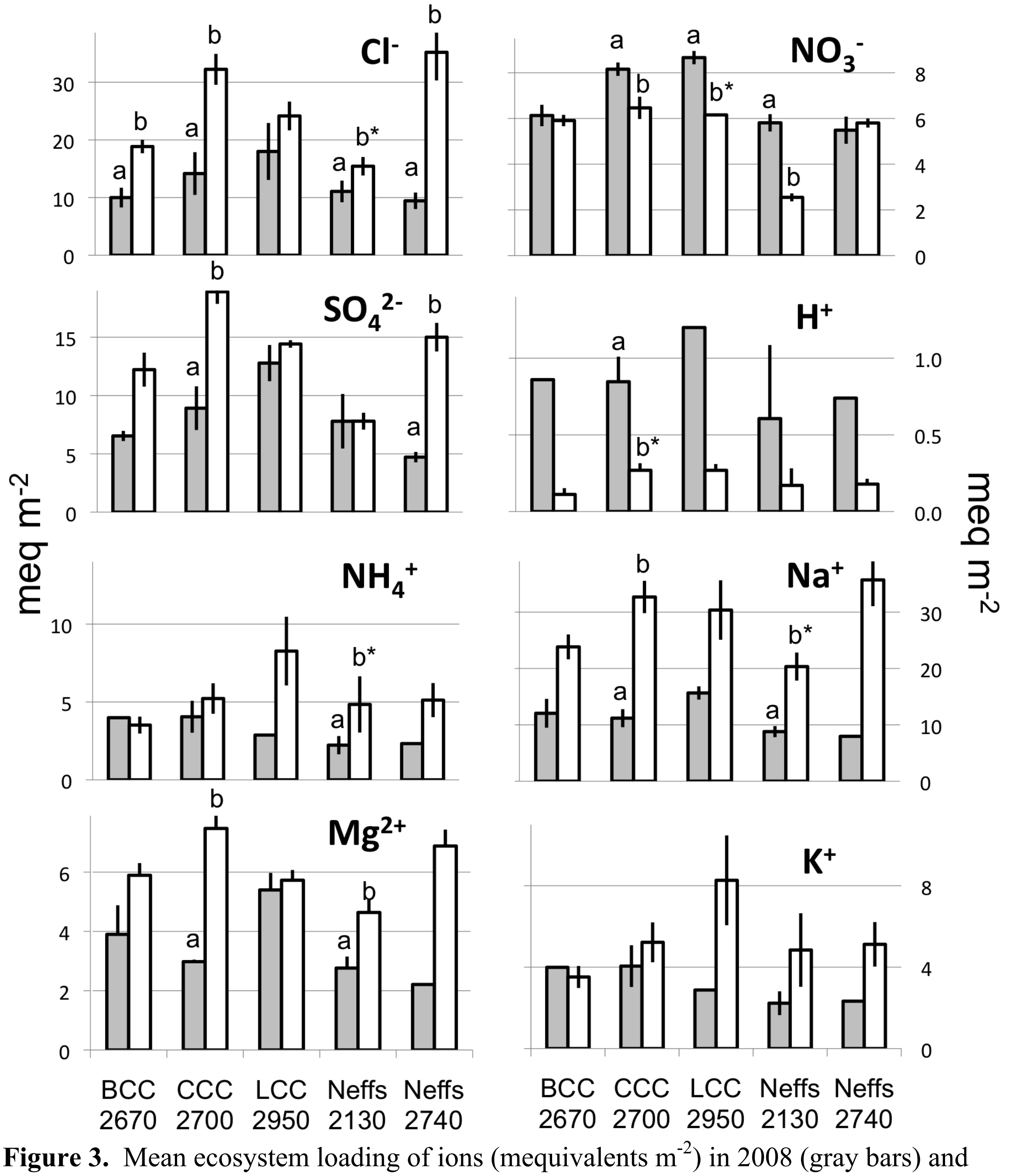

Figure 3. Mean ecosystem loading of ions (mequivalents m^{-2}) in 2008 (gray bars) and 2009 (white bars). Error bars denote 1 s.d. Paired bars with 'a' and 'b' above them represent significantly different values (t-test, $p<0.05$). Paired bars with 'a' and 'b*' also represent significantly different values (t-test, $p<0.1$). Data for Ca^{2+} was omitted because only one 2008 Ca^{2+} samples was analyzed.

Table 6. Results from linear regressions between distance from GSL and ion concentration (μeq L^{-1}) or ecosystem loading of ions (meq m^{-2}) and between elevation and ion concentrations or ecosystem loading in 2009. Values listed in table are coefficients of determination (r^2) from linear regressions. Missing values denote relationships without significant correlation ($p<0.05$).

Ion	μeq L^{-1} (distance)	meq m^{-2} (distance)	μeq L^{-1} (elevation)	meq m^{-2} (elevation)
Cl^-	0.36	·	0.45	·
NO_3^-	0.18	0.08	0.08	0.40
SO_4^{2-}	0.23	·	0.40	0.06
H^+	·	0.43	·	0.08
NH_4^+	0.06	·	·	0.05
Na^+	0.22	·	0.48	0.06
Mg^{2+}	0.17	·	0.44	·
K^+	0.04	·	·	0.05
Ca^{2+}	0.09	·	0.29	·

concentration and ecosystem loading. Higher correlations between elevation and ion concentration were observed for chloride, nitrate, sulfate, sodium and magnesium, potentially indicating GSL as a source of ion deposition. Correlations between distance from urban sources and deposition of ions was also evaluated, but no trends were observed.

