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Black Carbon Concentrations in Snow at Tronsen Meadow in Central Washington from 2012 to 2013: Temporal and Spatial Variations and the Role of Local Forest Fire Activity

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Key Points:
- Spatial variability of snow BC concentrations was constrained on the sub-100 m scale
- BC in the snowpack increases during spring from higher atmospheric BC and melt
- Charred tree postwildfire results in higher BC concentrations in the snowpack

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Black carbon concentrations in snow at Tronsen Meadow in Central Washington from 2012 to 2013: Temporal and spatial variations and the role of local forest fire activity

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Abstract Characterizing black carbon (BC) concentrations in the seasonal snowpack is of interest because BC deposition on snow can reduce albedo and accelerate melt. In Washington State, USA snowmelt from the seasonal snowpack provides an important source of water resources, but minimal work has been done characterizing BC concentrations in snow in this region. BC concentrations in snow were monitored over two winters (2012 and 2013) at Tronsen Meadow, located near Blewett Pass in the eastern Cascade Mountains in Central Washington, to characterize spatial and temporal variations in BC concentrations, and the processes affecting BC concentrations in the snowpack. BC concentrations were measured using a Single Particle Soot Photometer. Snowpit BC concentrations at spatial scales ranging from centimeter to 100 m scales were fairly homogenous during the accumulation season, with greater spatial variability during the melt season due to variable melt patterns. BC concentrations in snow increased in late winter-spring due to an increase in atmospheric BC concentrations and trapping of BC on the snow surface during melt. However, during a period of intense melt in 2013 BC concentrations decreased, likely caused by meltwater scavenging. In summer 2012 the Table Mountain forest fire burned adjacent to the study site, and BC concentrations in the snowpack in 2013 were far higher than in previous years, with charred trees postfire the likely source of the elevated BC.

1. Introduction

In the Western United States (U.S.) the seasonal snowpack acts as the largest reservoir of water storage, releasing water during the spring-summer when water demands are greatest [*Mote et al.*, 2005]. Widespread declines in the spring snowpack have occurred in the Western U.S. since the mid-20th century, affecting the availability of water resources. The snowpack decline is greatest in the Cascades, where there has been a 29% reduction in the 1 April snow water equivalent (SWE) from the 1945–1955 period to the 1990's [*Mote et al.*, 2005]. This trend is likely to persist as temperature increases of roughly 1.8°C are projected to result in a 1 April SWE reduction of 38 to 46% by the 2040's [*Elsner et al.*, 2010].

Observed and projected changes to the spring snowpack are most commonly attributed to rising temperatures; however, black carbon (BC) in the seasonal snow may be another factor contributing to the declining snowpack. BC is a dark absorptive particle produced by the incomplete combustion of fossil and biofuels and is second only to CO_2 in its contribution to climate warming [*Bond et al.*, 2013]. BC in the atmosphere absorbs light and causes atmospheric heating, whereas BC deposited on snow and ice reduces the albedo (i.e., reflectivity), leading to increased energy absorption and accelerated melt [*Hansen and Nazarenko*, 2004; *Warren and Wiscombe*, 1980].

The majority of previous research investigating BC concentrations in snow and ice has focused on the Arctic [e.g., *Clarke and Noone*, 1985; *Hegg et al.*, 2009] or Himalayas [e.g., *Kaspari et al.*, 2011, 2014; *Xu et al.*, 2009]; however, BC may also be affecting the snowpack and water resources in the Western U.S. A modeling study that simulated deposition of BC on snow in the Western U.S. indicated that BC is contributing to a decrease in spring snow water equivalent (SWE) and a shift to earlier peak runoff [*Qian et al.*, 2009], but there have been few observational studies to constrain BC concentrations in this region. *Hadley et al.* [2010] and *Sterle et al.* [2013] reported BC concentrations for the Sierra Nevada. No BC field measurements have existed for the Cascades with the exception of limited measurements from the 1980s [*Clarke and Noone*, 1985;

