Boreal blazes: biomass burning and vegetation types archived in the Juneau Icefield

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Abstract

The past decade includes some of the most extensive boreal forest fires in the historical record. Warming temperatures, changing precipitation patterns, the desiccation of thick organic soil layers, and increased ignition from lightning all contribute to a combustive combination. Smoke aerosols travel thousands of kilometers, before blanketing the surfaces on which they fall, such as the Juneau Icefield. However, many aerosols found in smoke plumes are also produced by other processes and therefore can be ambiguous indicators of fire activity. Here, we use the monosaccharide anhydrides levoglucosan, mannosan, and galactosan as specific indicators of biomass burning to unambiguously demonstrate that fire aerosols reach the Juneau Icefield and are integrated into the snowpack. Back trajectories and satellite observations demonstrate that smoke plumes originating in central Alaska and eastern Siberia affect the Juneau Icefield. These regional sources of fire differ from other combustion aerosols deposited on the Juneau Icefield, such as black carbon, that originate from local fossil fuel burning. Ratios of levoglucosan/mannosan (L/M) and levoglucosan/(mannosan + galactosan) (L/(M + G)) demonstrate that while the majority of fire aerosols reaching the Juneau Icefield originate from softwood burning, grasslands and hardwood forests are also sources. The presence of these hardwoods suggests that fire aerosols may reach the Juneau Icefield from locations as far away as East Asia.

1. Introduction

Massive fires have occurred in Siberia and interior Alaska over the last decade. Wildfire activity in the Arctic is expected to increase dramatically, potentially leading to far-reaching consequences on ecosystems and socioeconomic conditions (Kelly et al., 2013; Young et al. 2017). These fires are due in part to increasing temperatures and shifts in precipitation patterns, where the Arctic is one of the most rapidly warming regions of the world (Stjern et al. 2019).

Warmer Arctic temperatures, coupled with dark aerosols from fires and fossil fuel combustion, also influence Arctic glaciers and ice (Chung et al. 2005). Soot, black carbon (BC) and mineral dust all darken the bright surfaces of glaciers, absorbing more solar radiation, and can accelerate surface melt (Nagorski et al. 2019, and references therein). The low elevation (mostly below 2000 m) of glaciers in Southeast Alaska result in some of the most quickly melting glaciers anywhere on the planet (Radic et al., 2011, Sutherland et al. 2019). The meltwater pours into the ocean, freshening the saltwater, as well as depositing sediments, thereby affecting the coastal ecosystem and fisheries that are a vital economic resource (O’Neil et al. 2015).

Fires emit a combination of chemicals and aerosols into their smoke plumes including lignins, polycyclic aromatic hydrocarbons (PAHs), monosaccharide anhydrides (MAs) and a spectrum of combustion products ranging from black carbon to ash. Boreal fires can belch smoke plumes into the stratosphere,
creating their own pyrocumulus clouds and lightning storms, impacting the atmosphere as much as a volcanic eruption (Peterson et al 2018). While less dramatic than crown fires, the desiccation and burning of highly organic soil in the tundra is the largest contributor of carbon from combustion to the atmosphere (Walker et al 2019). Arctic fires are regularly left to burn until they naturally extinguish themselves through rainfall or running out of fuel. Earth observing satellites are often the first means of detecting these fires due to their remote locations and provide valuable information for how their aerosols are distributed over the Arctic.