In general, ion concentrations decreased with elevation, and ecosystem loading increased with elevation. Relatively strong correlations between elevation and ion concentration were observed for chloride, sulfate, sodium, magnesium and calcium. Weak correlations between ecosystem ion loading and elevation were observed, except for nitrate. The relationship between elevation and ion concentration or ecosystem loading was further explored by categorizing sites into low, middle and high elevation sites (Figure 4). Ion concentrations were significantly higher at low elevations compared to high elevations for chloride, sulfate, sodium and magnesium. For chloride and sodium, ion

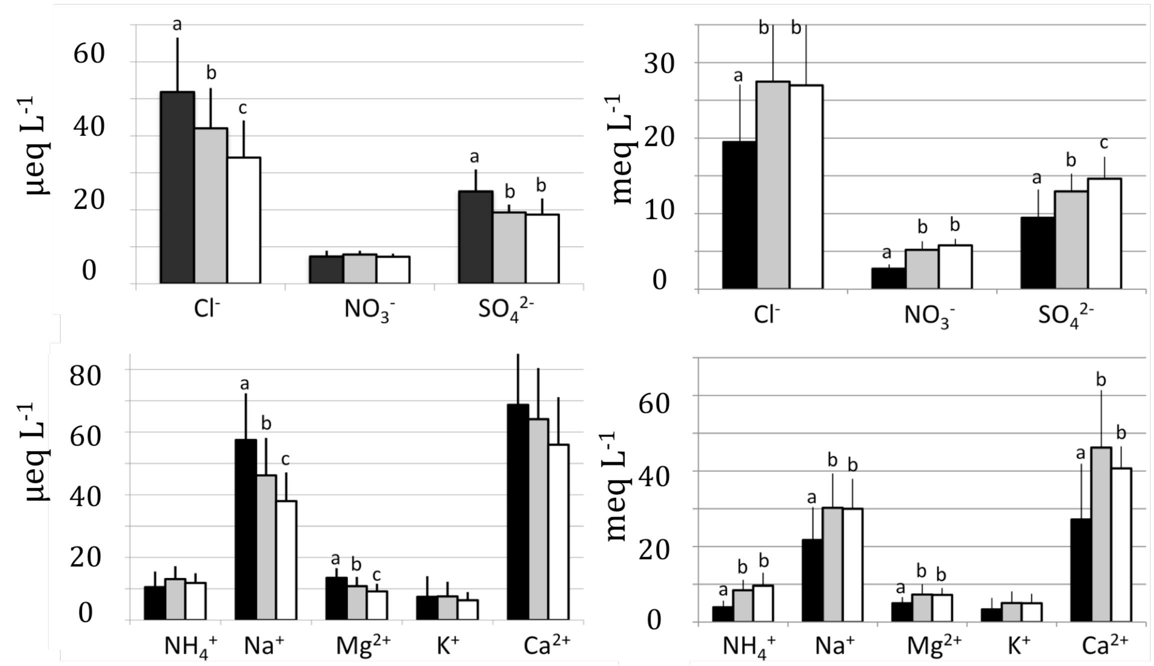

Figure 4. Snow ion concentrations (μeq L^{-1}) and ecosystem loading (meq m^{-2}) by elevation group. Sites were grouped as low elevation sites, 2,000-2,200 m (black bars), middle elevation sites, 2,200 m to 2,600 m (gray bars) and high elevation sites, 2,600-3,050 m (white bars). Error bars denote 1 s.d. Paired bars with different letters above them represent significantly different values (t-test, $p<0.05$).

concentrations were significantly different in all elevation groups (t-test, $p<0.05$) and showed a strong decrease with elevation. Ecosystem loading of all ions, except potassium, was significantly higher at high elevations compared to low elevations. Unlike the relationship between ion concentration and elevation, ecosystem loading at middle and high elevation sites was not different, but both middle and high elevation sites showed greater loading than low elevation sites.

Snow ion concentrations from samples collected in BCC in 2009 were compared to samples collected by Cerling and Alexander (1987) in Salt Lake City and in low elevations of BCC at Storm Mountains (Table 7). There was a clear trend of decreasing snow ion concentration as elevation increases. In 2009, snow ion concentrations decreased with increasing elevation for all ions except hydrogen, ammonium and potassium. During a severe temperature inversion in December 1985, concentrations of ions in snow were significantly higher at 1475 m in Salt Lake City compared to 1765 m in BCC. When 1985 data is compared to 2009 data, there is a very clear trend of decreasing snow ion concentration with elevation. Although data collected in Salt Lake City and Storm Mountain by Cerling and Alexander (1987) are not directly comparable to 2009 snow data, the comparison shows that snow and rime ion concentrations at very low elevations of BCC and Salt Lake Valley can be significantly higher than those observed at high elevations of BCC. Concentrations of all ions were significantly higher, often by an order of magnitude or more, at the lowest elevation sites at Storm Mountain in BCC and in Salt Lake City compared to BCC samples from 2009.