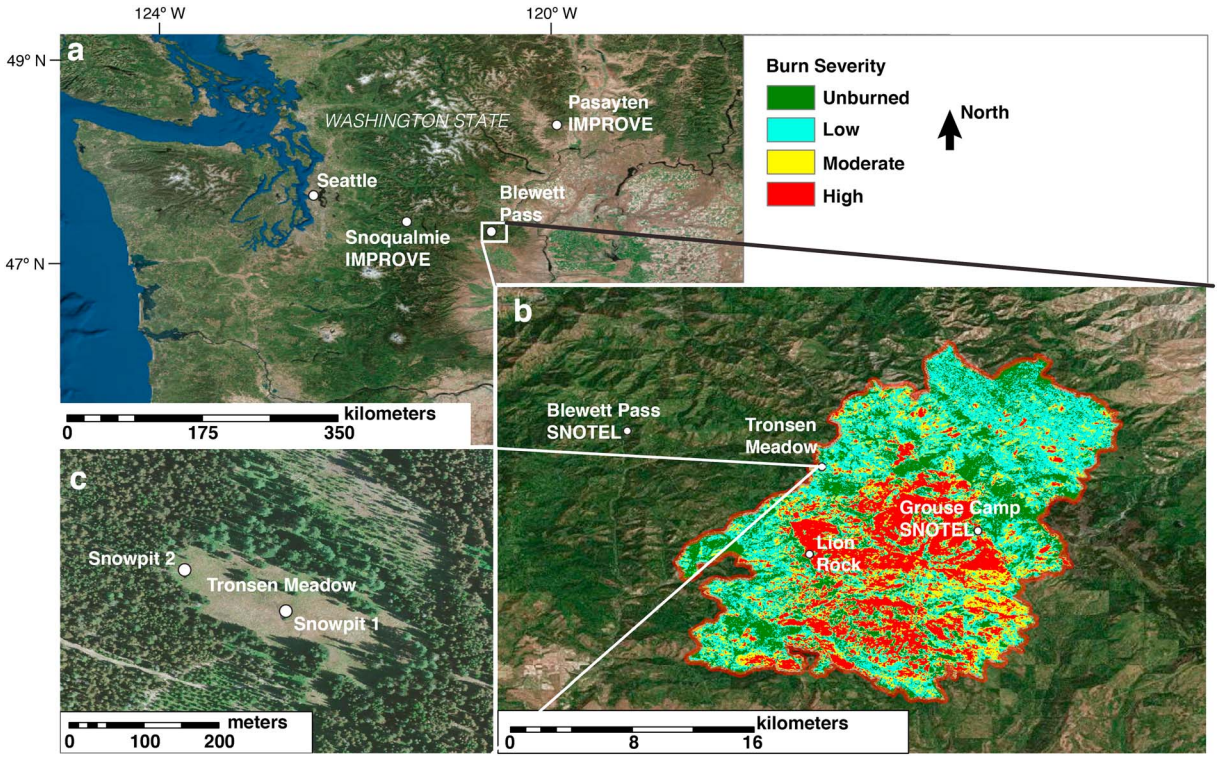

Figure 1. Map of the study area. (a) Location in Washington State, USA, of the Blewett Pass study area and Snoqualmie and Pasayten IMPROVE sites. (b) Burn severity map of the Table Mountain fire during 2012, and location of the Tronsen Meadow and Lion Rock study areas and the Blewett Pass and Grouse Camp SNOTEL sites. Burn severity is detailed in *Liu et al.* [2011]. (c) Snowpit locations within Tronsen Meadow.

Grenfell et al., 1981] and a recent study that linked BC deposition from wildfire with accelerated melt on Snow Dome on Mount Olympus in Washington State [*Kaspari et al.*, 2015]. As water availability in this region is dependent on persistent snowmelt through the summer months to maintain streamflow [*Vano et al.*, 2010; *Nolin and Daly*, 2006], assessing BC's characteristics in the Cascade snowpack is imperative.

By measuring BC concentrations in snow samples collected over four winters (November 2009 to May 2013) from a snow study site at Tronsen Meadow, near Blewett Pass, Washington, on the eastern slope of the Cascade Mountain Range, we begin to characterize BC in Washington's seasonal snowpack. Specifically, we examine BC spatial variability, seasonal evolution of BC in the snowpack, BC interannual variability, depositional and postdepositional processes affecting BC concentrations in the snowpack, and the effects of local forest fire activity. These findings will help assess the contribution of BC in decreased seasonal snowpack in the Cascade Mountains. Additionally, this research contributes to efforts to characterize BC in midlatitude snowpacks and enhances understanding of the processes controlling BC concentrations in the snowpack.

2. Site Description and Methods

2.1. Site Description

In November 2009 a snow study site was established in Tronsen Meadow near the summit of Blewett Pass (47.322°, −120.578°, 1295 m) on the east slope of the Cascade Mountains in Washington State (Figure 1). In March of 2013 snow samples were also collected from Lion Rock (~8.5 km south of Tronsen Meadow), an area burned during a forest fire in summer of 2012. Data pertaining to snow depth, snow water equivalent (SWE), temperature, and precipitation were obtained from the Blewett Pass SNOpack TELemetry (SNOTEL) site located 7 km west of Blewett Pass and maintained by the Natural Resource Conservation Service. For analysis of the Lion Rock sampling site, data from the Grouse Camp SNOTEL site were used. Average peak SWE at the Blewett Pass SNOTEL was 42 cm from 2004 to

2013, and average measured peak snow depth in Tronsen Meadow was 80 cm and 75 cm during 2012 and 2013, respectively. The average winter (1 November to 30 April) temperature at the Blewett Pass SNOTEL is −0.4°C and westerly winds dominate. This region of the Cascade Mountains is colder, drier, and generally receives less snow compared to the western slope of the range.

2.2. Snow Sampling

Snow samples were collected from the Tronsen Meadow snow study site during the snow-covered season between November 2011 and May 2013. Herein 2012 and 2013 refer to the 2011–2012 and 2012–2013 snow seasons, respectively. Snow samples were collected once a week in 2012 and one or two times a month in 2013. We collected snow samples weekly during the 2010 and 2011 snow seasons. However, data from these winters are not reported herein because the samples were not stored in a frozen state prior to analysis, resulting in substantially underestimated BC concentrations [*Wendl et al*., 2014].

Snowpits were dug with a shovel, and a clean plexi-glass scraper was used to remove the outer 5 cm of the snowpit wall to provide a clean and uncontaminated surface from which to collect samples. Subsequent snowpit sampling was conducted by removing ~60 cm of snow behind the wall of the previous snowpit sampling surface. Snow samples from the snowpits were collected continuously at 5 cm vertical resolution directly into 50 mL polypropylene sample vials. In low-density snow the side of the vial was tapped to consolidate the snow and allow collection of sufficient sample. In addition to snowpit samples, surface snow samples were collected by scraping a 50 mL polypropylene vial across the top 1–2 cm of the snow, where light-absorbing impurities influence albedo the most [*Painter et al*., 2012]. Polypropylene gloves were worn at all times during sampling, and care was taken to ensure that clothing fibers did not come in contact with the sample. Samples remained frozen until analysis.

During the 2012 season additional sampling was conducted to characterize BC concentrations at various spatial scales and to determine how representative a given sample location is of a larger area (section 3.1). Three columns, 5 to 15 cm apart, were sampled within each snowpit to determine variations at scales less than 0.5 m. Additionally, comparison of samples between snowpits roughly 150 m apart (Figure 1) and surface samples collected greater than 10 m apart constrained local variability on those respective scales.

2.3. BC Analysis

BC concentrations in the snow samples were analyzed for BC using a Single Particle Soot Photometer (SP2; Droplet Measurement Technologies, Boulder, CO) housed at Central Washington University. The SP2 uses laser-induced incandescence to measure the BC mass in individual particles (between 80 and 500 nm diameter in this study) quantitatively and independent of particle morphology and coatings with light scattering material [*Slowik et al*., 2007; *Schwarz et al*., 2006; *Stephens et al*., 2003]. The SP2 detects the mass concentration of refractory BC, sometimes referred to as rBC [*Petzold et al*., 2013]; the term BC is used here for simplicity. Other absorbing aerosol components such as mineral dust are generally not detected by the SP2, with the exception of when dust is present in very high concentrations (on the order of mg/L) [*Schwarz et al*., 2012]. This does not apply to this study as dust concentrations were not this high.