Since soot, ash, and BC are combustion products arising from multiple fuels including natural (e.g. forests and grasslands) and anthropogenic (fossil fuel) sources, interpreting the contribution of biomass burning to these combustion aerosols requires specific molecular markers. Monosaccharide anhydrides (MAs), and specifically levoglucosan (1,6-anhydro-β-D-glucose), mannosan (1,6-anhydro-β-D-mannopyranose), and galactosan (1,6-anhydro-β-D-galactopyranose) are only produced by burning cellulose and/or hemicellulose at temperatures centered around 250 °C (Kuo et al 2011). These burning temperatures suggest that MAs can capture relatively low-temperature fires such as burning grasslands but are also detectable in the emissions from higher temperature burns associated with the combustion of conifers (predominantly softwood) and deciduous forests (predominantly hardwood). Once emitted into the atmosphere, MAs can travel for thousands of kilometers (Pashynska et al 2002, Simonet et al 2004) before returning to the surface through both wet and dry deposition. All three isomers remain stable in ice and sediments for thousands of years (Simoneit et al 2004; Schüpbach et al 2015, Zennaro et al 2015; Argiriadis et al, 2018). The atmospheric lifetime of MAs depends upon relative humidity and exposure to hydroxyl radicals, with resulting atmospheric lifetimes of a few days (Hennigan et al 2010; Hoffman et al, 2010) to multiple weeks (Bai et al, 2013; Slade and Knopf, 2013). Here, we simultaneously quantify levoglucosan, mannosan and galactosan in snow and ice to determine: (1) whether fires deposit material on the Juneau Icefield, (2) how these fire depositions vary regionally across a transect, and (3) the composition of fire fuel sources.

2. Methods

2.1. Study area

All field work was carried out by cooperating with the Juneau Icefield Research Program (JIRP). We drilled a series of four firm cores in 2016 and two cores in 2017 (figure 1). The drilling sites were selected as the highest, flattest areas on saddles between glaciers in order to minimize the effects of any meltwater percolation or glacier movement on the cores. The sites were also selected to be at the top of different glacier valleys to investigate if there were any noticeable differences in chemical and stratigraphic records which may be due to the effects of upslope winds. The one exception is 2017 Core 1 which was selected because it is the site of 70 continuous years of mass balance data (O’Neil et al 2019). The 2016 core numbering is based on the order in which they were collected (figure 1). Core locations are also dependent upon their accessibility by ski.

The JIRP cores compose a transect that spans the high-precipitation southwestern slopes of the Juneau Icefield, to the relatively drier sites of the central plateau, and ends at the top of the Llewellyn Glacier, which is experiencing some of the most dramatic melt on the entire icefield (figure 1). Although annual accumulation rates vary across the Juneau Icefield, these maritime glaciers receive up to 10 m of precipitation per year (Miller and Pelto 1999). The majority of precipitation arrives between September and January from eastward-moving North Pacific frontal storms that encounter Southeast Alaska as one of the first land masses, resulting in the high precipitation (Nagorski et al 2019). Summer precipitation currently arrives as both rain and snow, where these rain-on-snow events are projected to increase in the future due to climate change (Shanley et al 2015). We collected the 2017 cores during especially rainy weeks in late June and early July when only 2 d were precipitation-free. We did not observe any pooling of water on the snow surface, but the 2017 core sections were consistently ‘wetter’ snow than the 2016 cores. A 209 m deep test ice core drilled in 2019 from the center of the Juneau Icefield (located near 2017 Core 2) demonstrated that the upper approximately 50 m of the firn was water saturated. This water may be due to rain-on-snow events and/or meltwater percolation.

2.2. Drilling

We drilled the cores using a Kovacs Mark II coring system. Each core section was 9 cm in diameter and between 72 cm and 1 m in length depending on the individual core. The final depth of each core was influenced by the presence of impenetrable ice layers. Each core contained at least one thick ice layer within the core, likely from summer melting, suggesting that each core encompasses more than one year of snowfall. The core stratigraphy and densities were analyzed in the field. The cores were cut into 10 cm sections, homogenized, and placed into previously washed 60 ml HDPE Nalgene bottles, and then triple bagged. Samples were carried in backpacks while skiing to the JIRP camps. The samples were flown by helicopter and then cargo plane from the Juneau Icefield to Denver, CO, and were unable to remain in a frozen state during transport. After arrival in the laboratory, the samples were frozen at −10 °C until analysis.
2.3. Stable isotopes
A total of 322 samples from JIRP 2016 Cores 1–4 were analyzed in the ice core chemistry laboratory at Dartmouth College using a L2120-i Picarro water isotope analyzer with Cavity Ring-Down Spectroscopy for determining stable oxygen and hydrogen isotopes ($\delta^{18}$O and $\delta^D$). The instrument was calibrated by using International Atomic Energy Agency (IAEA) standards including Vienna Standard Mean Ocean Water (VSMOW) and Greenland Ice Sheet Precipitation (GISP) standards with known $\delta^{18}$O and $\delta^D$ values. Three standards were placed at the beginning and end of each Picarro run, along with standards placed every 20 consecutive JIRP samples.

