Black Carbon and Dust Deposition on South Cascade Glacier Since 1750 AD: Implications for the Timing and Availability of Water Resources in Washington State

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BLACK CARBON AND DUST DEPOSITION ON SOUTH CASCADE GLACIER SINCE 1900 AD: IMPLICATIONS FOR THE TIMING AND AVAILABILITY OF WATER RESOURCES IN WASHINGTON STATE

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PI Susan Kaspari, Central Washington University

Abstract

Seasonal snowpack and glaciers provide an important source of water in Washington State, but in recent decades they have undergone substantial decline. Warming temperatures are commonly identified as the dominant cause of this decline, but the deposition of light absorbing impurities (LAI) onto snow and glacier surfaces can be an even larger driver of melt. LAI include black carbon (BC) produced by the incomplete combustion of fossil and biofuels, and dust emissions from desert regions and land use change. When deposited on highly reflective snow and glacier ice, LAI cause darkening of the surface, resulting in greater absorption of solar energy, heating of the snow/ice, and accelerated snow and glacier melt. We analyzed an ice core from South Cascade Glacier in the North Cascades of Washington State to assess variations in LAI deposited on snow and glacier surfaces since 1900 AD, and the associated implications on melt and the availability of water resources. The BC record is 75% complete, and the preliminary record indicates low background BC concentrations in the early 20th century, followed by approximately a magnitude increase in peak and background concentrations, and a subsequent reduction in BC at the top of the record. Concentrated BC layers in excess of 100 ng/g likely resulted from BC deposition from forest fire events. Once the dust analyses and dating are complete, we will be able to: determine the timing of LAI deposition on the glacier; assess the relative absorption of solar energy from dust versus BC; and evaluate the role of LAI in reducing glacier albedo in the context of glacier melt and water resources.

I. PROBLEM AND RESEARCH OBJECTIVES

Importance of snow and glacier melt

The seasonal snowpack and mountain glaciers play an important role in the earth system by modulating climate and providing a major source of water resources. More than one-sixth of the global population relies on melt water from snow packs and glaciers for their water supply, and in the Western United States melt water from mountain regions accounts for more than 70% of annual stream flow [*Barnett et al.*, 2005].

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 (Fig. 1). 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].
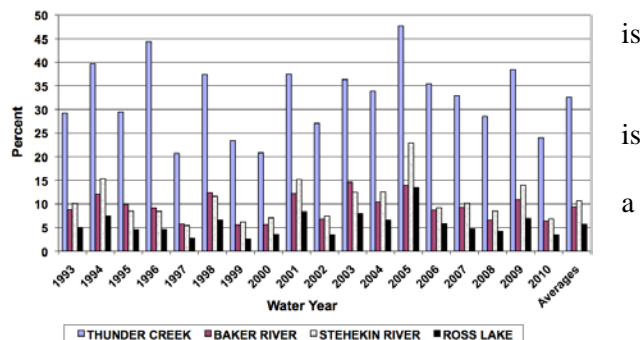

Fig. 1. Contribution of glacier runoff to in-stream flows in %. *Riedel and Larrabee* [2011].

Reduction in seasonal snowpack and glacier retreat in the Cascade Mountains

Observations show a global-scale decline of seasonal snow cover extent and duration, and mountain glaciers are shrinking [IPCC, 2007]. 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. 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 decline, glaciers in Washington State are also retreating (Fig. 2). For example, in the North Cascades, glacier area is estimated to have declined ~40% over the past 150 years [*Riedel and Larrabee*, 2011].
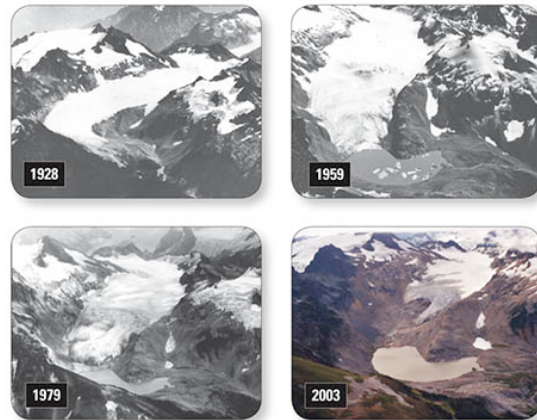