Snow samples were melted by submersion of the sample vial in warm water just prior to analysis. Subsequently, the melted samples were sonicated for 15 min. During BC analyses the samples were mixed using a magnetic stirrer, nebulized using a Cetac U-5000AT+ ultrasonic nebulizer, and the resultant aerosol was introduced to the sample inlet of the SP2. Gas Expansion TruFlo monitors were used to monitor the fraction of the liquid sample that was nebulized. Raw SP2 data were collected using Droplet Measurement Technologies' SP2 Acquisition Software version 4.1, and BC concentrations in the liquid snow samples were determined using Paul Scherrer Institut's SP2 toolkit 4000. Aqueous Aquadag (Acheson, USA, a graphite based lubricant) solution passed through a differential mobility analyzer was used to calibrate the incandescent light of a BC particle measured by the SP2 to the mass of the particle (referred to as internal calibration by *Wendl et al*. [2014]). All samples were blank corrected based on deionized water (~18 Ωm) method blanks, and measured concentrations were corrected based on Aquadag standard solutions to account for BC losses that occur in the nebulizer. *Wendl et al*. [2014] and *Kaspari et al*. [2014, and references therein] provide further details on the SP2 methodology.

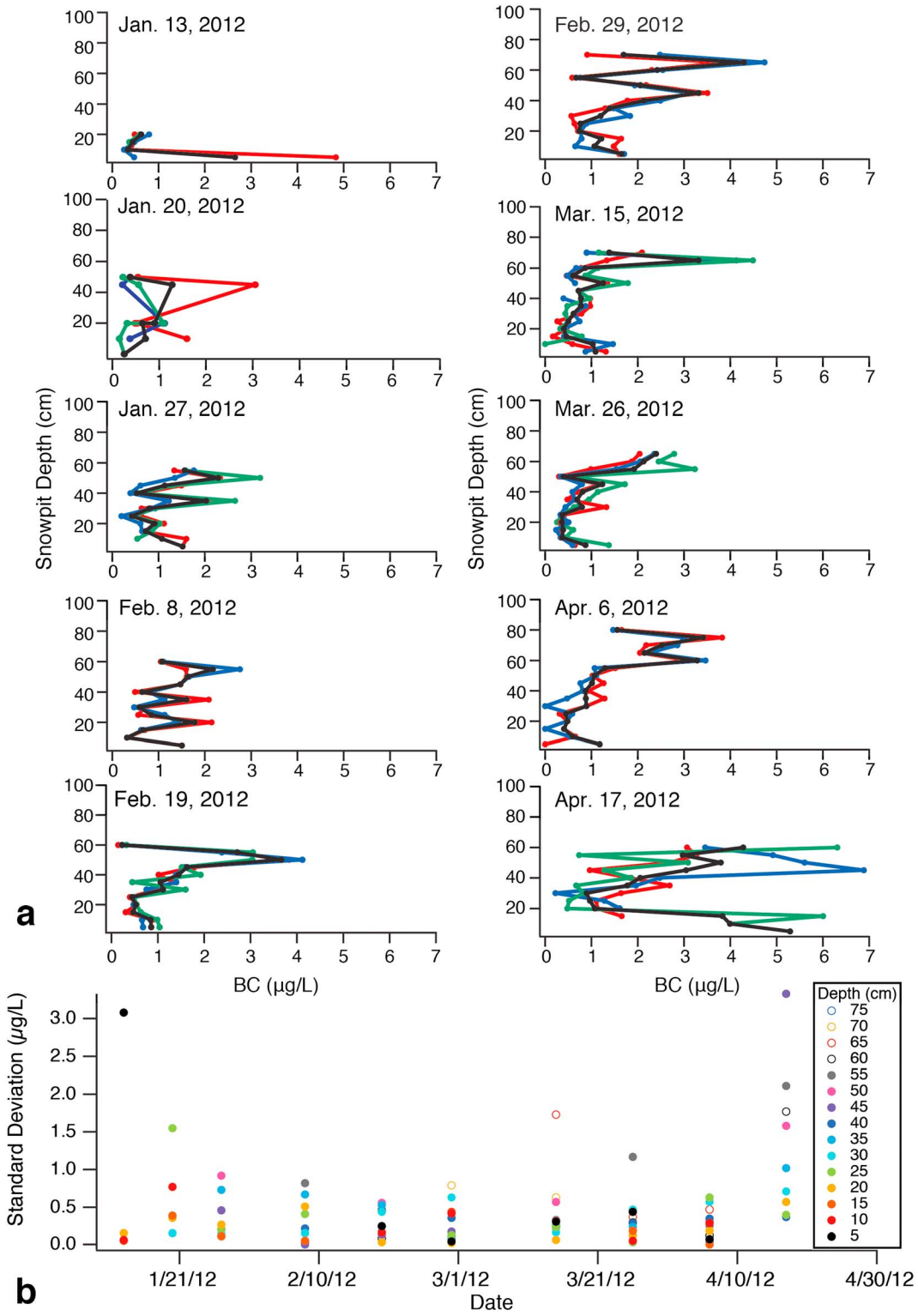

Figure 2. BC concentrations in Tronsen Meadow snowpit 1 during winter 2012. Vertical axes show snowpit depth (0 is ground surface); horizontal axes represent BC concentration. Colored lines represent individual sampling columns in the snowpit, while black lines represent average BC concentration for a given height in the snowpit.

