Response of River Runoff to Black Carbon in Snow and Ice in Washington State

Basic Information

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Publications

1. Delaney, Ian, 2013, Black Carbon Deposition on Snow and Glaciers in Washington State: Implications for Accelerated Snowmelt, MS Thesis, Department of Geological Sciences, Central Washington University, Ellensburg, WA.
2. Kaspari, Susan, Ian Delaney, McKenzie Skiles, Daniel A. Dixon, 2012, Abstract C41D-04, Black Carbon and Dust in Snow and Ice on Snow Dome, Mt. Olympus, American Geophysical Union Fall Meeting, San Francisco, CA.
3. Delaney, Ian, Susan Kaspari, Michael Larrabee, 2012, Abstract C53C-0862. Black Carbon Deposition on Glaciers and in the Seasonal Snowpack in Western Washington s Mountainous Regions, American Geophysical Union Fall Meeting, San Francisco, CA.

I. PROBLEM AND RESEARCH OBJECTIVES

Importance of snow and glacier melt

More than one-sixth of the global population relies on melt water from snow packs and glaciers for their water supply (Barnett et al., 2005). Water derived from snow and glacier melt refills reservoirs and supplies crucial summer flows to rivers used for fisheries, hydropower, irrigation, navigation, recreation and drinking water (Painter et al., 2007) and drives downstream processes such as groundwater recharge and ecological interactions (Bales et al., 2006).

In the Western United States, melt water from mountain regions accounts for more than 70% of annual stream flow. In the Cascade Mountains of Washington State, most of the annual precipitation falls during the winter-spring and is stored in the snowpack (Elsner et al., 2010; Vano et al., 2010). The majority of runoff is derived from the melting snowpack, transferring water from the relatively wet winter season to the typically dry summers (Mote et al., 2005). The timing and availability of water resources is thus strongly related to the duration of mountain snow cover.

Glacier melt water also provides essential water resources in Washington, particularly for watersheds that have a large concentration of glaciers. In some watersheds glacier melt water can account for nearly 50% of the May-September runoff. Glacier melt is variable from year to year, with glacier melt contributing a greater amount of water during years when the snow pack is minimal. Glaciers thus provide an important water resource that can act as a buffer during drought years (Riedel and Larrabee, 2011).

Reduction in seasonal snowpack and glacier retreat in the Cascade Mountains

Spring snowpack levels (snow water equivalent and spatial extent) in the Western United States have declined considerably since the 1950s. The largest decreases occur where winter temperatures are mild, with the Cascade Mountains having experienced some of the largest decreases (as great as 80% decrease since the 1950s). Previous studies suggest that climate change, particularly warming, is the dominant factor inducing earlier snowmelt-fed runoff (Mote et al., 2005). Regions with maritime climates, which have snow season temperatures in the range -5°C to 5°C, are particularly susceptible to warming. Because these regions lie close to 0°C, a slight warming can accelerate the melting rate of the snow pack, and change precipitation from falling in the form of rain rather than snow, preventing water from being stored in the snowpack. This in turn affects the timing and magnitude of water resources available during the comparatively dry summer months. Similar to the snowpack changes, glaciers in Washington State are also retreating. For example, in the North Cascades, glacier area is estimated to have declined ~40% over the past 150 years (Riedel and Larrabee, 2011).

While warming temperatures are a well-recognized factor leading to the reduction in the snowpack and glacier retreat, another cause of accelerated melt is the deposition of impurities onto the snow and glacier surfaces. Snow has the highest albedo (i.e., reflectivity) of any naturally occurring surface on Earth. When impurities such as black carbon (BC, described further below) or dust are present, the snow surface is darkened and snow albedo decreases (Conway et al., 1996; Warren and Wiscombe, 1980), resulting in greater absorption of solar energy and accelerated snow and ice melt (Flanner et al., 2009; Hansen and Nazarenko, 2004; Ramanathan and Carmichael, 2008). This in turn causes peak runoff to occur earlier, reducing water availability during the summer when water demands are highest.

BC (often referred to as soot) is a dark absorptive particle produced by the incomplete combustion of biomass, coal and diesel fuels. In the atmosphere, BC absorbs light and causes atmospheric heating. BC deposited on snow and ice affects climate and water resources by reducing the albedo of snow and ice surfaces and accelerating snow and ice melt (Hansen and Nazarenko, 2004; Ramanathan and Carmichael, 2008). BC has a short residence time in the atmosphere (days to weeks), resulting in regional variations in BC concentrations in the atmosphere and snow/ice. BC emissions have increased globally in recent decades, but emission trends vary regionally. The main sources of BC in the Pacific Northwest are from the transportation sector,

residential bio-fuel combustion (primarily wood burning stoves for heating) (Bond et al., 2004), forest fires, and long-range transport from Asia.