Table 7. Comparison of mean ion concentrations (μeq L^{-1}) from snow in along a gradient in elevation from Salt Lake City (1475 m) to high elevations of Big Cottonwood Canyon (BCC). Snow samples are from three 2009 sites in BCC (n=3), all 2009 snow samples (n =56) and snow and rime collected by Cerling and Alexander (1987) in Salt Lake City (1300 m) and in BCC at Storm Mountain (1765 m). Numbers inside parentheses denote 1 s.d.

Site	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**H^+**	**NH_4^+**	**Na^+**	**Mg^{2+}**	**K^+**	**Ca^{2+}**
BCC 2950 (2009)	25.7(2.3)	7.6(0.7)	19.2(1.0)	1.01(0.5)	8.8(1.4)	33.6(3.4)	5.34(1.0)	7.3(0.8)	61.3(9.5)
BCC 2670 (2009)	34.2(3.9)	7.6(0.8)	21.8(4.9)	0.20(0.1)	9.7(0.4)	42.4(7.6)	10.5(1.5)	6.3(1.0)	72.2(0.5)
BCC 2050 (2009)	60.4(2.8)	6.1(0.8)	30.6(2.7)	0.28(0.2)	9.0(1.2)	70.4(3.4)	14.4(2.3)	5.1(0.5)	102.0(19.9)
BCC Storm Mtn. (Cerling 1987)	530	390	440	72	570	500	50	15	120
Salt Lake City (Cerling 1987)	1910	1260	1160	91	1030	1690	240	60	1220
All Wasatch sites (2009)	37.8(15.8)	7.3(1.2)	20.0(6.1)	0.6(0.5)	11.6(4.1)	43.9(16.0)	10.6(3.6)	7.3(6.1)	60.4(22.8)
Niwot Ridge[a]	1.83	12.1	7.72	5.50	5.59	1.87	1.83	6.47	10.2

DISCUSSION

No study had previously assessed concentrations and ecosystem loading of ions in snow of the Wasatch Mountains. Proximity of the Wasatch Mountains Slat Lake City and Great Salt Lake (GSL) suggests that ion deposition may be both extremely high and unique compared to other locations. Two years of snow ion measurements in the Wasatch Mountains showed extremely high concentrations and ecosystem loading of salt-derived ions, including chloride, sulfate, sodium, magnesium and calcium. An examination of the chemical composition of hoar frost, rime and snow during a severe temperature inversion event in Salt Lake City, UT in 1985 also revealed very high concentrations of chloride, nitrate, sulfate, sodium and calcium exceeding 1 mmol L^{-1} (Cerling and Alexander 1987). Concentrations of chloride, sulfate, sodium, magnesium and calcium in snow during 2008 and 2009 were significantly lower than those observed by Cerling and Alexander (1987) but were up to an order of magnitude higher than those observed in any other published study of snow ion concentrations.

Studies in the Rocky Mountains revealed snow chloride concentrations ranging from 1 to 7 μeq L^{-1} compared to 10 to 60 μeq L^{-1} in the Wasatch Mountains (Barbaris and Betterton 1997; Heur et al. 1999; Turk et al. 2001; Williams et al. 2009). The highest previously observed snow chloride concentrations in North America were found in the southern Rockies and the Sierra Mountains in California (Laird et al. 1986; Turk et al. 2001). Sulfate concentrations in snow of the Wasatch Mountains were three to ten times higher than those observed in the Rocky Mountains (Barbaris and Betterton 1997; Heur et al. 1999; Turk et al. 2001; Williams et al. 2009). In general, snow concentrations of sodium were very low in the Rocky Mountains, averaging around 2 to 3 μeq L^{-1} (Turk et al. 2001; Williams et al. 2009) compared to concentrations of up to 70 μeq L^{-1} observed in the Wasatch Mountains. Concentrations of magnesium in Wasatch snow were two to three times higher than those observed at other sites in the Rocky Mountains. Snow calcium concentrations were also vey high in the Wasatch Mountains, nearly an order of magnitude higher than those measured at Rocky Mountain sites in Colorado. However, in 2006 at Niwot Ridge, CO, calcium concentrations of 35 μeq L^{-1} were observed, which approach values in the Wasatch Mountains (Williams et al. 2009). One study in the Alps revealed similarly high calcium concentrations of nearly 20 μeq L^{-1} (Kuhn et al. 2001). High snow calcium concentrations in 2006 at Niwot Ridge and in the Alps were likely a result of dust storm events coming from the Colorado Plateau and the Sahara, respectively (Kuhn et al. 2001; Williams et al. 2009).