Fig. 2. Retreat of the South Cascade Glacier in Washington State from 1928 (top left) to 2003 (bottom right). USGS.
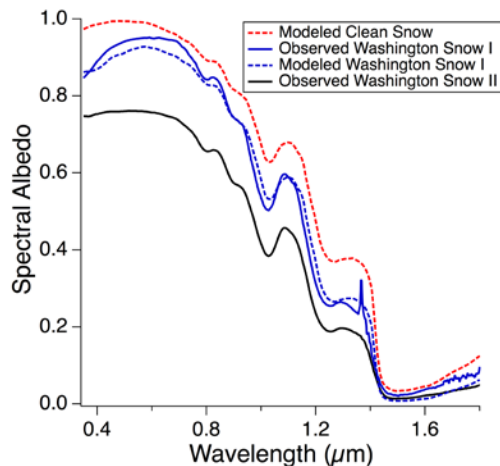

Fig. 3. Observed and SNICAR modeled snow spectral albedo for clean and observed snow in Washington State corresponding to 130 μg/L BC and 62 mg/L dust [*Kaspari et al.,* 2012]

Accelerated snow and ice melt due to the presence of light absorbing impurities (LAI)

While warming temperatures are a well-recognized factor leading to reduction in snowpack and glacier retreat, another cause of accelerated melt is the deposition of LAI onto snow and glacier surfaces. Net solar radiation is the most important component of the surface energy budget for mid-latitude glaciers and snowpack, with albedo (i.e., reflectivity) dominating the amount of energy available for warming and melt [*Anslow et al.*, 2008; *Oerlemans*, 2000; *Painter et al.*, 2007]. When LAI are present, the albedo of snow and glacier surfaces is reduced (Fig. 3) [*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]. For snowpack and glaciers with substantial deposition of LAI, these impurities are more important than temperature in driving melt [*Skiles et al.,* 2012].

LAI include black carbon (BC, often referred to as soot), dust, volcanic ash and colored organic material, with BC and dust being the most effective at reducing albedo [*Warren and Wiscombe*, 1980]. BC and dust are emitted into the atmosphere from both natural and anthropogenic sources. BC is emitted by incomplete combustion of biomass, coal and diesel fuels [*Bond et al.*, 2004], while dust is emitted from desert regions and human activities including agriculture, overgrazing, deforestation and construction [*Tegen et al.*, 2004].

The atmospheric residence time of BC and dust is short (days to two weeks), resulting in regional variations of these LAI in the atmosphere and snow/ice. BC emissions have increased globally in recent decades, but emission trends vary regionally (Fig. 4). An increase in dust emissions has been documented in the western US since the 19th century associated with western settlement and increased livestock grazing [*Neff et al.*, 2008]. LAI deposited on snow and glaciers in Washington State have a larger potential to accelerate melt than in many other regions because the snowpack is near 0°C, thus minimal energy needs to be added to the snowpack to result in melt. Our recent research in Washington State has documented BC and dust concentrations in snow at high

Fig. 4. Estimated fossil fuel BC emissions. *Novakov et al.* [2003].

enough concentrations to reduce albedo in excess of 20%, which can substantially accelerate snow and glacier melt (Fig. 3) [*Delaney et al.*, 2012; *Kaspari et al.*, 2012]. However, currently is it is not known how much of the LAI are from natural vs. anthropogenic sources, nor how deposition of LAI change over time.

Research objectives

The objectives of this project are to analyze the South Cascade Ice Core retrieved from the North Cascades of Washington State for BC and dust. This record enables us to assess changes in the frequency and magnitude of LAI deposited onto snow/glaciers in the region since ~1900 AD, and the associated impacts on albedo and melt. Furthermore, the ice core record is being used to differentiate the sources of the LAI between natural (e.g., from forest fires and background dust levels) versus anthropogenic sources (e.g. fossil fuel burning, land use change).