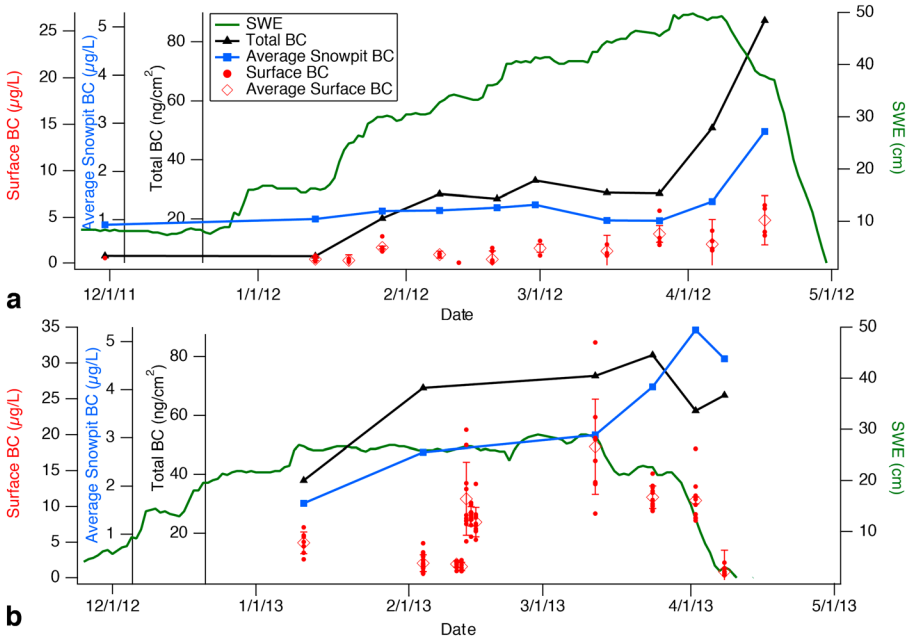

Figure 3. Tronsen Meadow BC concentrations in surface snow and total BC for 2012 and 2013. Diamonds represent average BC concentrations, with error bars at 1 standard deviation. SWE data are from the Blewett Pass SNOTEL (Figure 1).

3. Results and Discussion

3.1. Spatial Variability

Spatial variability in impurity deposition is visibly evident on high alpine snowpacks and midlatitude glaciers during the ablation season when concentrations of impurities are relatively high but are not visibly evident during the winter when impurity concentrations are lower. Previous research [*Betterton*, 2001; *Rhodes and Warren*, 1987] has documented that during periods of melt, impurities on the snow surface can migrate and concentrate in areas, explaining the spatial variability evident during the ablation season. However, minimal information exists regarding local scale variably in impurity concentrations in the snowpack during the accumulation season and snow deposition events. Sampling at 5 cm to 100 m spatial scales during the 2012 season was conducted to characterize spatial variability in BC concentrations in snow in Tronsen Meadow during the accumulation season as well as during melt and to address the spatial representativeness of an individual snow sample.

BC concentrations in snow sampled from equal heights and 5 to 15 cm apart within snowpits show relative consistency (Figure 2). One standard deviation (σ) of the three columns within one snowpit is generally less than 1 μg/L (25% difference from the average) for the accumulation season, showing rather homogeneous deposition of BC within the snowpack. This suggests that variations on the sub-half-meter scale are minimal during the accumulation season, and observations from a single profile in a snowpit are representative of this spatial scale. However, σ of the columns increased, in some cases above 3 μg/L, once snowmelt initiated (Figure 2; 17 April 2012). The increase in BC variability during the melt period could be due to scavenging processes, consolidation of the snowpack during melt, and/or preferential flow of meltwater during snowmelt (discussed in section 3.2.2).

BC spatial variability was assessed on the tens of meter scale using surface snow samples (Figure 3). During the accumulation season in 2012, spatial variability of BC concentrations in surface samples was relatively low, with 1 σ of the surface samples collected on a given day generally less than 1 μg/L and less than 25% variation from the same surface samples' average concentration. Spatial variability increased in late March–April coincident with melt events. During 2013 surface snow BC concentrations were spatially more variable during both the accumulation and melt seasons, with 1 σ of surface sample collected on a given day as high as 5 μg/L and 50% deviation from the same surface samples' average concentration (e.g., surface samples collected on February 2013 and on 12 March 2013 show this large variation; Figure 3). The greater

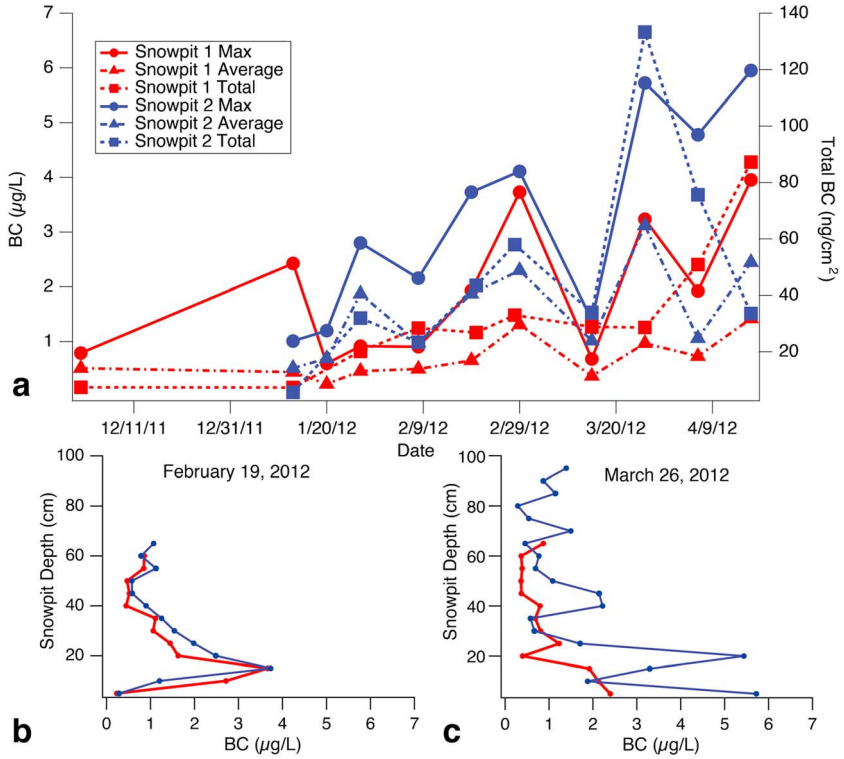

Figure 4. Comparison of Tronsen Meadow snowpits during the 2012 season. (a) Average, maximum (both left *y* axis) and total BC concentrations (right *y* axis) in snowpits 1 and 2. (b and c) Profiles from snowpit 1 (red) and snowpit 2 (blue) on 19 February 2012 and 26 March 2012, respectively.