Anomalously high concentrations of chloride, sulfate, sodium and magnesium in Wasatch Mountain snowpacks can likely be attributed to the proximity of GSL and other dry playas in the desert to the west of Salt Lake City. Because GSL is a closed basin lake, it is extremely saline, with salinity ranging from 12% in the southern portion of the lake to 28% in the northern portion (Jones et al. 2009). The greatest inputs of ions to GSL come from dilute calcium carbonate stream water and sodium chloride from springs and groundwater. The four dominant ion components of GSL waters are chloride, sulfate, sodium and magnesium, contributing 7.2%, 0.8%, 4.1% and 0.4%, respectively, to the lake’s salinity (Jones et al. 2009). Dissolved ions in the waters of GSL are not likely to enter the atmosphere for deposition in the Wasatch, but ions deposited in soils through evaporation as lake elevation drops may be available for atmospheric transport. Since GSL is a shallow closed basin lake, its elevation and surface area change as annual inputs of water and temperature change. Since 1847, lake elevation has fluctuated from a low of 1277.52 m in 1963 to a high of 1283.77 m in 1987. The 6 m change in lake elevation increased lake surface area from 2,500 km^2 in 1963 to 6.200 km^2 in 1987 (Stephens 1990). Currently, GSL elevation is 1278.58 m, approaching its historic low elevation (USGS data, 2010). The 5.5 m drop in lake elevation in the last 20 years has uncovered thousands of square kilometers of previously inundated soils. These inundated soils are likely rich in minerals and ions that precipitate from GSL waters as evaporation occurs. Calcite ($CaCO_3$), or magnesium-bearing calcite tends to precipitate first from saline waters, but halite (rich in chloride) and mirabilite ($Na_2SO_4 \cdot 10\ H_2O$) are also common precipitates from GSL waters during evaporation. Drought during the 1930s and 1960s caused significant salt (NaCl) precipitation, which was later re-dissolved as lake levels rose. Slight declines in lake concentrations of sulfate, magnesium, potassium and calcium from 1965-2002 may have been due to increased precipitation of these elements (Jones et al. 2009).

The large area of previously inundated soils around GSL is likely rich in ions prevalent in Wasatch Mountain snows (chloride, sulfate, sodium, magnesium and calcium) and may enter the atmosphere as dust and later deposited downwind through wet and dry depositional processes. Regression analysis between snow ion concentrations and site distance from GSL adds support to the hypothesis that high concentrations of chloride, sulfate, sodium and magnesium in snow originate from GSL.

Although correlations between site distance from GSL and ion concentrations were generally low, the highest correlations were found for chloride (r^2=0.36), sulfate (r^2=0.22), sodium (r^2=0.22) and magnesium (r^2=0.17). With the exception of nitrate, all other correlations between ion concentration and distance from GSL were low (r^2<0.1). Distance from GSL is clearly not the only determinant of snow ion concentrations of chloride, sulfate, sodium and magnesium, but it appears that GSL is a major source of snow ion deposition in the Wasatch Mountains.

While snow in the Wasatch Mountains had surprisingly high concentrations of ions prevalent in GSL saline waters, snow concentrations of nitrate were lower than expected. It was expected that snow nitrate concentrations in the Wasatch Mountains would be high relative to other studies in the Rocky Mountains due to proximity to and downwind location from SLV and the prevalence of pollution-concentrating valley temperature inversions (Long et al. 2003; Silva et al. 2007). Contrary to expectations, snow nitrate concentrations in the Wasatch Mountain were generally lower than those observed at Niwot Ridge, CO and other sites in the Colorado Rocky Mountains (Williams et al. 2009; Turk et al. 2001). During the winter, SLV routinely exceeds EPA air quality standards for PM 2.5 (particulate matter <2.5μm in diameter), which typically has high concentrations of nitrate, sulfate and ammonium (Long et al. 2003; Utah Division of Air Quality 2010). EPA revisions to 24-hour PM2.5 air quality standards in 2006 (reduction from 65 $\mu g\ m^{-3}$ to 35 $\mu g\ m^{-3}$) resulted in the designation of seven counties in Utah, including Salt Lake County, as non-attainment areas from the PM 2.5 standard (Utah DEQ 2007). Despite high levels of particulate matter air pollution in SLV, snow nitrate concentrations were relatively low. Snow ammonium concentrations in the Wasatch

Mountains were slightly higher and snow sulfate concentrations were significantly higher than those observed at other sites in the Rocky Mountains. Since both ammonium and sulfate can be constituents of particulate matter air pollution, elevated levels in snow could be due to the influence of urban air pollution.

Interactions between snow chemistry and the forest canopy may contribute to high concentrations of chloride and sulfate and lower concentrations of nitrate in snow. Unlike many snow chemistry studies, this study's snow samples (except for snow from LCC 3050) were collected from clearings within or adjacent to coniferous forests. Snow collected was not throughfall snow, but snow pits were close enough (2 m outside canopy drip-line) to the forest canopy that intercepted snow from the canopy may have impacted snow samples. Snow that is intercepted by the forest canopy is subject to sublimation and dry deposition that can affect snow ion concentrations (Laberge and Jones 1991; Jones et al. 1993; Pomeroy et al. 1998; Pomeroy et al. 1999). There are three mechanisms for changes in ion concentration of intercepted snow. First, dry atmospheric deposition to intercepted snow can increase ion concentrations relative to surface snow due to higher surface area of snow in the forest canopy. Second, in cold and dry climates, sublimation of snow from the canopy leaves snow with high ion concentrations relative to surface snow. And lastly, as snow sublimates, some ions may volatilize leaving intercepted snow with lower ion concentrations (Pomeroy et al. 1998).

