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Key Points:
- Aerosol black carbon (BC) concentrations observed in the McMurdo Dry Valleys of Antarctica were low, with the exception of local sources
- Insufficient BC is present in the accumulation area of McMurdo Dry Valley glaciers to significantly affect surface albedo
- A foehn wind event resulted in increased aerosol concentrations of rBC, likely due to resuspension of local BC on the valley floor

Supporting Information:
- Supporting Information S1

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Near-Surface Refractory Black Carbon Observations in the Atmosphere and Snow in the McMurdo Dry Valleys, Antarctica, and Potential Impacts of Foehn Winds

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Abstract Measurements of light-absorbing particles in the boundary layer of the high southern latitudes are scarce, particularly in the McMurdo Dry Valleys (MDV), Antarctica. During the 2013–2014 austral summer near-surface boundary layer refractory black carbon (rBC) aerosols were measured in air by a single-particle soot photometer (SP2) at multiple locations in the MDV. Near-continuous rBC atmospheric measurements were collected at Lake Hoare Camp (LH) over 2 months and for several hours at more remote locations away from established field camps. We investigated periods dominated by both upvalley and downvalley winds to explore the causes of differences in rBC concentrations and size distributions. Snow samples were also collected in a 1 m pit on a glacier near the camp. The range of concentrations rBC in snow was 0.3–1.2 ± 0.3 μg-rBC/L-H_2O, and total organic carbon was 0.3–1.4 ± 0.3 mg/L. The rBC concentrations measured in this snow pit are not sufficient to reduce surface albedo; however, there is potential for accumulation of rBC on snow and ice surfaces at low elevation throughout the MDV, which were not measured as part of this study. At LH, the average background rBC mass aerosol concentrations were 1.3 ng/m^3. rBC aerosol mass concentrations were slightly lower, 0.09–1.3 ng/m^3, at the most remote sites in the MDV. Concentration spikes as high as 200 ng/m^3 were observed at LH, associated with local activities. During a foehn wind event, the average rBC mass concentration increased to 30–50 ng/m^3. Here we show that the rBC increase could be due to resuspension of locally produced BC from generators, rocket toilets, and helicopters, which may remain on the soil surface until redistributed during high wind events. Quantification of local production and long-range atmospheric transport of rBC to the MDV is necessary for understanding the impacts of this species on regional climate.

Plain Language Summary Measurements of light-absorbing particles in the boundary layer of the high southern latitudes are scarce, particularly in the McMurdo Dry Valleys (MDV), Antarctica. During the 2013–2014 austral summer near-surface black carbon (BC) aerosols were measured in air by a single-particle soot photometer at multiple locations in the MDV, as well as in a 1 m snow pit. The BC concentrations in snow are too low to influence the surface albedo. Average atmospheric BC concentrations were also low, except during local activities and during a foehn wind event when the average BC concentration increased by more than a factor of 30. Here we show that the BC increase could be due to resuspension of locally produced particles, which may remain on the soil surface until redistributed during high wind events. Quantification of local production and long-range atmospheric transport of BC to the MDV is necessary for understanding the impacts of this species on regional climate.

1. Introduction

The McMurdo Dry Valleys (MDV) is the largest ice-free region of Antarctica with extensive exposed areas of soil, alpine and terminal glaciers, meltwater streams, and perennially ice covered lakes. The MDV, shown in Figure 1, is a cold polar desert with average air temperatures of −18°C (Doran et al., 2002). The average range of precipitation, which comes as snow, is 3 to 50 mm of water equivalent each year (Fountain et al., 2010). The predominant wind direction is from McMurdo Sound and toward the East Antarctic Ice Sheet (EAIS). However,