range of BC concentrations in 2013 compared to 2012 is likely related to prolonged periods without snowfall and/or melt, while the lower snow accumulation and the effects of a local forest fire (section 3.3) in 2013 would contribute to the higher BC concentrations. These results suggest that during periods of time with frequent snowfall surface snow BC concentrations may be more homogenous relative to dry periods. However, additional processes likely contribute to surface snow BC variability. For example, during the period 11–15 February 2013 we conducted daily sampling. On 13 February there was a rapid increase in BC concentrations coincident with a melt event identified from the Blewett Pass SNOTEL snow height and temperature data. However, we found no explanation for the subsequent drop in BC concentrations and σ after 13 February. To further characterize processes affecting BC spatial variability, future studies should collect a greater number of surface samples at more frequent time intervals, particularly during prolonged periods without precipitation.

In 2012 two snowpits on opposite sides of Tronsen Meadow (150 m apart) were used to compare BC concentrations at this spatial scale (Figure 4). At the beginning of the season snow accumulation in snowpits 1 and 2 was comparable; however, by the end of the accumulation season the snow depth in snowpit 2 was ~1.5 times greater than in snowpit 1 (Figure 4c). The higher snow accumulation in snowpit 2 is likely the result of lee deposition and formation of a small snowdrift near the forested edge of the meadow (Figure 1c). The differing snow accumulation between snowpits makes direct stratigraphic comparison of the snowpits difficult, so average and maximum BC concentrations from each were used to investigate spatial variations between the snowpits. Additionally, by calculating total BC content in the snowpack, variations in snow accumulation can be accounted for. The total BC metric quantifies the amount of BC deposited over a given area of the snowpack, independent of snow depth:

$$BC_{total} = BC_{avg} \times \rho \times D$$

where BC_{total} is the total deposited BC in ng/cm^2, BC_{avg} is the average BC concentration in the snowpit (ng/g), ρ is the density of the snowpack determined from the Blewett Pass SNOTEL and confirmed by field

measurements, and D is the snowpit depth (cm). Total BC provides a measure of BC deposited in the snowpack independent of snow accumulation and is useful to investigate processes that integrate or remove BC from the snowpack. Total BC differs from BC concentration, as BC concentration influences snow surface albedo and is affected by snow quantity.

Average and maximum BC concentrations in the two snowpits on opposite sides of the meadow (Figure 1c) show similar trends ($n = 10$, $r^2 = 0.55$, $P > 0.01$ for maximum BC concentration; $r^2 = 0.58$, $P > 0.01$ for average concentration; $r^2 = 0.12$ for total BC, $n = 9$) over the course of the season, although BC concentrations in snowpit 2 are higher (Figure 4). Differences in total BC between the snowpits that emerge in late March could be due to differing melt patterns. Additionally, higher total BC in snowpit 2 in late March may be the product of higher snow depth in snowpit 2 providing more BC to the snowpack through greater quantities of snow.

Based on sampling on the centimeter to 100 meter scale, BC concentrations in surface and subsurface snow appear to be relatively homogenous prior to the spring melt. Increases in spatial variability that occur with melt are associated with higher BC concentrations and are likely the result of heterogeneous snow deposition and snowmelt, not directly variable BC deposition. Due to the consistent nature of BC in the snowpack prior to melt, samples collected during the accumulation season are likely representative of a larger area (at least up to 100 m), provided that the sample is from a representative area not subject to uncharacteristic wind scouring or lee deposition. However, increased variability of BC concentrations in surface samples evident during melt and prolonged periods without precipitation indicate that in these circumstances more intensive sampling is required to characterize local variability.

3.2. Seasonal Variations

BC data collected over 2 years (2012–2013) during the winter and spring months at Tronsen Meadow show notable seasonal patterns. During both seasons, average BC concentrations increased at a relatively slow rate during the snow accumulation season, reaching a maximum just after peak SWE, when snowmelt initiated (Figure 3). Total BC increased prior to snowmelt, usually at a more rapid rate, showing that although the BC concentrations were relatively low during the accumulation season, the snowpack gained BC during this period of time. During 2013 sampling extended through the entire melt season, providing insight into the evolution of BC during melt. Once the spring snowmelt initiated in 2013, average BC concentration increased slightly and total BC decreased in the snowpack (Figure 3).

3.2.1. Processes Affecting Black Carbon Concentrations in the Snowpack

BC is integrated into the snowpack by dry and wet deposition. Dry deposition occurs when atmospheric particles fall directly onto the snowpack in the absence of rain or snow. Conversely, wet deposition integrates BC and other impurities into the snowpack by removing particles from the atmosphere during precipitation events by assimilation in and on snow crystals or raindrops [*Hadley et al*., 2010]. Attempts to constrain the dominant mode of deposition of BC in to the snowpack at Tronsen Meadow proved inconclusive. However, daily, high-resolution sampling of the snow surface during a 5 day dry period (11–15 February 2013) to constrain dry deposition showed minimal increases (<1 μg/L) attributed solely to dry deposition (Figure 3). Additionally, given the high frequency of precipitation in the region, it is likely that wet deposition contributes the majority of BC to the snowpack.

Mechanical trapping and scavenging are postdepositional processes that can affect BC concentrations in the snowpack, especially during the melt period (Figure 3). Previous studies have documented that impurities can become trapped and integrated at the surface of the snowpack during melt and sublimation, enriching surface concentrations [*Conway et al*., 1996; *Painter et al*., 2012]. During both 2012 and 2013, BC concentrations in the surface snow and subsurface were enriched during the initial spring snowmelt, suggesting mechanical trapping of BC at the surface and within the snowpack (this was also observed during the 2010 and 2011 sampling seasons, although data from these years are not reported in this publication as discussed in section 2.2). In addition to mechanical trapping from melt, sublimation could also concentrate BC. Sublimation has been found to reduce snowpack height by up to 10 mm per month in maritime snowpacks [*Fassnacht*, 2004]. This potentially concentrates BC in the snowpack during the winter months, whereas snowmelt concentrates BC on the snow surface later in the season (March–April).