Investigations of intercepted snow chemistry have typically focused on chloride, nitrate and sulfate and have often produced conflicting results. At a boreal forest site in the Canadian Arctic, intercepted snow had significantly higher concentrations of chloride, sulfate and nitrate and concentrations of chloride and sulfate were similar to those observed in the Wasatch Mountains. Despite higher ion concentrations of intercepted snow, snow collected along transects moving away from individual trees showed that snow 0.5 m away from the tree trunk was not influenced by high ion concentrations of intercepted snow, suggesting that snow samples in this study were not influenced by intercepted snow. In a more southern Canadian boreal forest, increases in chloride and sulfate concentrations of intercepted snow were also observed, but concentrations of nitrate in intercepted snow were lower relative to surface snow, suggesting some volatilization of nitrate during sublimation (Pomeroy et al. 1998). Most studies investigating the influence of canopy interception on snow ion concentrations were located in very cold boreal forests with much different weather and forest canopies than the Wasatch Mountains. Despite differences between sites where snow interception was studied and the Wasatch, snow samples collected in 2008 and 2009 may have been influenced by sublimation and volatilization, which would tend to increase snow chloride and sulfate concentrations while decreasing concentrations of nitrate.

Sampling snow from a variety of locations and elevations in the Wasatch Mountains adjacent to SLV allowed for an examination of some factors that influence ion deposition, such as distance from an ion source, elevation and geographic location. Linear regression analysis showed some correlation between distance and ion deposition, but correlations between elevation and ion deposition were much stronger. It was impossible to separate the effects of distance and elevation because high elevation sites in a specific canyon were always further away from SLV and GSL than low elevation sites in the same canyon. Despite difficulties in evaluating distance and elevation independently, some clear patterns emerged. Site distance from GSL was best correlated with snow concentrations of chloride, nitrate, sulfate, sodium, magnesium and calcium potentially indicating GSL as a source of these ions. With the exception of nitrate, the only significant correlations between snow ion concentration and distance from GSL were with ions that are typically abundant in GSL (Jones et al. 2009).

There were generally differences in measured ion concentrations and ecosystem ion loading between 2008 and 2009, but one site at 2,950 m in LCC tended to have very similar ion concentrations and ecosystem loading in 2008 and 2009. The lowest concentrations of all ions in 2009 were observed at 3,050 m in LCC. This site was unique because it was the highest elevation site and was located in alpine terrain devoid of trees. Similar ion concentrations and loading between years and low ion deposition at the highest elevations of LCC may illustrate a common pattern of ion deposition in snow of high elevation locations. While several studies have shown that ion deposition in snow can vary with elevation (Taylor et al. 1999; Bacardit and Camarero 2009), others have shown that there is a threshold elevation above which ion concentrations tend to be relatively low. In regions with great vertical relief, like the Wasatch Mountains, ion deposition at the highest mountain elevations is often more representative of regional background levels of deposition and not strongly influenced by local sources during winter**.** In the winter, cold temperatures tend to reduce the thickness of the planetary boundary layer, which causes reduced mixing of low and high elevation air masses (Baltensperger et al. 1998). Low levels of snow ion deposition observed at 2,950 m in LCC during 2008 and 2009 and 3,050 m in 2009 may be explained by reduced high elevation air mass mixing with SLV.

There is significant variation in ion concentration in snow and ecosystem ion loading between most sites measured in the Wasatch Mountains. While low levels of ion deposition at high elevations of LCC and BCC may be explained by reduced winter mixing of valley air to high elevations, there are other potential explanations for variations in deposition. Ionic deposition can vary with geographic location, proximity to regional/local sources, aspect, elevation, and year (Bowman 1992; Baron and Denning 1993; Kuhn, Haslhofer et al. 1998; Hiltbrunner, Schwikowski et al. 2005). While elevation does not explain the majority of variation in ion concentration or loading, it does account for 30-50% of the variation at many sites. Measurements of bulk precipitation along a 800m gradient in altitude in northern England showed that hydrogen, ammonium, nitrate and sulfate ion concentrations were 20-120% greater at the highest elevation site (Taylor et al. 1999), a pattern opposite to that observed in the Wasatch Mountains. Conversely, an examination of trace elements in snow between 2,000 m and 3,500 m in the Pyrennes Mountains found the highest concentrations at 2,050 m (Bacardit and Camarero 2009). Elevation clearly influences deposition of ions at many sites around the world and it appears to influence snow ion deposition in the Wasatch Mountains such that the highest elevations receive the lowest concentrations of ions in snow, but the highest ecosystem loading. Opposing trends of snow ion concentration and ecosystem loading of ions with altitude can likely be explained by consistently higher accumulation of snow as elevation increases. Lower relative snow ion concentrations are common at high elevations, but snow water equivalent (SWE) at the highest elevation sites was approximately 90% - 250% greater than SWE at the lowest elevation sites. Significantly greater values of SWE cause higher ecosystem loading of ions at high elevations despite relatively low snow ion concentrations.