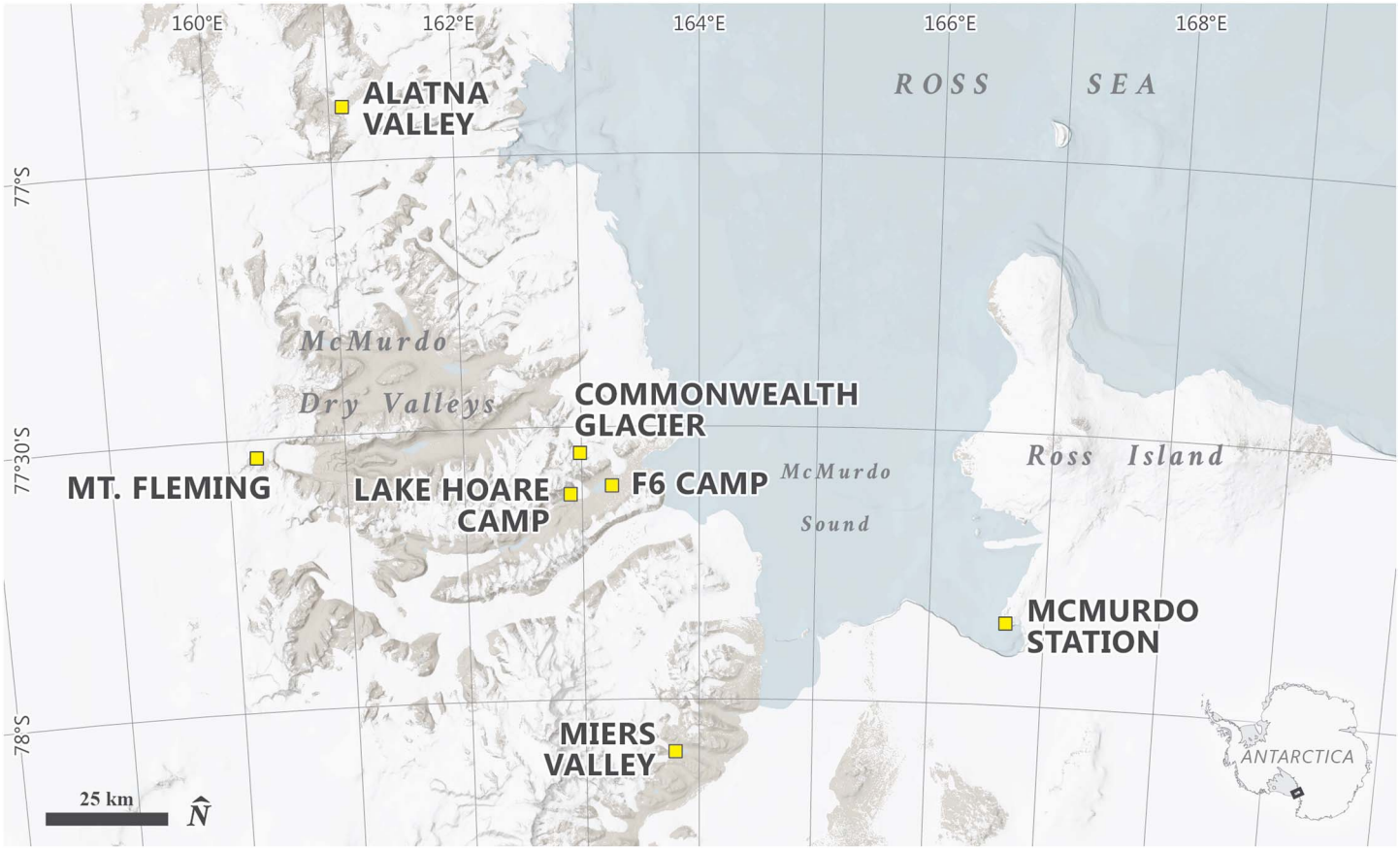

Figure 1. Map of sampling sites within the McMurdo Dry Valleys.

foehn wind events, first introduced as katabatic winds (Nylen et al., 2004) and later identified as foehn winds (Speirs et al., 2010; Steinhoff et al., 2014), change the wind direction, bringing cold air from the polar plateau of the EAIS which expands, warms, and accelerates as it flows down through the MDV. These foehn wind events are more prevalent in winter months, with average wind speeds >6 m/s. Eolian transport of marine aerosols and valley floor sediments has been shown to influence snow chemistry in the accumulation area of the MDV glaciers (Lyons et al., 2007; Witherow et al., 2006) and thus contributes solutes and potentially other species to glacial meltwater entering the streams and lakes (Lyons et al., 2003).

Studying the chemistry of polar snowpacks in glacial accumulation areas can help decipher long-term aerosol chemistry. Previously reported total organic carbon (TOC) concentrations in snow on the Commonwealth Glacier in the MDV are very low, <8 μM, suggesting that terrestrial and anthropogenic emissions of organic carbon have little influence on coastal Antarctic snow (Lyons et al., 2007). TOC deposition was found to negatively correlate with sea-salt aerosols (Lyons et al., 2007) on Commonwealth Glacier, with highest TOC concentrations occurring as sea ice extent is decreasing during the spring to summer period through early winter, whereas Cl^- concentrations are suggested to be highest when sea ice extent is at a minimum (Legrand & Mayewski, 1997).