The role of absorbing impurities in accelerating snow and glacier melt is an emerging research topic, and few studies have taken place investigating the impacts of absorbing impurities on snow and ice melt in the Pacific Northwest. Two early studies investigated the BC content in snow in Washington. (Grenfell et al., 1981) measured the snow albedo and impurity content in the snowpack in the Cascade Mountains, and determined that impurities were reducing the snow albedo. Similarly, (Clarke and Noone, 1985) collected old and new surface samples of snow on the Olympic peninsula. BC concentrations were slightly lower than those reported by Grenfell. (Conway et al., 1996) applied manufactured BC on the snowpack at Snow Dome on Blue Glacier in the Olympic Mountains, and found that BC applied in high enough concentrations to cause a 30% reduction in albedo increased melting by 50%.

More recently, (Qian et al., 2009) conducted a modeling study that simulated the deposition of BC on snow, and the resulting impact on the snowpack and hydrological cycle in the western United States. Their results suggest that the majority of BC deposited on the snowpack in the Western US is transported from populated metropolitan regions west of the mountains, leading to a decrease in spring snow water equivalent and a shift to earlier peak runoff in the spring. The authors note that more BC-in-snow measurements are necessary in order to improve the accuracy of their models.

Research Objectives

The primary objectives of this study were to further characterize the spatial and temporal variability of BC deposited in Washington snow and glacier ice, and to begin to assess the potential role of BC in accelerating snow and glacier melt.

II. METHODOLOGY

Study Sites

Snow samples were collected from a seasonal snow study site at Blewett Pass, Washington during the winter months of 2013 and from glaciers in the Cascade and Olympic mountains during the spring and summer of 2012 (Figure 1). Kaspari and MS student Matt Jenkins established the Blewett Pass seasonal snow site in 2009, and the snowpack has been sampled every winter since then.

At Blewett Pass during the 2010-2012 winters we had sampled the snowpack at high temporal and spatial resolution. During the winter of 2013 our primary objectives were to characterize surface spatial variability in BC concentrations, dry deposition processes, and interannual variability (by comparing BC concentrations from the winter of 2013 to the prior three winters). To meet these objectives, once or twice a month during the winter we collected snow samples from an established snow pit along with numerous surface samples. Additionally, to investigate BC from dry deposition, surface snow samples were collected daily over a five-day period in February 2013 during which no precipitation fell. MS student Ian Delaney conducted the field sampling at Blewett Pass during the 2012 and 2013 winters.

Seven glaciers were selected for snow sampling during the study period (Figure 1, Table 1). These glaciers were chosen because they are monitored for annual mass balance by the University of Washington (Blue Glacier) and National Park Service (NPS, all other glaciers) and geographically they represent much of the glaciated regions of Washington State.

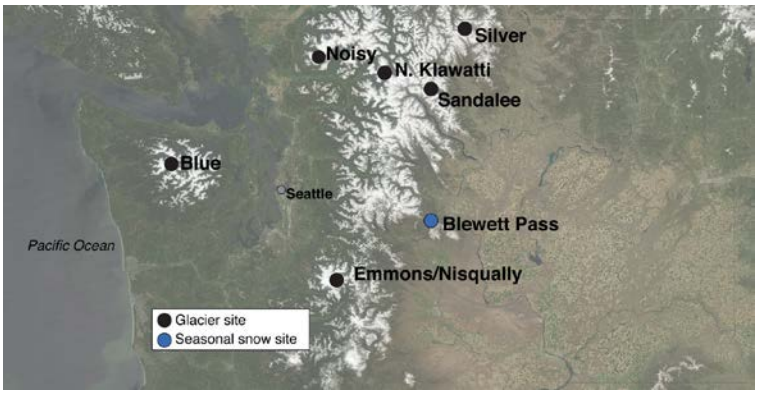


Figure 1. Map of Washington State showing location of sites where snow samples were collected during 2012-2013. Black circles identify glacier sites, and the blue circle identifies the seasonal snow study site at Blewett Pass established in 2009.

Date Sampled	Region	Glacier	Elevation Sampled (m)	Aspect
4/15/12	Rainier	Nisqually	1778-2175	S
4/21/12	Rainier	Emmons	1580-1970	NE
4/23/12	N. Cascades	Sandalee	1996	NE
4/23/12	N. Cascades	N. Klawatti	2080	E
5/10/12	Rainier	Nisqually	2974	S
5/11/12	Rainier	Nisqually	3382	E
6/21/12	Rainier	Emmons	2810-3118	NE
7/19/12	N. Cascades	Noisy	1820-1740	W
7/24/12	N. Cascades	Sandalee	2254-1996	NE
8/24/12	Olympics	Blue	2040	--
8/30/12	N. Cascades	Silver	2290-2075	NW
9/18/12	Rainier	Emmons	2810-3118	NE

Table 1. Date sampled, region, glacier, elevation range, and aspect of snow samples collected from Washington State during the study period. This table does not include sampling conducted at Blewett Pass between December 2012-April 2013.