Further evidence of decreases in snow ion concentration with elevation was evident when snow ion concentrations from BCC in 2009 were compared to data collected by Cerling and Alexander (1987). Concentrations of chloride, nitrate, sulfate, sodium and calcium in snow were significantly higher in Salt Lake City (1300 m) during a 1985 severe temperature inversion compared to BCC (1765 m). While the trend of higher snow ion concentrations in Salt Lake City compared to BCC in 1985 was likely related to the elevation of the temperature inversion, the same pattern of decreasing snow ion concentration with increasing elevation is present in 2009 snow samples from BCC and the Wasatch Mountains. Concentrations of ions in snow at peak snowpack in 2009 were one to two orders of magnitude lower than those observed during the valley inversion of 1985. The valley temperature inversion in late December of 1985 was the most severe in several decades (Cerling 2010 personal communication).

The Wasatch Mountains receive moderate loads of ions important to plant growth, e.g., nitrate and ammonium. Deposition of nitrate was lower than expected, but deposition of ammonium was higher than expected, leading to similar total inorganic nitrogen (N) deposition in the Wasatch Mountains and at Niwot Ridge (Williams et al. 2009, etc.). N deposition in the Front Range of Colorado has increased soil N pools, altered foliar chemistry (Baron et al. 2000) and increased productivity of some subalpine forests (Sievering et al. 2007). Slightly higher levels of N deposition than observed in the Wasatch Mountains altered aboveground net primary production of eastern deciduous forest in both positive and negative directions (McNulty et al. 1996; Magill et al. 2000;

Magill et al. 2004). Effects of atmospheric N deposition on forests, especially western subalpine forests, are not clearly understood. Deposition of nitrate and ammonium in snow of the Wasatch Mountains may affect ecosystem processes essential to the health of Wasatch Mountain forests. Further study is necessary to evaluate the impact of N deposition.

The presence of GSL has likely caused high deposition of salt-derived ions to subalpine forests of the Wasatch Mountains for many millennia. Many plants are intolerant to salinity and the presence of high salinity in snow may affect plant growth and ecosystem processes. Mining effluent, high in chloride, sulfate and sodium, reduced seedling growth of *Picea glauca, Picea mariana* and *Pinus contorta* in soils subject to high concentrations of Na_2SO_4. Leaves of *Salix* spp. and *Populus tremuloides* were rapidly lost, but very quickly replaced by morphologically unique leaves (Renault et al. 1998). Increased marine aerosol deposition (high in NaCl) may be a primarily driver of the *Picea abies* mortality in southern Sweden (Gustafssen 1997). Finally, an examination of the effect of road salt ($MgCl_2$) *P. tremuloides, P. engelmannii* and *A. lasiocarpa* found high foliar chloride concentrations correlated strongly with percent foliar damage and significant effects of road salt were found in soils and vegetation 100 m distant from roads (Goodrich et al. 2009). Most studies investigating effects of salinity on forest health use salt concentrations higher than those that likely exist in soils of the Wasatch Mountains. While subalpine forests of the Wasatch Mountains may be adapted to relatively higher levels of salt common in precipitation, changes in GSL lake level may further alter precipitation chemistry, potentially affecting forest and ecosystem processes.

CONCLUSION

The Wasatch Mountains, adjacent to the metropolitan area defined by SLV, were subject to extremely high ecosystem loading and concentrations of chloride, sulfate, sodium, magnesium and calcium in snow. Concentrations and amounts of these ions were among the highest observed in snow chemistry studies and likely reflect proximity to GSL, a closed basin saline lake. Nitrate deposition in the Wasatch Mountains was lower than expected considering proximity to a city with significant particulate matter air pollution problems. Total inorganic N deposition (nitrate and ammonium) was similar in the Wasatch Mountains and the Colorado Rockies. Moderate deposition of inorganic N and high deposition of salt-derived ions may affect forest and ecosystem processes of the Wasatch Mountains. While distance from GSL and elevation affected concentrations and ecosystem loading of ions in snow, deposition was dominated by ions likely derived from salt flats surrounding GSL.

APPENDIX

FOLIAR CHEMICAL COMPOSITION AND NITRATE DEPOSITION

Needles and leaves of the dominant subalpine tree species of the Wasatch Mountains (*Abies lasiocarpa, Picea englelmanii, Populus tremuloides* and *Pseudotsuga menziesii*) were collected in late August and early September of 2008 and 2009 from a subset of sites where snow was sampled. Foliage was sampled from eight sites in 2008 and four sites in 2009. Three randomly chosen trees of each species were sampled. Needles and leaves were sampled using a 4 m tree-pruning saw. From each tree three small branches exposed to the sun for part of the day were clipped and stored in coin envelopes. In the laboratory, conifer needles were separated into this current year needles and last year's needles. Leaf and needle samples were stored in coin envelopes, oven-dried at 60˚C, and ground into a fine powder with mortar, pestle and liquid nitrogen. All leaf samples were analyzed for C, N, δ^{13}C and δ^{15}N using a Finnigan Delta Plus XP continuous-flow stable isotope ratio mass spectrometer coupled with an elemental analyzer (Thermo Electron Corp., Waltham, MA).