Black carbon (BC) is a light-absorbing aerosol (LAA) generated as a byproduct of combustion of biomass burning and fossil fuels (Goldberg, 1985) and has important impacts on atmospheric radiation, air quality, and surface albedo (Bond et al., 2013). Deposition of LAAs such as mineral dust and BC on snow/ice reduces the surface albedo and can lead to earlier and more rapid snow/ice melt (Kaspari et al., 2013; Painter et al., 2010). The presence of BC has been confirmed on the Antarctic continent (Bauer et al., 2013; Bisiaux et al., 2011, 2012; Warren & Wiscombe, 1981). Biomass burning in Australia, South America, and Africa has been found to be the primary source of BC in the Southern Hemisphere (Crutzen & Andreae, 1990). New Zealand and Australia have also been shown to be key sources of mineral dust to Antarctica (Neff &

Table 1
Average Aerosol rBC Concentrations Across MDV

Sample location	Geographic position	Average BC (ng/m^3)	Instrumentation method	Run time	Reference
Mt. Fleming	77°32′01.86″S, 160°14′38.26″E	0.09	SP2	1 h	This study
Alatna Valley	76°54′00.43″, 161°06′39.60″E	0.11	SP2	1 h	This study
F6 Camp	77°36′29.95″S, 163°15′20.45″E	4.6, 0.15	SP2	3 h	This study
Lake Hoare Camp	77°37′23.32″S, 162°54′04.05″E	1*	SP2	1 month	This study
Miers Valley	78°05′47.45″S, 163°47′23.27″E	1.3	SP2	3 h	This study
Halley Station	75°35′S, 26°14′W	0.3–2.0	Aethalometer		Wolff and Cachier (1998)
Neumayer Station	70°39′S, 08°15′W	2.6	Aethalometer		Weller et al. (2013)
Lake Hoare Camp	77°37′23.32″S, 162°54′04.05″E	5	Aethalometer		
South Pole Station	90°S	<8	Aethalometer		Sheridan et al. (2016)
Ferraz, King George Island	62°05′S, 58°23′W	8.3	Aethalometer		Pereira et al. (2006)
McMurdo Station	77°51′S, 166°41′E	~20 to ~300	Aethalometer		Hansen et al. (2001)

Note. Local contamination up to 200 ng/m^3. This study refers to refractory black carbon (rBC) measured by single-particle soot photometer (SP2); the two F6 values are from during helicopter activity (4.6) and without helicopter activity (0.15). Previous studies reported below are referred to as effective black carbon (eBC) and measured by aethalometers.

Bertler, 2015). Regionally, measurements of refractory black carbon (rBC) mass in vertical profiles over the Pacific Ocean in the 60–65°S range by single-particle soot photometer (SP2) found that concentrations were <1 ng/m^3 (Schwarz et al., 2013).

Seasonal and decadal variations in long-range BC transport to Antarctica can occur due to climatic influences on biomass burning sources in the Southern Hemisphere. Bisiaux et al. (2012) showed that rBC transport to Antarctica was affected by El Niño–Southern Oscillation climate patterns due to changes in biomass burning, resultant aerosol emissions, and regional hydrology in the Southern Hemisphere. Two ice cores from the West Antarctic Ice Sheet (WAIS) and Law Dome on the edge of the EAIS displayed significant annual to decadal variability (Bisiaux et al., 2012).