Sample Collection

Polypropylene gloves were worn at all times during sample collection and care was taken to ensure that clothing fibers did not come in contact with the sample. All samples were collected into either 50 mL polypropylene vials or Whirlpak bags.

At Blewett Pass, 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. Snowpit samples were collected continuously at 5 cm depth resolution, and numerous spatially distributed surface samples were collected from the top 1-2 cm of the snow surface, where light absorbing impurities (i.e., BC, dust) influence albedo the greatest (Painter et al., 2012b).

At the glacier sites surface snow samples were collected, in addition to subsurface snow samples. MS student Ian Delaney accompanied the National Park Service Glacier Monitoring Program to several of the glacier sites in spring-early summer. The NPS used a manually operated snow-coring device to remove snow cores (up to 4.5 m total depth) for mass-balance purposes. Delaney sampled these snow cores at 10-30 cm increments. During July through September, Delaney sampled snow from shallow (60 cm) snow pits at 5-10 cm resolution. During August of 2012 Kaspari and Delaney collected a 7 m ice core from Snowdome on the Blue Glacier, Mt. Olympus using a 5 cm diameter electromechanical ice drill.

Samples were prevented from melting in the field and during transport to the lab using frozen ice packs or dry ice. Because of the remote location of the study sites, the logistics of maintaining

the snow and ice at below freezing temperatures is challenging. In the case of the ice core collected from the Blue Glacier (a 20 mile approach up the Hoh valley), a helicopter was used to fly the ice out to Port Angeles, WA where a freezer was staged. All samples were maintained frozen until prior to analysis. The NPS Glacier Monitoring Group and Bill Baccus at Olympic National Park provided invaluable logistical support in enabling this research to occur.

Sample Analysis

Samples were melted just prior to analysis, sonicated for 20 minutes, and stirred with a magnetic stirrer during analysis. The liquid sample is pumped using a peristaltic pump, nebulized using a CETAC U-5000 AT+ ultrasonic nebulizer, and the resultant dry aerosol is coupled to the sample inlet on a Single Particle Soot Photometer (SP2). The SP2 uses laser-induced incandescence to determine the mass of refractory BC in individual particles (Schwarz et al., 2006; Stephens et al., 2003). Monitoring of liquid sample flow rate pumped into the nebulizer, fraction of liquid sample nebulized and purge airflow rate allows BC mass concentrations in the liquid sample to be determined. Because BC is not nebulized with 100% efficiency, Aquadag standards were used to correct the measured BC concentrations. Nebulization efficiency for the CETAC nebulizer drops at particle sizes greater than 500nm (Schwarz et al., 2012, results confirmed in our laboratory). The concentrations reported herein predominantly represent the mass of BC particles 500 nm and smaller, which corresponds to the size range where the mass absorption cross section of BC particles is greater relative to larger particles, meaning that smaller BC particles absorb light and reduce albedo more efficiently (Schwarz et al., 2013).

To facilitate inter-method comparison, select snow samples were also analyzed for elemental carbon using a Sunset Thermal-Optical Analyzer. This work is still ongoing, thus we don't present results here. Additionally, select snow samples were also filtered through a pre-weighed 0.45μm Millipore filter (Millipore Membrane Filter, Lot no. ROHA46035) using a vacuum pump. The dry mass on the filter is used to determine the total impurity load, which is assumed to largely reflect the dust mass of the sample.

III PRINCIPLE FINDINGS AND SIGNIFICANCE

Blewett Pass

Repeat sampling of snowpits at Blewett Pass over the past four winters have shown that BC concentrations are relatively low during the winter accumulation season, and rapidly increase during the spring melt in late March-April (Figure 2). The higher BC concentrations during the spring may be due to higher atmospheric concentrations during spring, or post-depositional melt processes. Analysis of atmospheric BC data from nearby IMPROVE (Interagency Monitoring of Protected Visual Environments) sites indicate that atmospheric BC concentrations rise in the spring-summer relative to the winter (data not shown here), however our results indicate that the higher atmospheric concentrations do not account for the higher BC concentrations observed in the spring snowpack. Rather, the higher BC