Data from 2008 is presented in Tables 8-11. Data from 2009 will be presented in the final manuscript (and likely available for discussion on 3/9/10). Table 8 presents foliar chemistry data for *Abies lasiocarpa*, Table 9 presents data for *Picea engelmannii*, Table 10 presents data for *Pseudotsuga menziesii* and Table 11 presents data for *Populus tremuloides*. Mean values of foliar $\delta^{15}N$ measured in 2008 for *A. lasiocarpa, P. engelmannii, P. tremuloides and P. menziesii* (Tables 8, 9, 10 and 11) were compared to mean site nitrate deposition using linear regression (Microsoft Excel:Mac, 2008). Significant correlations between nitrate deposition and foliar $\delta^{15}N$ were found with *A. lasiocarpa* (r^2=0.57), *P. engelmannii* (r^2=0.66) and *P. tremuloides* (r^2=0.64) (Figure 5). Mean values of foliar $\delta^{15}N$ and nitrate deposition were used for linear regression because snow and foliar samples were collect independently at the same site, such that a foliar sample is not paired with a specific snow sample. Snow nitrate data used for linear correlations was collected identically to specifications in the methods, but snow nitrate was by first converting all $NO_3^-$to NO_2^-through copper-cadmium reduction and then quantifying concentrations through spectrophotometric analysis (Cruz and Loucao 2002). Significant correlations between nitrate deposoition and foliar $\delta^{15}N$ in 2008 were found with *A. lasiocarpa* (r^2=0,57), *P. engelmannii* (r^2=0.66) and *P tremuloides* (r^2=0.64) (Figure 5).

Table 8. Chemistry of *Abies lasiocarpa* needles, including stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), percentage nitrogen (%N) and percentage carbon to percentage nitrogen ratio (C:N), collected at sites in August to September of 2008 and 2009. All site locations can be found in Table 1 except for Neffs 2790, which is located on a south-facing slope in Neffs Canyon at 2,790 m (N 40° 39.693', W 111° 43.677') and BCC 2700 located in Big Cottonwod Canyon at 2,700 m (N 40° 37.992', W 111° 40.202'). Numbers inside parentheses denote 1 s.d. and n=3 for all samples.

Sites	**Year**	**$\delta^{13}C$**	**$\delta^{15}N$**	**%N**	**C:N**
BCC 2700	2008	-26.1(1.7)	-4.7(4.4)	1.00(0.17)	54.7(10.6)
BCC 2670	2009	-27.8(0.1)	-0.6(1.2)	1.07(0.24)	48.5(4.2)
BCC 2950	2009	-26.7(0.6)	-1.4(0.5)	1.03(0.41)	51.7(12.7)
CCC 2700	2008	-26.3(0.7)	-1.3(1.1)	1.10(0.19)	44.7(4.9)
LCC 2950	2008	-25.4(1.4)	-2.6(0.8)	1.50(0.31)	35.3(6.4)
Neffs 2370	2009	-26.3(0.8)	-3.3(0.4)	1.25(0.50)	42.0(7.6)
Neffs 2740	2008	-24.9(0.8)	-1.7(1.6)	1.32(0.03)	38.5(1.1)
Neffs 2740	2009	-26.5(0.6)	-1.4(0.8)	1.20(0.17)	43.1(2.2)
Neffs 2760	2008	-25.4(0.4)	-2.3(1.4)	1.13(0.05)	45.1(3.5)

Table 9. Chemistry of *Picea engelmannii* needles, including stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), percentage nitrogen (%N) and percentage carbon to percentage nitrogen ratio (C:N), collected at sites in August to September of 2008 and 2009. Numbers inside parentheses denote 1 s.d. and n=3 for all samples.

Sites	**Year**	**$\delta^{13}C$**	**$\delta^{15}N$**	**%N**	**C:N**
BCC 2700	2008	-23.9(0.4)	-6.6(0.4)	0.90(0.10)	54.9(6.8)
BCC 2670	2009	-26.0(0.1)	-1.5(0.5)	0.94(0.58)	53.3(1.9)
BCC 2950	2009	-26.8(0.5)	-1.6(0.4)	0.90(1.56)	54.1(3.0)
CCC 2700	2008	-25.9(0.6)	-1.6(1.3)	1.00(0.05)	47.2(3.1)
LCC 2950	2008	-25.3(0.5)	-3.5(1.7)	1.00(0.05)	52.2(5.2)
Neffs 2740	2008	-24.9(0.8)	-3.6(0.2)	0.88(0.12)	57.9(9.0)
Neffs 2740	2009	-26.4(1.5)	-2.1(0.6)	0.92(0.55)	55.5(3.2)

Table 10. Chemistry of *Pseudotsuga menzeisii* needles, including stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), percentage nitrogen (%N) and percentage carbon to percentage nitrogen ratio (C:N), collected at sites in August to September of 2008 and 2009. All site locations can be found in Table 1 except CCC 2740, which is located in City Creek Canyon at 2,072 m (N 40° 49.821', W 111° 45.874') and Neffs 1840 located at 1,840 m in Neffs Canyon (N 40° 40.327', W 111° 46.025'). Numbers inside parentheses denote 1 s.d. and n=3 for all samples.