Observations of equivalent black carbon (eBC) have been collected by aethalometers deployed at the Halley Station located on the Brunt Ice Shelf in the Weddell Sea (Wolff & Cachier, 1998), on the Antarctic Peninsula (Pereira et al., 2006), at Neumayer Station on the Eefkström Ice Shelf in the Northeast Weddell Sea (Weller et al., 2013), at McMurdo Station (Hansen et al., 2001), and over several decades at the South Pole Station (Bodhaine, 1995; Hansen et al., 1988; Sheridan et al., 2016; Warren & Clarke, 1990). In general, these studies found that eBC is present on the continent at low concentration (0.3–8.3 ng/m^3, Table 1) at their respective locations, with the exception of higher concentrations around field camps (~20 to ~300 ng/m^3 at McMurdo Station, Table 1). Previous measurements in the MDV region (Hansen, 2003) showed ~5 ng/m^3 equivalent eBC loads. Another important finding is that eBC concentrations in the boundary layer of the atmosphere decreases with proximity to the South Pole (Weller et al., 2013). At the Neumayer Station, there was no correlation of increased eBC or mineral dust concentration during periods of southerly katabatic flow (Weller et al., 2013). Katabatic winds are strong descending winds that bring cold high-density air from the polar plateau down the ice sheet to coastal Antarctica. It is important to note that these previous measurements on the Antarctic continent were collected by aethalometer, which measures eBC based on the amount of BC that would cause an equivalent amount of aerosol absorption; therefore, these loadings may also be attributable to non-rBC absorption.

Despite the existence of policies to minimize human impact in Antarctica, localized regions of human activity are vulnerable to local atmospheric transport of LAAs, such as BC. BC aerosol concentrations have been found to be highest close to research stations and camps. In the early 1980s it was documented that the South Pole Station produces enough local pollution to reduce the surface albedo of pure clean snow (Warren & Wiscombe, 1980; Warren & Clarke, 1990). In the MDV, regional transport of anthropogenic aerosols from McMurdo Station and local sources associated with science activities may add to the aerosols coming by long-range transport from the Southern Hemisphere from biomass burning and anthropogenic activities there. It was found that local pollution in the McMurdo Station area ranged from a low of 20 ng/m^3 to 300 ng/m^3 eBC when the winds came from the direction of the station during peak work hours (Hansen et al., 2001). Furthermore, in the MDV, the chemical signature of BC in the surface waters of MDV lakes has shown a shift in the past two decades toward modern anthropogenic sources of BC (Khan et al., 2016, 2017), while the

chemical signature of the BC in the brines in the lake bottom waters reflects an ancient biomass burning source. The recent shift may be a result of the local use of helicopters, diesel generators, all-terrain vehicles, and combustion toilets, which contributes 3.4×10^5 g aerosol elemental carbon annually in the MDV (Lyons et al., 2000), with the majority coming from helicopter emissions (95%). However, the shift may also reflect a regional source from McMurdo Station or changes in the chemical signature of BC in long-range transport from the Southern Hemisphere.

This study examines BC aerosols in a glacier snow profile and in the atmosphere in the MDV, Antarctica. Our overall hypothesis was that local and regional sources of BC are currently the dominant sources, accounting for the recent observed shift in the surface waters of the MDV lakes (Khan et al., 2016). The specific goal was to explore trends in rBC aerosols in the snow accumulation area of a glacier in the MDV and in the boundary layer of the atmosphere. We evaluated ion chemistry of the snow to explore timing of rBC deposition. Remote sites far from McMurdo Station and MDV camps with limited science activities were included to evaluate long-range Southern Hemisphere transport and to determine if there is a measurable local anthropogenic signal of BC in the MDV. Remote sites and MDV field camps were visited by helicopter. At remote sites the SP2 collected measurements after the helicopter had either shut down or departed from the field site. At Lake Hoare Camp, the SP2 was set up 200 m from the helicopter pad; a heat detection camera was set up to observe helicopter activity. Local contamination spikes due to helicopter activity were removed from the data. Observations were also compared to smoke aerosol optical thickness (AOT) reanalysis from the Navy Aerosol Analysis and Prediction System (NAAPS) model (Lynch et al., 2016).

2. Methods

2.1. Site Description

Within Antarctica, the alpine glaciers and ice-free valleys of the MDV provide a unique setting to distinguish local aerosol inputs from regional and long-range atmospheric transport affecting Antarctica via direct measurements of aerosols deposited in glacial snow and suspended in the air in both remote and near-camp locations. The Taylor and Wright Valleys have been the primary focus of field research in the MDV, now and in the past (Figure 1). The elevation gradient from the valley floor to the accumulation region of the glaciers is approximately 360 m. Foehn winds dramatically influence the MDV climate (Nylen et al., 2004), and the spatial distribution can vary significantly. Nylen et al. (2004) found that for every 10 km upvalley toward the ice sheet, winter events can increase by 14%, and summer events increase by 3%.