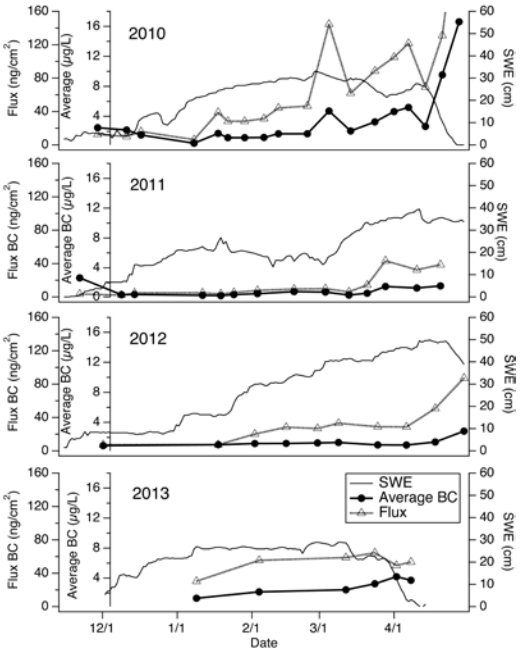


Figure 2. Average BC, BC flux (BC corrected for differences in snow water equivalent (SWE), and SWE from Blewett Pass from the 2010-2013 winters.

concentrations during the spring occur primarily due to melt processes that cause BC and dust to become mechanically trapped at the snow surface (Conway et al., 1996; Painter et al., 2012a). The highest BC concentrations at Blewett Pass were observed in surface snow samples, with subsurface concentrations also elevated during the melt period, consistent with results reported from the Sierras (Sterle et al., 2013). Analysis of surface snow samples collected over a five-day dry period in February 2013 demonstrated the role of melt in causing surface enrichment. Higher temperatures on February 13 coincided with 1 cm of snowmelt, and a doubling in surface snow BC concentrations (Figure 3).

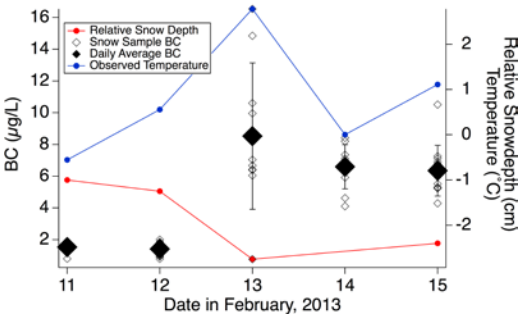


Figure 3. BC concentrations in surface snow samples, snow height and temperature over a five-day period in February 2013.

While BC concentrations were observed to increase during spring each year, average BC concentrations varied interannually. This can be due to differences in BC concentrations in the atmosphere, the processes that integrate BC into the snowpack (dry and wet deposition), or snow accumulation. Regional atmospheric BC data from the IMPROVE network is not yet available from the most recent two winters, thus we don't yet have a means to investigate interannual variations in the atmospheric BC load. Average BC concentrations were highest during 2010 and 2013 (Figure 4), both years with relatively lower snow accumulation at Blewett Pass (Figure 3).

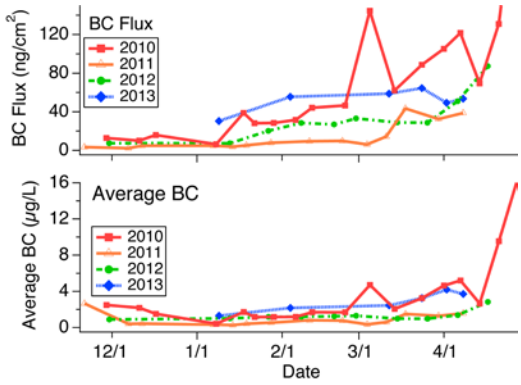


Figure 4. Interannual comparison of BC Flux (BC concentrations corrected for snow accumulation) and Average BC during the 2010-2013 winters.

We can apply a flux correction, in which the snow water equivalent of the snowpack is multiplied by the average BC concentration in the snowpack, allowing any dilution effect from more or less accumulated snow to be corrected for. That BC Flux is higher in 2010 and 2013 indicates that the higher BC snow concentrations are not due solely to lower snow accumulation. 2013 concentrations were likely higher due to BC related to recent fire activity (discussed below), but we have not yet determined why BC concentrations were elevated during 2010. This is a focus of continued interpretation by MS student Delaney.

Two forest fires occurred in the vicinity of Blewett pass in August and September of 2012. The Taylor Bridge fire (August 13 to August 28, 2012; 95 km^2) burned in the Kittitas Valley southeast of Blewett Pass, and the Table Mountain Fire (September 8 to October 5, 2012; 170 km^2) burned in the vicinity of Blewett Pass. These fires left charred material from burned snags that likely introduced an additional and proximal source of black carbon to the snowpack during the 2013 winter (Figure 5), contributing to the elevated BC concentrations during 2013. Spatial sampling in the region surrounding the Table Mountain Fire indicates that BC concentrations in snow are highest in heavily burned areas. This additional source of BC has the potential to remain for years to come.

