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Impacts of anthropogenic emissions and cold air pools on urban to montane gradients of snowpack ion concentrations in the Wasatch Mountains, Utah

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HIGHLIGHTS

- We measured ions in snow across urban – natural sites experiencing air pollution.
- Ion deposition increased over time with atmospheric particulate concentrations.
- Fog/dry ion deposition was greatest at intermediate elevations.
- Ion concentrations in fresh snow decreased by 4–130 fold from urban to remote sites.

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ABSTRACT

Urban montane valleys are often characterized by periodic wintertime temperature inversions (cold air pools) that increase atmospheric particulate matter concentrations, potentially stimulating the deposition of major ions to these snow-covered ecosystems. We assessed spatial and temporal patterns of ion concentrations in snow across urban to montane gradients in Salt Lake City, Utah, USA, and the adjacent Wasatch Mountains during January 2011, a period of several persistent cold air pools. Ion concentrations in fresh snow samples were greatest in urban sites, and were lower by factors of 4–130 in a remote high-elevation montane site. Adjacent undeveloped canyons experienced significant incursions of particulate-rich urban air during stable atmospheric conditions, where snow ion concentrations were lower but not significantly different from urban sites. Surface snow ion concentrations on elevation transects in and adjacent to Salt Lake City varied with temporal and spatial trends in aerosol concentrations, increasing following exposure to particulate-rich air as cold air pools developed, and peaking at intermediate elevations (1500–1600 m above sea level, or 200–300 m above the valley floor). Elevation trends in ion concentrations, especially NH_4^+ and NO_3^-, corresponded with patterns of aerosol exposure inferred from laser ceilometer data, suggesting that high particulate matter concentrations stimulated fog or dry ion deposition to snow-covered surfaces at the top of the cold air pools. Fog/dry deposition inputs were similar to wet deposition at mid-elevation montane sites, but appeared negligible at lower and higher-elevation sites. Overall, snow ion concentrations in our urban and adjacent montane sites exceeded many values reported from urban precipitation in North America, and greatly exceeded those reported for remote snowpacks. Sodium, Cl^-, NH_4^+, and NO_3^- concentrations in fresh snow were high relative to previously measured urban precipitation, with means of 120, 117, 42, and 39 μeq l^{-1}, respectively. After exposure to atmospheric particulate matter during cold pool events, surface snow concentrations peaked at 2500, 3600, 93, and 90 μeq l^{-1} for these ions. Median nitrogen (N) deposition in fresh urban snow samples measured 0.8 kg N ha^{-1} during January 2011, with similar fog/dry deposition inputs at mid-

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elevation montane sites. Wintertime anthropogenic air pollution represents a significant source of ions to snow-covered ecosystems proximate to urban montane areas, with important implications for ecosystem function.

1. Introduction

Snow represents the dominant form of precipitation in many arid montane regions and provides a primary source of nutrient ions to ecosystems, with potentially detrimental impacts on water quality and ecosystem function when ion inputs are enhanced by anthropogenic emissions (Lewis et al., 1983; Cerling and Alexander, 1987; Jeffries, 1990; Williams and Tonnessen, 2000). In particular, nitrogen (N) inputs from atmospheric deposition can contribute to undesired increases in productivity, species changes, and aquatic eutrophication, especially in seasonally snow-covered environments where nutrients rapidly elute during melting (Jeffries, 1990; Williams and Tonnessen, 2000; Baron et al., 2011). Many studies of snow chemical composition over the past three decades have explicitly avoided measurements of urban emission hot-spots (Jeffries, 1990; Nickus et al., 1997), instead focusing on remote wilderness sites (Williams and Melack, 1991; Pomeroy et al., 1999; Kang et al., 2004; Williams et al., 2009). Cities often exhibit higher ion concentrations and fluxes in rainfall and dry deposition relative to adjacent areas, with trends varying among chemical species (e.g. Lewis et al., 1984; Gatz, 1991; Fenn et al., 2003). However, urban ion deposition studies have typically focused on summer rainfall (Lovett et al., 2000; Bettez and Groffman, 2013; Rao et al., in press), and very few comprehensive measurements of snow ions have been reported in urban environments (Lewis et al., 1983). Little is known about spatial and temporal variation in ion deposition to snow across urban to rural gradients, and whether snow ion concentrations vary systematically with urban proximity as observed for rainfall. Even less is known about temporal couplings between urban air pollution events and ion inputs to snow. These patterns may be critical for understanding and predicting nutrient inputs to seasonally snow-covered ecosystems.