Scavenging of BC by entrainment of particles by meltwater has been shown to remove BC from the snowpack during periods of rapid melt [*Xu et al*., 2012; *Conway et al*., 1996; *Doherty et al.* [2013]]. Scavenging may have

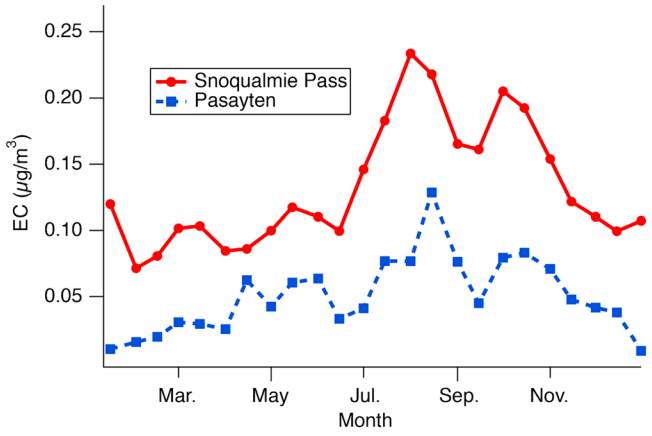

Figure 5. Median atmospheric elemental carbon (EC) concentrations (2004–2013) from the Snoqualmie Pass and Pasayten IMPROVE sites. Data from 2006 were excluded due to anomalously high concentrations.

occurred in spring 2013 when total BC decreased with the onset of snowmelt in late March. At the next sampling event on 2 April 2013 enough BC was removed to lower the average snowpit BC concentration (Figure 3). This process was not observed during the 2012 season. However, it may have taken place during the final stages of melt that spring, which was not captured due to foreshortened sampling. It is conceivable that during periods of very rapid melt, or liquid precipitation (which introduces water to the snowpack), large amounts of impurities could be scavenged from the snow surface, increasing albedo and slowing melt [*Conway et al.*, 1996]. However, because melt is associated with an increase in snow grain size and a reduction in albedo [*Warren and Wiscombe*, 1980], further high-resolution sampling of BC and other impurities in the snowpack and changes in snow grain size during high melt and liquid precipitation conditions are needed to test this hypothesis in the natural environment (*Conway et al.* [1996] used synthetic, hydrophobic soot). This process could be important on alpine snowpacks and glaciers that undergo extended periods of intense melt during the summer months or rain on snow events.

High BC concentrations (286 μg/L) were observed at the end of the melt season in 2010 following an extended period of snowmelt (61 days from peak SWE to melt out compared to 35 days from peak SWE to melt out in 2013) (data from 2010 not shown here due to sample storage (section 2.2)). This suggests that slow snowmelt can maximize mechanical trapping of BC, reduce scavenging, and substantially increase BC concentrations in the snowpack.

3.2.2. Influence of Atmospheric Elemental Carbon Concentrations and SWE on Snowpack BC Concentrations

Prior studies have found that BC concentrations in the snowpack are strongly linked to atmospheric concentrations [*Hadley et al.*, 2010]. To examine the relationship between atmospheric BC concentrations and those observed in the Tronsen Meadow snowpack, regional atmospheric elemental carbon (EC) concentrations from the IMPROVE (Interagency Monitoring of Protected Visual Environments) network were used. EC is used to describe thermal-chemical characteristics of the aerosol, whereas BC describes optical properties. Although determined using different methods, EC can be a proxy for BC [*Andreae and Gelencser*, 2006]. The Pasayten IMPROVE site (48.388°N, 119.927°W, 1627 m) is located ~130 km north of Tronsen Meadow and experiences a similar climatic regime. The Snoqualmie Pass site (47.422°N, 121.426°W, 1049 m) is closer to Tronsen Meadow (~65 km), but as it lies to the west near the Cascade Crest, it experiences different storm patterns and greater precipitation. Atmospheric EC concentrations at both sites are generally lowest during the winter months and peak during the summer months (Figure 5). Lower winter atmospheric EC concentrations are likely due to the high frequency of precipitation events during the winter and the propensity of precipitation to remove EC from the atmosphere [*Baltensperger et al.*, 1998; *Hadley et al.*, 2010]. BC emissions from wood burning for residential heating could be elevated during the winter months [i.e., *Kim et al.*, 2007]. However, it seems unlikely that these emissions greatly influence BC in the snowpack at Tronsen Meadow. This is likely due to remoteness from nearby communities, infrequent formation of inversions (that allow for the buildup of atmospheric BC) due to the relatively high elevation of Tronsen Meadow, and the low BC concentrations observed in the snowpack during this period of time. Causes for the higher atmospheric concentrations during the spring and summer months include lower precipitation rates, increased height of the planetary boundary layer which enables BC to be transported to higher elevations [*Lugauer et al.*, 1998], and forest fire activity.

Seasonal BC concentrations in snow at Tronsen Meadow, including surface snow concentrations and snowpit average and maximum concentrations, increase coincident with atmospheric concentrations (Figures 3 and 5).

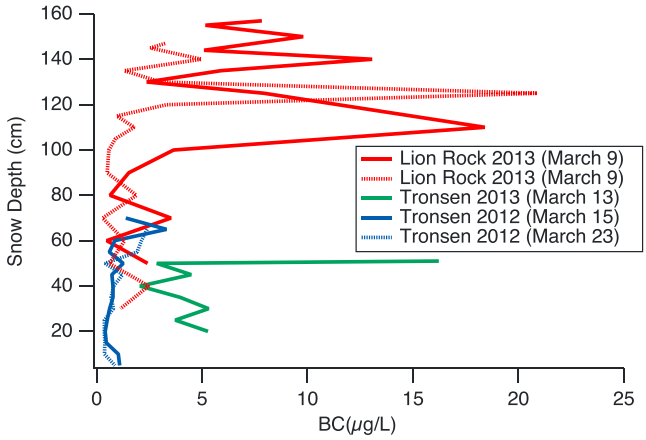

Figure 6. Black carbon concentrations in snowpits from Tronsen Meadow and the severely burned Lion Rock area. Snow depth 0 represents the ground for each snowpit.