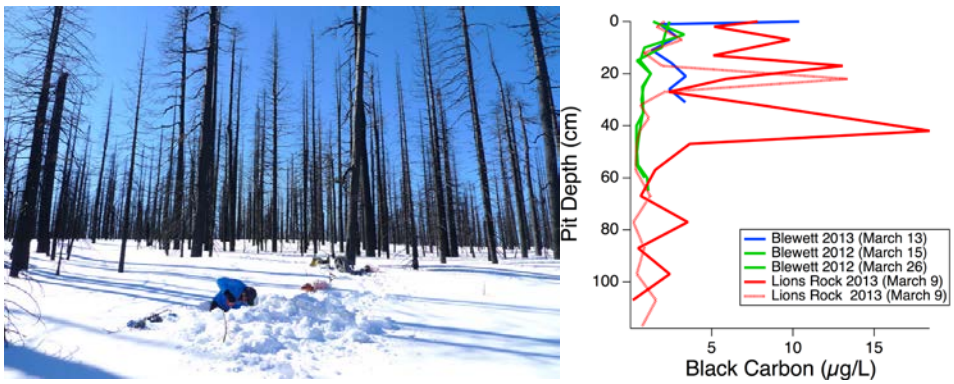


Figure 5. Left: MS student Ian Delaney digging a snowpit in front of burned snags near Lion's Rock. Right: BC concentration in snowpits near Lion's Rock within the Table Mountain burn area, and at Blewett Pass, 9 km away. The highest BC concentrations from the 2013 pits correspond to a relatively dry period during February. Snowpit profiles from 2012 at Blewett Pass are showed for comparison. Note that depths between pits do not correlate to the same time.

Snow Samples from Glaciers in Washington State

We hypothesized that BC concentrations in Washington's snow would show regional differences due to varying proximity to major BC emission sources. However, BC concentrations from subsurface snow samples from around Washington State used as a proxy for BC concentrations in winter snow were fairly uniform (Figure 6). This is due to either relatively uniform BC deposition in snow around the state, or potentially post depositional processes that could move BC to deeper in the snowpack. Previous studies have documented that under strong melt conditions BC can be transported through the snowpack (Xu et al., 2012).

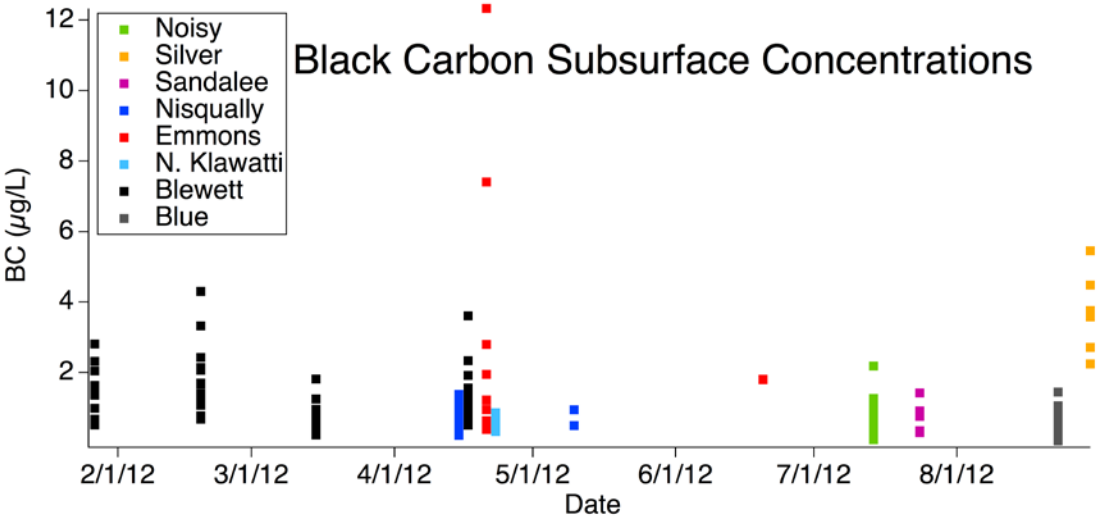


Figure 6. Subsurface BC concentrations, used as a proxy for BC concentrations in winter snow, from the eight study sites.