Sites	**Year**	**$\delta^{13}C$**	**$\delta^{15}N$**	**%N**	**C:N**
BCC 2700	2008	-24.4(0.5)	2.1(0.8)	1.10(0.33)	48.0(12.5)
CCC 2070	2008	-28.0(1.0)	-1.9(0.4)	0.90(0.01)	53.7(1.0)
Neffs 1840	2008	-25.2(0.8)	1.3(1.3)	0.90(0.06)	55.5(6.8)
Neffs 2130	2008	-26.8(1.0)	-1.7(0.1)	0.94(0.04)	54.2(5.2)
Neffs 2740	2008	-25.2(0.7)	-2.0(0.2)	0.91(0.02)	55.0(2.5)

Table 11. Chemistry of *Populus tremuloides* needles, including stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$), percentage nitrogen (%N) and percentage carbon to percentage nitrogen ratio (C:N), collected at sites in August to September of 2008 and 2009. Numbers inside parentheses denote 1 s.d. and n=3 for all samples.

Sites	**Year**	**$\delta^{13}C$**	**$\delta^{15}N$**	**%N**	**C:N**
BCC 2670	2009	-27.1(0.3)	2.1(0.8)	1.82(0.10)	27.3(0.9)
BCC 2950	2009	-26.9(1.3)	-1.9(0.4)	2.35(1.25)	21.2(2.1)
CCC 2070	2008	-26.6(1.1)	1.3(1.3)	2.50(0.11)	19.8(1.7)
Neffs 2370	2009	-26.6(0.2)	-1.7(0.1)	2.04(0.60)	24.7(5.0)
Neffs 2740	2008	-26.8(0.9)	-2.0(0.2)	2.32(0.17)	21.7(2.9)
Neffs 2740	2009	-26.9(0.3)	-1.7(0.9)	2.21(0.19)	22.2(0.9)
Neffs 2790	2008	-23.6(0.6)	-1.4(0.3)	2.22(0.14)	22.1(1.7)

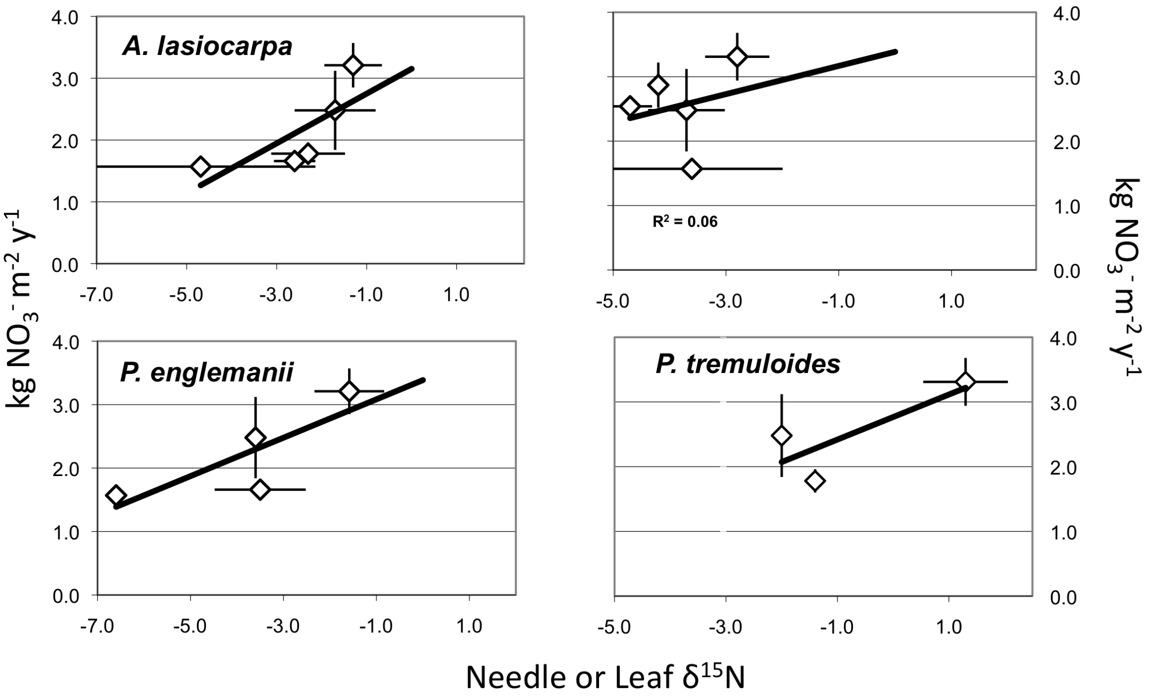

Figure 5. Linear regressions between foliar δ^{15}N and winter nitrate deposition during 2008. Winter nitrate deposition was measured at peak snowpack in 2008 as mass of nitrate per ground area. Leaf and need samples from *Abies lasiocarpa, Pseudotsuga menziesii, Picea engelmannii* and *Populus tremuloides* were collected in late August to early September 2008. Both foliar δ^{15}N and winter nitrate deposition nitrate deposition are the mean of three independent samples. Error bars represent 1 s.d.

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