2.4. Dust
We analyzed particle count and size distribution using an Abakus (Klotz) laser particle counter and particle size analyzer in the ice core chemistry laboratory at Dartmouth College on 322 JIRP samples (2016 Cores 1–4). A peristaltic pump (2 min at a pump rate of 5.8 rpm) drew water from each 20 ml vial of a thawed JIRP sample. The capped vials containing JIRP samples were weighed before and after the sample was drawn to calculate volume per analyzed sample. As the Abakus is a continuous online analyzer, we ran blank samples from a Milli-Q water purifier between each JIRP sample for approximately 2 min to create separation between samples. The conductivity meter attached to the Abakus ensured that samples were constantly flowing during analysis.
2.5. Dating
The JIRP cores are not independently dated as they are 10 m firm cores of surface accumulation that do not extend deep enough to encompass absolute markers such as peaks in beta radioactivity resulting from atmospheric thermonuclear bomb tests in the 1950s and 1960s. Due to the high accumulation rates of as much as 10 m per year, with up to 3 m of annual mass loss, the JIRP cores likely only comprise a total of a few years (Miller and Pelto 1999, O’Neel et al. 2019). We use minima in $\delta^{18}O$ and $\delta^D$ near 4 m in each 2016 core as the winter 2015/2016 precipitation, where the snow above this minima is considered as 2016 deposition, and the snow below this minima is considered as from 2015 (figure 2). These features are consistent between the 2016 cores, even with their geographic variation (figures 1 and 2).

2.6. Major ions
All 322 JIRP samples from 2016 Cores 1 to 4 were analyzed for Na$^+$, K$^+$, NH$_4^+$, Mg$^{2+}$, Ca$^{2+}$, Cl$^-$, NO$_3^-$, and SO$_4^{2-}$ at South Dakota State University (figure 2). The analysis was carried out using two Dionex (Thermo Scientific) ICS-1500 Ion Chromatography Systems (one for anions and one for cations), each injecting a sample volume of 125 µL. External calibration standards were diluted from stock solutions made from Certified ACS solid
reagents. Procedural blanks comprising ultrapure water were used to ensure lack of contamination.

2.7. Monosaccharide anhydrides
We created a GC-MS/MS analytical method to separate the isomers galactosan, mannosan, and levoglucosan, resulting in the first time that all three isomers can be quantified in ice core samples with initial sample sizes of 2 ml or less (figures 3, 4, and 5). In short, 1.0 ml of melted ice samples were evaporated to dryness, derivatized with a mixture of N,O-bis-(trimethylsilyl)trifluoroacetamide + 10% trimethylchlorosilane (BSTFA + 10% TMCS) combined with pyridine in a 2:1 (v:v) ratio, and analyzed in multiple reaction monitoring (MRM) mode using an Agilent Technologies 7890 gas chromatograph coupled to an Agilent 7000 triple quadrupole mass spectrometer. The MRM transition ions included m/z 333 as the precursor ion and three diagnostic product ions at m/z 171, 143, and 103. Quantification of the derivatized MAs was based on an isotopic dilution calibration procedure using chromatographic peak area ratios of the individual MAs to that of levoglucosan-$^{13}$C$_6$ spiked into each sample.