II. METHODOLOGY

Ice core processing

The 158 m long South Cascade Ice Core was drilled in 1994, and has been archived at the National Ice Core Laboratory (NICL) in Denver, CO. In June 2013 Kaspari, Central Washington University MS student Dan Pittenger, University of Colorado undergraduate students Nicholas Story and Garrett Rue, University of S. California postdoctoral researcher Nik Buenning, and three NICL employees processed the ice core. This included: imaging the ice core to identify LAI layers; making longitudinal cuts to the ice core

Figure 5: MS student Dan Pittenger identifies a dust layer in a section of the South Cascade ice core.

(outer sections were used for total impurity mass measurements, while inner sections were used for BC, trace element, isotope, ^{210}Pb and tritium measurements). The longitudinal sections of the ice core were sampled at 7-10 cm resolution, resulting in a total of 1989 samples. The ice sections were bagged in whirlpak bags, and stored frozen at NICL until shipped to Central Washington University for analyses. Additional samples were sent to University of S. California for stable isotope analysis by postdoctoral researcher Nik Buenning, and to the Paul Scherrer Institut in Switzerland for ^{210}Pb measurements. The work conducted by University of S. California and the Paul Scherrer Institut is being conducted with no cost to the USGS grant.
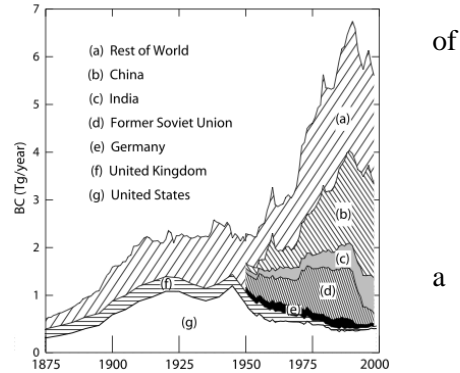
Ice core dating

The ice core is being dated using a combination of ^{210}Pb dating, glacial flow modeling, tritium dating, and glacial mass balance records. ^{210}Pb dating indicates the bottom age of the ice core is 1916 +- 18 AD (Fig. 6). Soon the stable isotope analyses will be complete, after which the remaining sample water will be sent to the National Isotope Centre in New Zealand to identify the 1963 tritium peak associated with atmospheric hydrogen bomb testing [*Morgenstern and Taylor*, 2009]. Below 1963, we will use a glacial flow model [*Nye*, 1952] to further constrain the age of the bottom half of the core. The upper section will be constrained by a combination of annual layer counting and mass balance data provided by the United States Geological Survey.

Figure 6: ^{210}Pb dating on the South Cascade ice core, dating the bottom of the core to 1916 +- 18 years. Depth is in meters water equivalent.

Black carbon analyses

The ice samples for BC analyses were rinsed with MQ water to remove any potentially decontaminated ice, and stored frozen in acid pre-cleaned polyproplylene vials. The 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).

Dust analyses

Once the BC analyses are complete, the samples will be analyzed for trace elements via Inductively Coupled Mass Spectrometry. In the meantime, an outer latitudinal section of the ice core is being sampled for total impurity mass, which is a proxy for dust concentrations. For this measurement the ice core is being sampled at ~20-100 cm resolution, rinsed with MQ water, sonicated, and filtered through pre-weighed 0.45μm Millipore filters using a vacuum pump. The filters are dried in a laminar flow hood and re-weighed to provide a record of impurity mass. Additionally, optical differences in the impurities trapped on the filters will provide information in changes in impurity deposition over time.