A significant relationship between elevation and BC concentration does exist, with BC concentrations higher at lower elevations (Figure 7). This is likely due to higher snow accumulation rates at higher elevations that dilute BC in the snowpack, and potentially lower atmospheric BC concentrations at higher altitudes. That BC concentrations are generally lower at

higher elevations has been confirmed by analyzing BC data from the IMPROVE network, however the BC concentrations observed in snow are complicated by a combination of wet, dry and post-deposition processes.

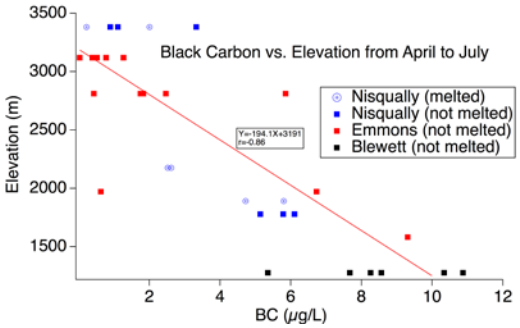


Figure 7. BC concentration vs. Elevation. These samples represent surface snow from prior to the onset of melt at various elevations. A few of the Nisqually snow samples partially melted during transport from the field as noted by 'melted.'

Similar to the increase in BC concentrations observed during the melt season at Blewett Pass, surface snow samples from the glacier sites also demonstrate a strong trend towards higher BC concentrations over the summer (Figure 8). Because the glacier sites are at higher elevations (~2000-3000 m, Table 1) relative to Blewett Pass (1295 m), melt commences much later in the year (late summer for high elevation sites relative to spring at Blewett Pass). The higher BC concentrations later in the season are due to both melt-induced enrichment at the glacier surface, and dry deposition during the relatively dry summer months.

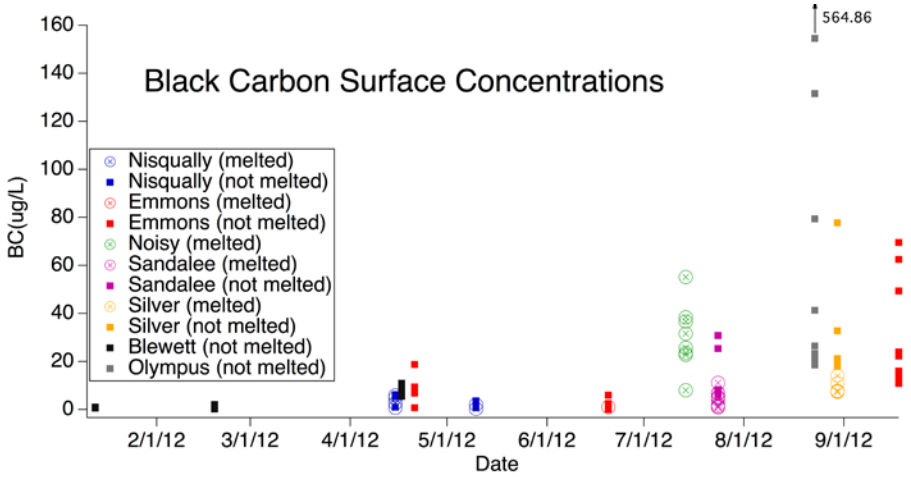
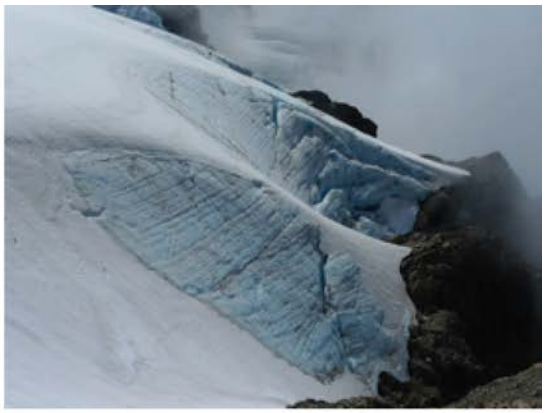


Figure 8. BC concentrations in surface snow during 2012, showing a substantial increasing trend over the summer.

Shallow Ice Core and Surface Snow Samples Retrieved from Snowdome, Mt. Olympus

We initially targeted Snowdome on the Blue glacier of Mt. Olympus as a prime sampling site because it potentially represented background BC concentrations in snow since it was upwind of major regional BC sources in the Puget Sound area, and because Snowdome is a favorable site in regards to glacier dynamics for collecting a shallow ice core. The largest BC sources upwind of Snowdome likely come from ocean shipping traffic, and potentially from trans-Pacific transport of Asian emissions (Hadley et al., 2010). In addition to PI Kaspari and MS student Delaney, PhD student McKenzie Skiles from UCLA/JPL and Dr. Daniel Dixon from the University of Maine participated in fieldwork at Snowdome. Skiles brought a field spectrometer to measure snow surface albedo, and Dixon assisted with ice core drilling. Figure 9 shows pictures from Snowdome fieldwork.