The method detection limits (MDLs) are 150, 70, and 140 pg ml$^{-1}$ for galactosan, mannosan, and levoglucosan. MDLs were determined using the U.S. Environmental Protection Agency (EPA) statistical approach of multiplying the standard deviation of a low calibration standard (n = 8) by the corresponding single-tailed student t-value at the 99% confidence interval (USEPA, 2016). Ice core sample data were also eliminated when the chromatographic peaks for the analyte had a signal to noise ratio less than 3 or an elution time greater than ± 0.05 min from the expected retention time. 2016 Cores 1–3 contain individual points with concentrations that are orders of magnitude greater than the rest of the data in the cores (Supplementary Information figures 1–3 available at stacks.iop.org/ERL/15/085005/mmedia). These individual points contain neighboring samples that also have relatively high concentrations, suggesting the influence of either a large fire or a nearby fire. In order to visualize the variability in the MAs without the influence of these individual points, but in order to still preserve the peaks, we smoothed the data using a locally weighted regression (loess) with a sampling proportion of 0.100 and a polynomial degree of 1 (figure 3). The mannosan concentrations in 2017 Core 1 and all MA concentrations in 2017 Core 2 contain too many gaps in the data due to samples below the method detection limits to allow applying a loess regression (figure 3(b)).

3. Results

The core depths of the $\delta^{18}$O and $\delta$D minima in the 2016 Cores 1 and 3 suggest that they were subject to slightly higher accumulation than the 2016 Cores 2 and 4 where this accumulation could be from either precipitation or windblown snow (figure 2). Even with these local differences, the isotope and particle size data remain remarkably consistent between the 2016 JIRP cores, suggesting a continuity of events across the icefield (figure 2). The 2017 cores were collected a year after the 2016 cores, and thus are not included in the comparison of the depths of events (figure 2) as they contain an additional year of accumulation. The 2017 cores encompass a record of MAs (figures 3 and 4) but not stable isotopes or major ions, and therefore we can only compare MAs between the 2017 and 2016 cores. The peaks in levoglucosan, mannosan, and galactosan, at the depth of ~ 5 m in the 2017 cores may correspond to the uppermost fire peaks in the 2016 cores, which is within the range of Juneau Icefield accumulation rates (figure 3).

Levoglucosan is present in higher concentrations than its isomers mannosan and galactosan (figure 3). Levoglucosan and mannosan peak at similar depths in an individual core, but galactosan can peak at depths that differ from the other two isomers, such as in 2016 Core 1 (figure 3(a)). This difference in the concentrations between the three isomers allows for investigating the ratios between levoglucosan, mannosan and galactosan, which in turn can help identify what vegetation types burned in the past (figures 4 and 5). While the depths of the individual isomers vary (figure 3), the depths of peaks in the ratios are consistent between cores that are geographically closer to one another (e.g. 2016 Cores 1 and 4; figure 4). The peaks in the three individual isomers and their ratios in the 2016 cores demonstrate a major fire in both the summer of 2016 and 2015 where smoke aerosols were deposited on the Juneau Icefield (figures 2–5).

4. Discussion

Juneau Icefield summer temperatures are often well above 0 °C resulting in slushy snow on glacier surfaces, where this melt is accelerated by light absorbing particles including BC (Nagorski et al 2019). The summer mass loss on the Mendenhall Glacier on the southwestern section of the Juneau Icefield (figure 1) is approximately 3 m of snow water equivalent (Motyka et al 2003). The Lemon Creek Glacier, the site of 2017 Core 1, records a similar mass loss of 3.1 m water equivalent per year (O’Neel et al 2019). The dark aerosols accelerate melt on the surface but do not affect the snow chemistry in the upper ~2 m of the snowpack (Nagorski et al 2019). Fire aerosols (MAs) neither peak nor dip with the stable isotope minima suggesting that, similar to snow pit and surface analyses of BC and mineral dust (Nagorski et al 2019), the surface melt does not affect the distribution of MAs within the snowpack (figures 2 and 3). This lack of influence of melt on the MA concentrations
in the snow allows examining the differences in MAs throughout the cores.