Wintertime meteorological characteristics of urbanized montane valleys have the potential to significantly increase snowpack ion loading in wet, dry, and cloud deposition. High pressure events persisting for days to weeks often stabilize cold air pools, trapping local anthropogenic emissions, and leading to the accumulation of ion-rich primary and secondary fine particulate matter (PM 2.5) in the atmosphere (Silcox et al., 2012; Kelly et al., 2013; Lareau et al., 2013; Whiteman et al., 2014). These conditions prevail in many rapidly growing metropolitan areas in the Western United States (e.g. Salt Lake City, Utah; Boise, Idaho; Reno, Nevada) and physiographically similar regions worldwide (e.g. Santiago, Chile; Chen et al., 2012; Cereceda-Balic et al., 2012). Cold air pools associated with elevated PM 2.5 also occur in non-mountainous regions over shorter timescales (e.g. Wallace and Kanaroglou, 2009), and could thus represent a widely important phenomenon for wintertime urban ion deposition.

Empirical studies linking atmospheric aerosol concentrations with ion deposition remain uncommon, especially for snow (Yalcin et al., 2006; Dolislager et al., 2012). Ammonium nitrate and ammonium sulfate originating from anthropogenic precursors—ammonia, nitrogen oxides, and sulfur dioxide—comprise the majority of PM 2.5 in many urban areas (Hand et al., 2012; Kelly et al., 2013). The impact of urban atmospheric emissions and particulate matter on snowpack ion loading is largely unknown, but Cerling and Alexander (1987) documented extremely high concentrations of ions in rime and snow at sites in and adjacent to Salt Lake City during a prolonged cold air pool in 1985. Dry and fog deposition of gases and particles to snow-covered surfaces have previously been shown to comprise relatively minor sources of ions in comparison with snowfall (Bergin et al., 1995; Björkman et al., 2013). Rather, net losses of NO_3^- from the snowpack between precipitation events can be significant (Williams and Melack, 1991; Pomeroy et al., 1999; Williams et al., 2009). However, this subject has received little attention in urban environments, where elevated aerosol concentrations during cold air pools could enhance dry or cloud deposition in addition to wet deposition, and yield ecologically significant fluxes of ions to the snowpack.

Here, we assessed spatial and temporal patterns of ion concentrations in bulk snow and snow surface samples across urban to montane gradients in Salt Lake City, Utah, USA, and the adjacent Wasatch Mountains. This major metropolitan area experiences frequent wintertime atmospheric temperature inversions that promote particulate matter accumulation over time, yielding PM 2.5 concentrations that routinely violate national ambient air quality standards (Silcox et al., 2012; Kelly et al., 2013; Whiteman et al., 2014). We demonstrated that urban air pollution associated with cold air pools significantly affected spatial and temporal patterns of snow ion concentrations, with implications for water quality and ecosystem function.

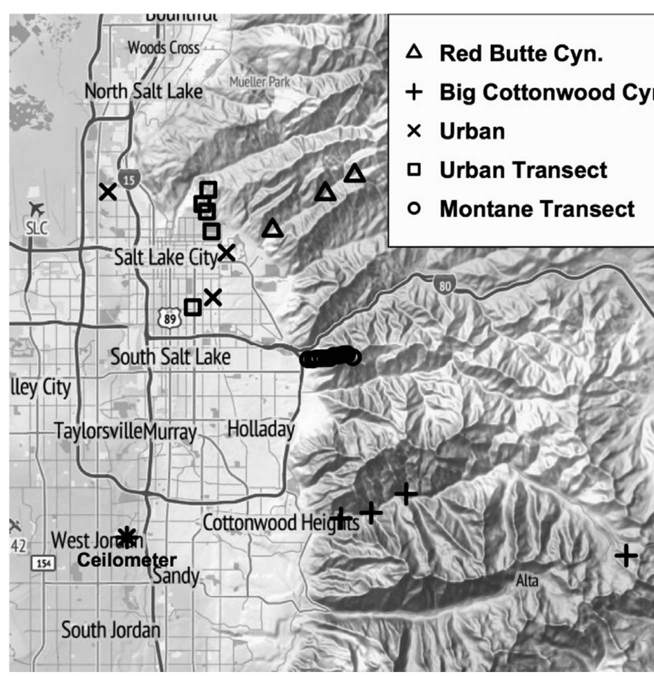

Fig. 1. Sampling locations in the Salt Lake Valley metropolitan area and adjacent Wasatch Mountains. Triangles, pluses, and × marks denote stormboards in Red Butte Canyon, Big Cottonwood Canyon, and urban sites, respectively. Squares and circles denote urban and montane elevation transects. The asterisk represents the laser ceilometer.