Snowdome, Mt. Olympus. Surface variations in light absorbing impurities are visible on the snow surface.



Side of Snowdome showing distinct layering in light absorbing impurities with depth.

MS student Delaney making measurements on an ice core.

High impurity layer in the ice core corresponding to the 2011 summer layer.

Kaspari operating the electromechanical ice core drill.

Figure 9. Pictures from fieldwork on Snowdome.

Measured BC and dust concentrations from Snowdome surface snow samples that appeared relatively 'clean' and 'dirty' were compared to the spectral albedo as measured using the field spectrometer. The relatively clean snow had lower BC and dust concentrations, corresponding to a maximum albedo of .95 in the visible (Figure 10). BC and dust concentrations were markedly higher in the visibly dirtier snow, which was reflected by a maximum measured albedo of .82 in the visible. We used the Snow, Ice, and Aerosol Radiation (SNICAR) model (Flanner et al., 2007) to estimate albedo reductions due to the measured BC and dust concentrations. The measured and

modeled albedos agree well for relatively clean snow, but there was less agreement for the dirtier snow. This may be due to differences in the modeled and actual optical properties of the absorbing impurities in the snowpack. This portion of the study documented that BC and dust concentrations can be highly variable over small spatial scales, and that impurities are present in high enough concentrations to reduce albedo by at least 13%.

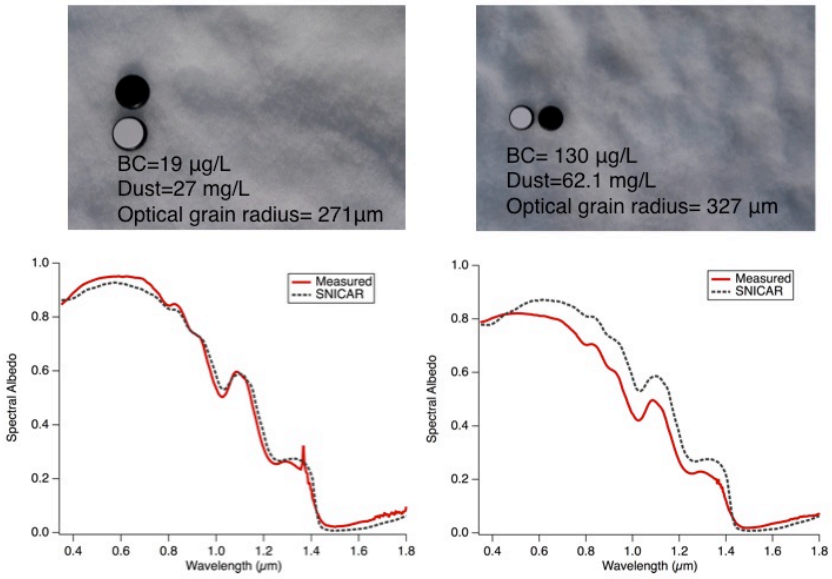


Figure 10. Top: pictures of the snow surface with Spectralon reference panels, and measured BC and dust concentrations. Bottom: Measured and SNICAR modeled spectral albedo. The snow on the left was relatively clean, whereas the snow on the right appeared visibly darker.

The 7.8m shallow ice core collected from Snowdome using an electromechanical drill allowed us to sample through the 2011 summer snow layer at 6.8 m depth (Figure 11). As we observed on other glaciers in Washington, BC concentrations were elevated at the surface of the snowpack. The finding that was not anticipated was the extremely high BC concentration layer (3000 µg/L) found at the 2011 summer layer, which is considerably higher than any other surface snow sample collected during this study. Potential explanations for the formation of this high concentration layer include: 1) Melt and dry deposition during the 2011 summer season. An additional month of melt and dry deposition would have occurred at the 2011 summer surface compared to the surface snow samples that were collected from Snowdome in 2012, or 2) melt and dry deposition during the 2011 summer season combined with percolation through the snow accumulated during the 2012 winter, which coalesced at the 2011 summer horizon. Xu et al. (2012) monitored BC concentrations in the snowpack above the superimposed ice layer on a Tien Shan glacier over a year, and found that relative to freshly fallen snow, during the melt season BC was enriched in the surface snow and to an even greater extent in the snow/firn directly above the superimposed ice layer. Xu et al. propose that meltwater can flush BC through the upper ~1m of the snowpack. This results in lower BC concentrations in the snow