The concentrations of MAs in the Juneau Icefield samples are within the range of other Northern Hemisphere MAs recorded in ice. The majority of levoglucosan concentrations in Tibetan Plateau ice cores are less than 1000 pg ml$^{-1}$ (You and Xu 2018, and references therein), up to 1445 pg ml$^{-1}$
Figure 4. L/M ratios across the Juneau Icefield transect. The cores are plotted in order of their location as shown on figure 1.

in the deep NEEM, Greenland ice core (Zennaro et al. 2014) and up to 600 pg ml\(^{-1}\) (Kehrwald et al. 2012) in a Greenland snow pit. However, these locations are half a hemisphere away from Alaska. The Ushkovsky, Kamchatka ice core (Kawamura et al. 2012) provides a North Pacific record of MAs, where the majority of the detections are less than 3000 pg g\(^{-1}\) ice between 1700 to 2000 CE (Kawamura et al. 2012). The Aurora Peak, Alaska ice core is the geographically closest record of levoglucosan to the Juneau Icefield. The Aurora Peak record does not quantify mannosan or galactosan and has a mean levoglucosan concentration of 543 pg g\(^{-1}\) from 1650 to 2010 CE, which is substantially less that the Kamchatka results. Arctic ice core records of MAs can extend as far back as 15 000 years ago (Zennaro et al. 2015). As Arctic fires increase in number and intensity, these paleofire records help identify trends in fire-climate-vegetation relationships. Analysis of MAs in ice cores provide essential data of past wildfires where few or no such records exist.

4.1. Specificity of MAs
Because levoglucosan, mannosan, and galactosan can only be produced by biomass burning (Kuo et al. 2011), the presence of these MAs unequivocally demonstrates that fires deposit aerosols on the Juneau Icefield (figure 3). The specificity of these markers contrasts with the potassium concentrations in the same cores, where potassium is sometimes used as an indicator of biomass burning (figures 3 and 4). However, water-soluble potassium can be
transferred with sea salts, be a product of biological activity (Rankin and Wolff 2000), or arrive at glacier surfaces with mineral aerosols (Laj et al 1997). The calcium to potassium ratio (Ca/K) helps determine the relative contribution of fires versus mineral dust, where a lower Ca/K number indicates a potential fire source (figure 3). Only 2016 Core 4 contains a Ca/K minima which corresponds to a peak in potassium as well as peaks in levoglucosan and mannosan at ~4.2 m (figures 2 and 3(a)). Therefore, levoglucosan, mannosan, and galactosan record fires that otherwise would have been missed by other markers (figures 2 and 3). This partial correspondence between the specific fire markers of MAs and other biomass burning proxies with multiple sources is consistent with results from a Greenland snow pit (Kehrwald et al 2012) and deep ice cores (Zennaro et al 2014, 2015).

4.2. Fires and fossil fuel combustion

Juneau, Alaska, is the largest city near the Juneau Icefield, with a population of approximately 35 000 people. The vegetation surrounding the Juneau Icefield is primarily temperate rainforest that rarely naturally burns, with many coastal sites not experiencing fire for as long as 6000 years (Lertzman et al 2002). We therefore discount local vegetation burning as a possible source of MAs to the Juneau Icefield. Household fires do not produce smoke plumes that extend as high into the atmosphere as boreal forest fires. If household fires from Juneau were the main source of the biomass burning aerosols to the icefield, the highest levoglucosan, mannosan, and galactosan concentrations would be expected to occur on the southwestern section of the icefield, near Juneau. The 2017 JIRP cores, which are those that are
Figure 6. (A) MODIS imagery from July 11–27, 2016, for the Steamboat Creek fire (light blue triangle), the candidate fire for the summer of 2016 biomass burning signal identified in the JIRP cores (green star HYSPLIT modeling of the Steamboat Creek 2016 wildfire. The backward trajectories (B) represent the temporally regressive movement of aerosols from the JIRP core drill site and the (C) forward trajectories represent the temporally progressive movement of aerosols from the Steamboat Creek fire.

located closest to the coast, contained the greatest number of samples that were below the MA levels of detection. These low concentrations in the 2017 cores may be due to the lack of or limited input from local fires or possible dilution from the anomalously high rain and snow events during June and July 2017.