Low BC concentrations found in the snow mimic the low EC concentrations found in the atmosphere prior to March, and the increase in snow BC concentrations during the later spring months is generally simultaneous with increased atmospheric concentrations. Increases in BC concentrations in the snowpack prior to peak SWE are gradual and likely the result of wet and dry deposition that move atmospheric BC to the snowpack. The increase in BC concentrations in the snowpack, once the spring melt has initiated, is rapid enough that postdepositional process (discussed above), such as mechanical trapping, is likely the cause.

Atmospheric measurements from the IMPROVE network data likely do not capture local-scale variability in atmospheric EC as it applies to BC in the Tronsen's snowpack. Additionally, atmospheric concentrations from the IMPROVE network could be affected by precipitation events that remove BC from the atmosphere [e.g., *Hadley et al.*, 2010], lowering atmospheric concentrations but increasing the quantity of BC in the snowpack. It is assumed that local atmospheric BC concentrations are manifested in the snow by the total BC measurements, because this metric is not influenced by the quantity of snow (see section 3.1).

SWE can have a strong effect on BC concentrations in the snowpack. Assuming a set amount of BC in the snowpack, an increase (decrease) in SWE will result in a decrease (increase) in snow BC concentrations. Thus, an increase in the BC concentration of snow could result from atmospheric inputs or a reduced amount of snow. As a result, examination of the causes of the observed seasonal increase in the snow's BC concentration, from either atmospheric increases or changes in SWE, is needed. At Tronsen meadow, BC concentrations in the snow correlate more strongly with atmospheric BC ($n = 46$, $r^2 = 0.73$, $P < 0.001$; inferred from total BC) than with SWE ($n = 46$, $r^2 = 0.30$, $P < 0.01$); n is the number of sampling events. This suggests that the observed increases in BC concentration in snow in the late winter-spring are controlled more so by increased atmospheric EC concentrations observed at the IMPROVE stations (Figure 5) than reduced SWE.

3.3. Local Forest Fire Events as a Possible Source of Black Carbon

Two forest fires occurred in the vicinity of the study area in August and September of 2012. The Taylor Bridge fire (13 August to 28 August 2012; 95 km^2) burned in the Kittitas Valley southeast of Tronsen Meadow, and the Table Mountain Fire (8 September to 5 October 2012; 170 km^2) burned in the vicinity of Tronsen Meadow (Figure 1). The fire activity left charred material from the snags and burned vegetation that likely contributed BC to the snowpack during the 2013 winter via sloughing and wind entrainment. The sample site at Tronsen Meadow during 2013 exhibited a charred understory in the surrounding forested area. This site was classified as low burn severity [*Liu et al.*, 2011] using Monitoring Trends in Burn Severity maps [*Eidenshink et al.*, 2007]. The samples collected near Lion Rock were from a high burn severity area that contained heavily charred snags. Samples from Tronsen Meadow collected in 2012 were used to assess prefire BC concentrations.

BC concentration and total BC were substantially higher in the snowpits from the high burn severity sites at Lion Rock (97.5 ng/cm^2 and 156.8 ng/cm^2) when compared to snowpits from Tronsen Meadow (9 km away and low burn severity site) in 2013 (78.2 ng/cm^2) and the prefire environment in Tronsen Meadow during 2012 (Figure 6 and Table 1). One site at Lion Rock contained twice the total BC of the Tronsen Meadow site, and the total BC from 2012 in Tronsen Meadow was under half that of 2013 (Table 1).

Increased total BC in the snowpack in 2013, when compared to 2012, indicates the propensity for burned areas to provide BC to the snowpack even after the fire has been extinguished. Atmospheric concentrations

Table 1. Black Carbon (BC) Concentrations in Snow and Total BC With Respect to Burn Severity as Classified by *Liu et al.* [2011][a]

Location and Date	Burn Severity	Snowpit Average BC (in)	Snowpit Max BC (μg/L)	Surface BC (Top 1–5 cm) (μg/L)	Total BC (ng/cm^2)
Blewett: 15 March 2012	Prefire	1.1	3.1	1.4	33.4
Blewett: 26 March 2012	Prefire	1.0	2.4	2.4	28.6
Blewett: 12 March 2013	Low burn severity	3.3	10.4	10.4	78.2
Lion Rock 1: 9 March 2013	Proximal: high burn severity	2.4	18.4	12.2	156.8
Lion Rock 2: 9 March 2013	Proximal: high burn severity	1.6	13.8	3.3	96.7

[a]Data collected prior to the Table Mountain fire are classified as prefire.

of EC at the Pasaytan IMPROVE site were lower from 1 November 2012 to 30 March 2013 relative to 1 November 2011 to 30 March 2012, while atmospheric EC concentrations at the Snoqualmie Pass IMPROVE site were roughly equal between the 2 years. This suggests that elevated BC concentrations in the snowpack are from charred material resultant from forest fire activity as opposed to regionally elevated atmospheric concentrations.

Despite high BC concentrations and total BC in the burn area, the bottom sections of the snowpits at Lion Rock displayed relatively low BC concentrations (Figure 6). The lack of ice layers and consistent snow grain structure in this part of the snowpack suggested that this portion of the snowpack accumulated during a single storm, or multiple storms in rapid succession, most likely during mid-December 2012. High snow storm occurrence would lead to lower BC concentrations in the snowpack due to atmospheric BC having already largely been scavenged, and greater snow accumulation causing the available BC, both from the atmosphere and nearby charred material, to be diluted (i.e., lower BC concentration). Higher concentrations within the snowpack were found closer to the surface, where ice and melt affected layers were present. Dry and warm periods preceding the sampling from mid-January to mid-February prolonged the exposure of the snow surface and likely caused the formation of the ice layers containing high concentrations of BC. Thus, the greatest BC deposition due to forest fire activity most likely takes place over periods without precipitation when BC is integrated into the snowpack through dry deposition processes, possibly during windy periods that can entrain and deposit charred material.