III PRINCIPLE FINDINGS AND SIGNIFICANCE

Due to federal sequestration measures the funding for this project was reduced to 60% of the initial budget. Due to the smaller budget, we were not able to work on the project during summer 2013 with the exception of processing the ice core at NICL in June 2013. As a result, the proposed work has not been completed on the timeline initially proposed, and some work had to be eliminated (mainly measuring elemental carbon with the Sunset analyzer to facilitate method
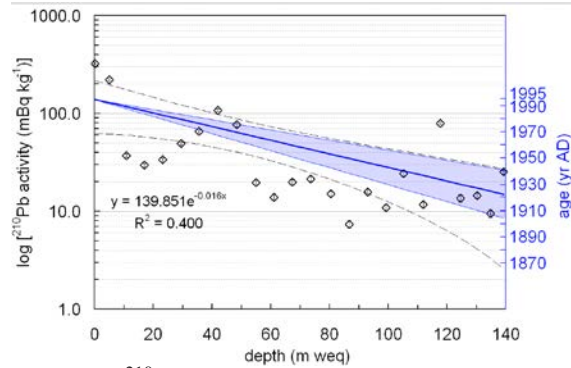
intercomparison). We have been granted a no-cost extension through the end of June 2014, and acquired some additional funds from other sources to help conduct the research. Thus the proposed project will largely be completed, but on a delayed schedule from what was initially proposed. Below we present the results of this research up to May 2014.
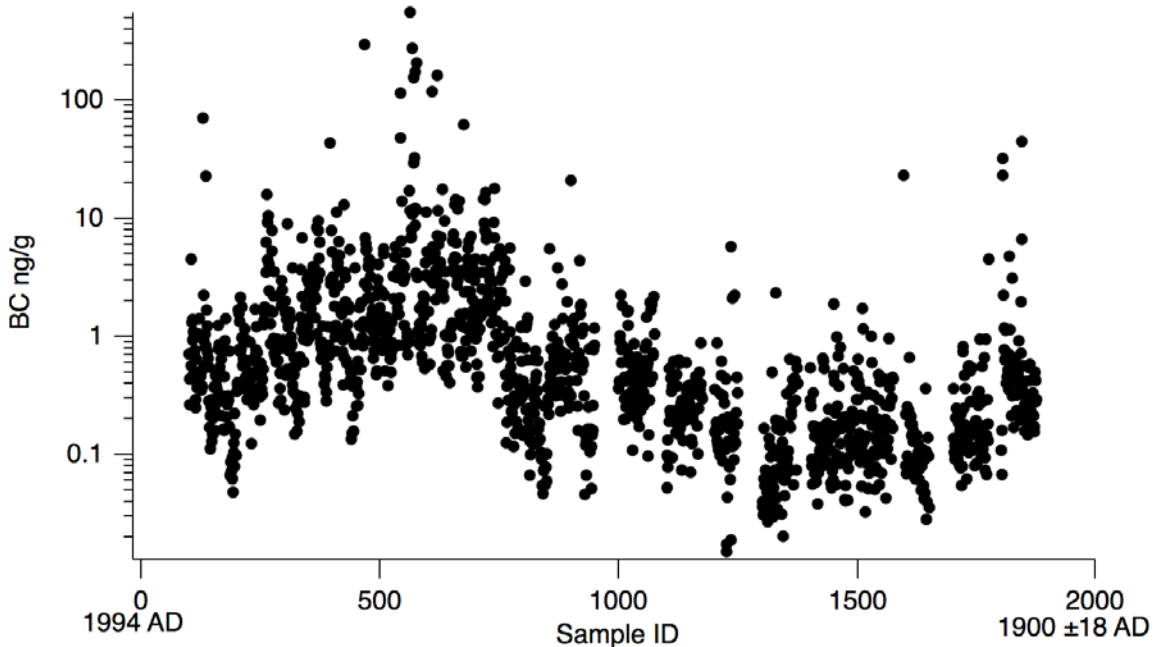

Figure 7: Preliminary BC data from the South Cascade Ice Core. 1994 AD marks the top of the record, and 1900 ±18 AD marks the bottom of the record based on ^{210}Pb dating.