The generally higher concentrations of MAs with distance from Juneau (figures 1, 4, and SI figures 1–3) differs from the distribution of BC across the icefield (Nagorski et al 2019). BC samples that were collected in May 2016 before the start of the summer melt season demonstrate that both BC and mineral dust concentrations were highest at the perimeter of
the icefield. As the melt season continued, both surface BC and mineral dust concentrations increased by up to a factor of 10, with no noticeable influence on concentrations due to elevation or the distance from the coast (Doherty et al 2013, Nagorski et al 2019). These high BC and mineral dust concentrations remained at the surface and did not migrate deeper into the～2.4 m of sampled snowpack (Nagorski et al 2019). The sources of BC are likely due almost entirely to local fossil fuel burning (Nagorski et al 2019). As hydropower provides almost all of Juneau’s electricity, transportation is one of the main sources of fossil fuel burning (ADEC 2009). Cruise ships ply the Inland Passage and helicopter tours carry people over the icefield, supplying services to the over one million tourists who visit the region each summer.

While local household fires and neighboring temperate rainforests that rarely burn may not contribute

Figure 7. (A) MODIS imagery from June 18–28, 2015, for the Dennison Fork fire (light blue triangle), the strongest candidate for the 2015 summer biomass burning signal identified in the JIRP cores (green star). Note the high amount of fire pixels in the surrounding area, not associated with the Dennison Fork fire. HYSPLIT dust modeling of the Dennison Fork 2015 wildfire. The backward trajectories (B) represent the temporally regressive movement of aerosols from the JIRP Core drill site and the forward trajectories (C) represent the temporally progressive movement of aerosols from the Dennison Fork fire.
fire aerosols to the Juneau Icefield, the quantifiable presence of MAs demonstrates that fire aerosols definitively reach the icefield (figure 3). MAs can be transported for up to thousands of kilometers in the atmosphere (Zhu et al. 2015, and references therein) where regional to transcontinental fire plumes can influence the Juneau Icefield (figures 6–8, and SI figures 4 and 5). Compilations of TERRA/MODIS imagery of active fires for 8-day intervals during the 2016 and 2017 drilling seasons demonstrate candidate fires in eastern Siberia and central Alaska (SI figure 4). A single summer of Eastern Siberian fires burned ~ 24,000 km² as of mid-August 2019 (NASA; Huge fires in Russia’s Siberian Province continue; Accessed August 22, 2019), which is larger than the area of the entire country of Slovenia or about the size of the U.S. state of Vermont. Fire aerosols from these boreal burns can reach SE Alaska (figure 8, SI figures 4 and 5). Regional Alaskan fires demonstrate links between individual fires and deposition on the Juneau Icefield as documented by both forward and back trajectories (HYSPLIT; 500 m AGL, 192 h run time, trajectories every 8 h; Dunham et al. 2018; figures 6 and 7). Levoglucosan, mannosan, and galactosan are sugars that do not darken the surface of glaciers by themselves, but

Figure 8. Smoke from Siberian fires traveling towards Alaska. This satellite image was collected by NASA/NOAA Suomi National Polar-orbiting Partnership (S-NPP) on July 29 (U.S. half) and July 30 (Siberian half), 2019. The red points in Siberia and Alaska denote actively burning fires. Image Courtesy: NASA Worldview, Earth Observing System Data and Information System (EOSDIS). Accessed August 20, 2019: https://www.nasa.gov/image-feature/goddard/2019/siberian-smoke-heading-towards-us-and-canada.
accompanying dark aerosols from fires can change glacier albedo (Xu et al 2009). Regional fires and local fossil fuel burning therefore both contribute aerosols to the Juneau Icefield, with implications for glacier melt (Zieman et al 2016, Nagorski et al 2019, O’Neel et al 2019).