These samples were analyzed with the SP2 method using an ultrasonic nebulizer (section 2.3), thus, particles larger than 500 nm were analyzed with low efficiency [*Schwarz et al.*, 2012; *Wendl et al.*, 2014]. Due to the proximal source of the BC and its attachment to charred trees, a large amount of the BC mass in the snow samples could be contained in particles larger than those analyzed in this study. As a result, BC concentrations from the Lion Rock sampling area could be substantially underestimated. However, the BC particles analyzed from the fire in this study have the greatest ability to reduce albedo and absorb radiation because of the higher mass absorption cross section of smaller BC particles, whereas Mie theory suggests that larger particles are less efficient at absorbing radiation [*Schwarz et al.*, 2013]. Given the reduced amount of charred material on snags in proximity to Tronsen Meadow, greater deposition of BC at the Tronsen site could be a result of transport of smaller BC particles from the Table Mountain fire area.

Prior studies have investigated postfire effects on the seasonal snow cover. Forest fires decrease the forest canopy, which results in greater snow accumulation due to a lack of canopy interception, and increase incident incoming solar radiation and winter ablation [*Harpold et al.*, 2013; *Molotch et al.*, 2009]. Research in the Oregon Cascades showed that snow albedo decreased 40% in forest fire areas and reduction of forest canopy allowed for 60% more solar radiation to reach the snowpack; the combined effects resulted in melt out 23 days earlier compared to unburned areas [*Gleason et al.*, 2013]. The current study is the first time that postfire BC deposition has been reported. A study of modern fire frequency in the Teanaway River basin, adjacent to the Table Mountain sampling area, determined that large fires (>40 km^2) occur on average every 27 years [*Wright and Agee*, 2004]. Fires of this size could burn areas with the intensity found at the Table Mountain area, thus providing the charred material to supply the snowpack with additional BC. Because it can take years for the forest to regrow vegetation and for charred material to decompose, forest fire areas could provide additional light-absorbing impurities to the local snowpack for years to come.

4. Conclusions and Implications of Study

Assessment of spatial variability in BC concentrations showed that individual snow samples are representative of larger areas at the submeter to 100 meter scale; provided variations in snow deposition and melt are considered. Concentrations of BC both on the snow surface and in snowpits are predominantly homogeneous early in the season and increase in variability after snowmelt initiates. Following the initiation of snowmelt, the increased variability in BC concentration in surface samples indicates that more intensive sampling is required to characterize local-scale variability.

BC concentrations in snow at Tronsen Meadow were relatively low prior to late March (generally less than 1 μg/L), after which BC concentrations increase. Increases seen during the late accumulation season are largely coincident with seasonal increases in EC atmospheric concentrations measured by the monitoring sites of the IMPROVE network. However, during the melt season, large increases in BC concentrations are likely the result of mechanical trapping of BC on the snowpack surface during the onset of melt, whereas scavenging during rapid melt conditions can potentially lead to lower BC concentrations in the snowpack. These results suggest that intense snowmelt may have the potential to moderate BC's effect on snow albedo, initiating a negative feedback wherein BC in the snowpack lowers albedo and causes melt, which in turn removes BC from the snowpack. While the removal of light-absorbing impurities from the snowpack could increase albedo, this does not account for the increase in snow grain size that occurs during melt and reduces albedo [*Warren and Wiscombe*, 1980]. Further research is needed to examine the linkages between light-absorbing impurity concentrations, snowmelt, snow grain size, and snow albedo.

During the 2013 season, the severely burned area of the Table Mountain fire provided additional BC material to the snowpack from charred trees after the fire was extinguished. Not only were BC concentrations higher in the heavily burned area but also at the Tronsen Meadow site, 10 km upwind from the severely burned area. This suggests that areas burned by forest fires can elevate BC concentrations in the snowpack on a local scale. As the charred material from the fire will remain in the environment for years before it fully decomposes, it will potentially provide elevated inputs of BC to the snowpack for years subsequent to the fire. Because the decreased canopy cover caused by fire allows more solar radiation to reach the snowpack [*Harpold et al*., 2013; *Molotch et al*., 2009], the postfire snowpack experiences increased effects of albedo reduction as the prefire snow experienced both higher albedo and lower amounts of solar radiation. As a result, heavily burned areas not only provide additional impurities to the snowpack but also increase the effectiveness of these impurities in accelerating snowmelt by reducing canopy cover and allowing more incoming solar radiation to reach the snow.

While this study predominantly focused on characterizing spatial and temporal variations in BC concentrations and the processes affecting BC concentrations in the snowpack, the role that BC can play in reducing albedo and accelerating melt is of interest. The BC concentrations reported herein are relatively low, and lower than those measured in snow from the Sierras in California by the same method [*Sterle et al*., 2013]. However, as the study site in the Sierras was located at a ski area there may have been more localized sources of BC than at Tronsen Meadow. Despite the relatively low BC concentrations at Tronsen Meadow, BC may affect melt timing because the snowpack in this region is close to 0°C, and additional energy added to the snowpack by BC may initiate melt, particularly during spring when BC concentrations in the snowpack increase coincident with increases in solar radiation. However, it should be noted much of the area surrounding the study site, and even in the Pacific Northwest at this elevation, is forested and thus receives less solar radiation through shading compared to alpine and subalpine snowpacks with minimal or no canopy cover [*Molotch et al*., 2009]. Forested areas will be less affected by albedo reduction due to BC as opposed to alpine and glaciated environments above tree line, which receive greater amounts of solar radiation. Future research in this region should further address the contribution of BC to snowmelt.

Climate projections suggest a significant decrease in the Pacific Northwest snowpack by the 2040's due to warmer temperatures and precipitation occurring more frequently as rain than snow [*Elsner et al*., 2010; *Vano et al*., 2010]. This will lead to earlier snowmelt and could potentially result in decreased BC concentrations during the melt season, as the snow season would not coincide with increased atmospheric BC concentrations that occur nowadays in later spring. However, should similar atmospheric BC concentrations persist in the future, BC concentrations in the snowpack could be higher due to the lower snow water equivalent in the snowpack, exacerbating albedo reduction.

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