BC record
The South Cascade ice core BC record is 75% complete. Based on the preliminary data (Figure 7) there are several notable findings:
1. There is a clear trend to the record, with BC concentrations relatively low in the oldest part of the record (samples 1000-1989), approximately a magnitude higher for samples ~300-700, and a return to lower concentrations for the most recent portion of the record.
2. The period of high BC concentrations (samples ~300-700) is evident in the maximum and background concentrations, suggesting a period of continuously higher BC concentrations in the atmosphere during this time. Once dated, this record will be very valuable in reconstructing past atmospheric concentrations of BC.
3. BC concentrations were measured in high enough concentrations to result in a marked reduction in the glacier albedo, particularly during the period of time when BC is elevated (samples ~300-700) and BC concentrations are in excess of 100 ng/g. Lower glacial albedo causes greater energy absorption, which causes melt.
4. Based on visual observations of a thin black layer in the ice core, the source of many of the high BC concentrations layers is likely from forest fires.
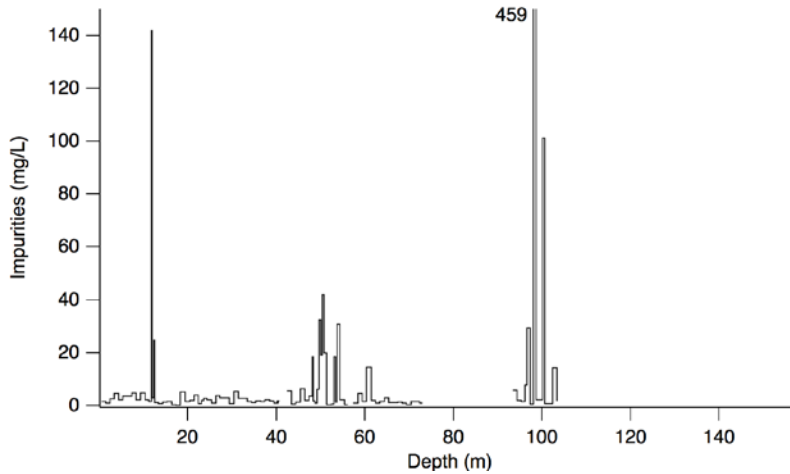
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Figure 8: Preliminary gravimetric impurity data from the South Cascade ice core.

Impurity record

The gravimetric impurity record is 50% complete (Figure 9). Based on the preliminary record, it appears that background concentration of impurities deposited on the glacier is ~4 mg/L, punctuated by periods with high impurity concentrations. Visual inspection of the filters used to capture the impurity mass indicates that the composition of the impurities changes over time (Figure 9). The record will need to be completed and compared to the BC record to inform our interpretation of LAI deposited on South Cascade glacier.

Figure 9: Filters showing optical differences in impurities deposited on South Cascade Glacier (bottom, including ice core depths), and black and white Spectralon color standards (top).

Further work

We are completing the BC and gravimetric impurity analyses on the South Cascade ice. Additional work that needs to be completed includes:

1. Dating the ice core. The stable isotope analyses (not supported by this grant) are nearly complete, and remaining sample volume will be sent to New Zealand for tritium analysis. We will integrate the tritium and ^{210}Pb data into a glacier flow model to date the ice core record.
2. Conduct ICPMS analysis on select high impurity samples. The iron and BC data will be used to assess the relative absorption of solar energy from dust versus BC.
3. Calculate historic albedo reductions using the Snow, Ice, and Aerosol Radiation (SNICAR) model (Flanner et al., 2007). The modeled albedo reductions will enable energy balance calculations to be made (Ricchiazzi et al., 1998) to assess the role that LAI have played in 20th century glacial melt and the availability of water resources.

LIST OF STUDENTS SUPPORTED

-Dan Pittenger, Central Washington University MS student. Pittenger participated in processing the ice core at NICL, and is conducting the BC measurements under Kaspari's advisement. This project is the basis for Pittenger's MS theses.

-University of Colorado undergraduate students Nicholas Story and Garrett Rue assisted in processing the ice core at NICL for one week in June 2013.

-Three Central Washington University undergraduate students (Katarina Wells, Curtis Reid, and Beck Luchansky) conducted the gravimetric impurity analyses. The research supplies and their time were supported by Central Washington University.

PRESENTATIONS

 An abstract including results from this study has been submitted to the Pacific Northwest Climate Conference to be held in Seattle, WA in September 2014. Additionally the results of this research will be presented by Pittenger and Kaspari at the American Geophysical Union fall meeting in December 2014.

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