4.3. Vegetation
The ratios of L/M and L/(M + G) may distinguish between types of vegetation that burned (Fabbri et al 2008; Kirchgeorg et al 2014). Although the ratios can overlap between vegetation types, (Oros and Simoneit 2000) argue that L/M ratios greater than 22 only indicate grassy vegetation. Other ratios are less specific where L/M and L/(M + G) ratios of 0.6–13.7 and 0.4–6.1 represent softwood combustion, while 3.3–22 and 1.5–17.6 characterize hardwood burning, and 2.0–33.3 and 1.7–2.5 depict grass combustion (Oros and Simoneit 2000, Nolte et al 2001, Pashynka et al, 2002; Fine et al 2004, 2004, Yttri et al 2005, Engling et al 2006, Ward et al 2006, Schmidl et al 2008, Fabbri et al 2008). Softwood burning therefore does not have a specific indicator, and the L/M and L/(M + G) ratios for organic soil burning are currently unknown. Because much of the Arctic fires burn conifer forests and organic soil (Mack et al 2011, Walker et al 2019), the L/M and L/(M + G) ratios therefore highlight vegetation that is less common in boreal burning.

All cores contain peaks with L/M ratios above 22, indicating grassy vegetation as a source (figure 6). The 2016 cores do not all contain these peaks at similar depths but do have similar peaks with their neighboring cores. 2016 Cores 2 and 3 both demonstrate grassy vegetation as a source for fire aerosols at a depth of ~6.5 m, while 2016 Cores 1 and 4 contain wide peaks between ~4 and 5.5 m depth. The 2017 Cores 1 and 2 both demonstrate L/M ratios above 22 at a depth of ~1.75 m. The majority of the L/(M + G) ratios are within the 0.4 to 6.1 and/or 1.7 to 2.5 ranges (figure 6) that represent softwood and grassy vegetation burning, respectively. All cores contain evidence of fire aerosols from hardwood burning, with congruent peaks between 2016 Cores 1, 3, and 4, and similar peaks between the two 2017 cores.

Conifer forests dominate southern Alaskan vegetation, although stands of poplar and birch in south-central Alaska are a potential source (Anderson et al, 2019, and references therein). Kenai Lowlands fire return intervals are ~194 years (Lynch et al 2004). Birch and poplar are relatively rare in both interior and south-central Alaska and primarily only grow in well-drained areas (Lynch et al 2002). Although the majority of the source regions are the coniferous forests draping central Alaska and eastern Siberia, a similar signal of hardwood burning is also evident in the Kamchatka ice core (Kawamura et al 2012), which has a primarily Siberian source of aerosols. (Kawamura et al 2012) ascribe this hardwood signal to East Asian forests south of Siberia. Asian aerosols account for half of the aerosols in the atmosphere over North America (Yu et al 2012), and while the majority of these aerosols are mineral dust, combustion products form part of this aerosol mixture. East Asian forests may therefore also contribute to the fire aerosols reaching the Juneau Icefield.

5. Conclusions
Fire aerosols are unequivocally deposited on the Juneau Icefield, where the impact of these fires remains relatively spatially consistent across the icefield. These fires originate in central Alaska and eastern Siberia, with a minor influence from fires in central East Asia, as suggested by the contribution of hardwood combustion aerosols. While MAs themselves are colorless anhydrosugars, these fire aerosols can be accompanied by other combustion products such as soot and ash that can diminish the albedo of the ice fields on which they are deposited. The presence of MAs depicting regional or transcontinental fires provide a comparison with combustion products such as BC that derive from local fossil fuel burning (Nagorski et al 2019). Knowing the origin of aerosols (e.g. wildfires versus fossil fuel combustion) is essential in order to mitigate their effect on glacier melt. Emissions from local fossil fuel combustion are easier to manage than are aerosols from fires burning large areas of boreal forest from both nearby and distant sources.

The quantifiable presence of levoglucosan, mannosan, and galactosan on the Juneau Icefield demonstrates the opportunity for producing a longer North Pacific fire history recorded in these glaciers. The detections of MAs in ice core layers not only can build historical paleofire records for the North Pacific region, but the relative ratios of these MAs can provide valuable information on the types of vegetation burned during fires. As fires intensify in central Alaska and Siberia, such records of past fires are fundamental for placing recent fire activity into a longer timeframe and improving our understanding of fire-climate-vegetation interactions.

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Data Availability Statement:
The data that support the findings of this study are openly available at: https://doi.org/10.5066/P9DNAN1M

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