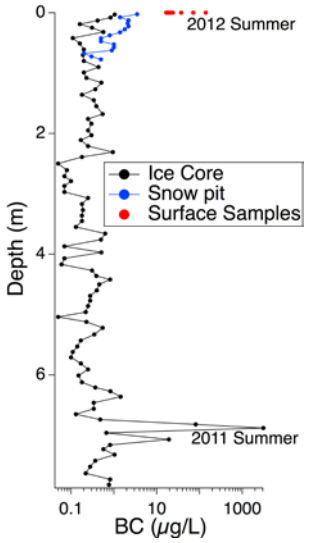


Figure 11. BC concentrations vs. depth from the 7 m snow core retrieved from Snowdome on Mt. Olympus in August 2012.

between the surface and bottom depths of snow/firn, with BC unable to flow below the superimposed ice layer, resulting in build-up of BC at this horizon. The snow accumulation rate at Snowdome was 6.8m (uncorrected for water equivalence), which is much larger than the 1 m Xu et al. discussed. However, there was a clear superimposed ice layer below the 3000 μg/L BC layer that would have prevented BC flow to deeper in the glacier. Lastly, this is one measurement of BC concentrations from the 2011 summer horizon. Due to concerns that our ice core drill would become stuck in the glacier, we were not able to drill additional shallow cores to characterize the spatial variability in the 2011 horizon. The entire 2011 summer horizon potentially may not have BC concentrations as high as 3000 μg/L, but concentrations are likely considerably higher than measured in the surface snow during 2012. The clearly visible horizons of light absorbing impurities on the side of Snowdome indicate that these features are widespread (Figure 9, top right).

Significance

BC concentrations in Washington's winter snowpack were found to be relatively low, with BC concentrations increasing in spring and summer (Figures 2, 4, 6, 8). The timing of the increase in BC at the spatially distributed sites coincided with the onset of melt conditions (i.e., melt commenced earlier at lower elevation sites). In addition to melt resulting in concentration of BC at the snow surface, increased dry deposition associated with an increase in the planetary boundary layer height and minimal precipitation likely contributed to the higher spring-summer BC concentrations. The significance of this finding is that the effects of BC deposition onto the Washington snowpack are greatest during spring to summer. This means that BC induced melt could accelerate the timing of spring snowmelt at lower elevations, however BC induced melt is likely largest at relatively high elevations where the snowpack persists into the summer months when BC concentrations were observed to be highest.

Results from sampling the snowpack at Blewett Pass over four winters demonstrated that BC concentrations are highest during years with low snow accumulation (Figure 2). This has important implications for Washington's snowpack under a changing climate. The winter snowpack is already decreasing (Mote et al., 2005), and is projected to continue to decline in both spatial extent and temporal duration as temperatures continue to increase (Elsner et al., 2010). Our findings indicate that as long as there is not a substantial reduction in BC emissions, a shallower snowpack will result in higher BC concentrations in snow, accelerating snowmelt.

The 2012 forest fires in the vicinity of Blewett Pass likely contributed to the higher BC concentrations observed in the 2013 snowpack, with BC concentrations highest in the vicinity of areas heavily burned (Figures 4, 5). These findings provide insight into an effect of forest fires on the landscape and water resources that has not previously been studied, and could potentially have policy implications for forest fire management practices in regards to prescribed fires vs. wildfires.

The extremely high BC concentration measured in the 2011 summer horizon from Snowdome (Figures 9, 11) suggests that much higher impurity layers may reside below the most recent year's snow accumulation on Washington's glaciers. In a study based on Tibetan glaciers, Xu et al. (2012) noted that due to the coupled impacts of greenhouse-gas warming and BC enrichment in surface snow, dirty ice that can at present form in the accumulation zone underlying the snowpack can be exposed in the future as the glacier equilibrium line altitude (ELA) increases. If the high BC concentration 2011 summer layer was exposed at the glacier surface, albedo would greatly decrease and melt would be substantially accelerated. This is a concern for the future of Washington's snowpack and glaciers, as glacier ELAs will continue to rise and the winter snow accumulation will continue to decrease as temperatures rise.

This study predominantly focused on characterizing the spatial and temporal variability of BC concentrations in Washington's snowpack. In the future, we would like to expand upon this work to characterize other light absorbing impurities (e.g., dust, colored organic material) in the snowpack, and begin to assess the absorption and albedo reduction of BC relative to these other impurities. While BC has the highest efficacy at absorbing radiation, other absorbing impurities

(most notably dust) can be present in considerably higher concentrations. To conduct this work, the optical properties of the other light absorbing impurities would need to be characterized. In addition, substantial work is needed to tie the impurity concentrations to albedo reductions and melt rates. As part of this study we documented a 13% reduction in visible albedo due to the presence of absorbing impurities (Figure 10), but more detailed work is needed.

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