2.2. Snow Measurements

In December 2013 during a period without recent snowfalls, a 1 m deep snow pit was dug in the accumulation area of the Commonwealth Glacier approximately 100 m from the location of the SP2 atmospheric measurements on Commonwealth Glacier, which is centrally located in the Taylor Valley (see Figure 1). A helicopter moved the field team from Lake Hoare Camp to the accumulation region of the Commonwealth Glacier; the team then walked approximately 100 m away from the helicopter landing site to dig the snow pit. Density and temperature were identified in the pit (Figure S1). Additionally, snow samples were collected in precleaned amber glass bottles every 10 cm depth for snow chemistry and rBC analysis. Snow samples were transported frozen in coolers to the Crary Lab at McMurdo Station and then to the Institute of Arctic and Alpine Research (INSTAAR) in Boulder, CO. Snow samples were then melted for the first time immediately before analysis. Approximately 30 mL of well-mixed melted snow was then analyzed by a Shimadzu TOC-V CSN Total Organic Carbon Analyzer at the Kiowa Lab at INSTAAR in Boulder, CO. Approximately 30 mL of well-mixed melted snow was also transported to the Byrd Polar Research Center at Ohio State University for chemical analysis for major ions as per Welch et al. (2010), with detection limits of 0.003–0.2 mg/L depending on the ion. A Dionex DX-120 instrument was used for the cations and a ThermoDionex ICS-2100 for the anions, which uses IonPac AS19 and AG19 columns and a potassium hydroxide eluent with gradient delivered by eluent generation.

Eleven snow samples within the 1 m deep snow pit were analyzed for rBC mass mixing ratios (MMR). Briefly, snow samples were melted then immediately aerosolized with a carefully calibrated nebulizer and sampled with an SP2 following the approach of Schwarz et al. (2012). The SP2 has excellent sensitivity and selectivity

for rBC with minimal interference from non-BC materials. Here two different nebulizer systems were interfaced with the SP2. First, a customized CETAC U5000 (CETAC Technologies, Inc) nebulizer was used in which the ultrasonic piezo was replaced by a concentric pneumatic nebulizer to reduce size-dependent aerosolization efficiency effects. Second, a CETAC Marin-5 nebulizer, essentially the (original) commercial version of the customized nebulizer, was used. For both systems the size-dependent nebulization efficiency was characterized with concentration standards of polystyrene latex spheres (PSLs) in the size range 220–3,000 nm diameter, confirming low sensitivity to particle size over this range, consistent with recent results with concentric pneumatic nebulizers (Lim et al., 2014; Mori et al., 2016; Wendl et al., 2014). Hence, no size-dependent corrections were applied for nebulizer size dependence. The two nebulizers had different overall efficiencies, which were measured using PSL and BC gravimetric standard calibrations; hence, the results obtained with the two systems are equivalent. The SP2 used for the snow measurements was calibrated with fullerene soot (Alfa Aesar, Woodbridge, MA, LotF12S011). Background rBC contamination levels were bounded by measuring blank samples. The average blank concentration over 8 min of sampling was 0.14 μg/L with a highest blank concentration of 0.16 μg/L, indicating a low enough background to avoid significant interference with the rBC MMR measurements. The blanks provide an upper bound on possible contaminants associated with the estimated 60% uncertainty for rBC MMR in the snow, which conservatively accounts for uncertainties dominated by calibration issues (Schwarz et al., 2012). The SP2 was configured for these measurements such that rBC particles with volume equivalent diameter (VED) larger than 0.7 μm saturated its detectors; hence, these particles were not included in our analysis.

2.3. Atmospheric Measurements

Another SP2 was used to quantify rBC-aerosol concentrations in the atmosphere. The SP2 was stationed at Lake Hoare Camp, which generally had sufficient solar power to run the SP2 continuously over 1 month. Occasionally, on cloudy days a diesel generator was run. Other local sources of combustion products include extensive helicopter traffic, a "rocket toilet," which combusts human waste over a 6 h period, and a barbecue grill. These local signal spikes were identified and removed from the time series data. The SP2 was also run for one to several hours at a series of other sites during the austral summer daytime, shown in Figure 1, including Lake Fryxell Camp, a MDV camp located closer to McMurdo Sound, and four remote sites, Miers Valley (farthest south measurement), Alatna Valley (farthest north measurement), Mt. Fleming (farthest west measurement), and in the accumulation area of the Commonwealth Glacier in the Taylor Valley. The total instrument run time varied based on battery power and solar conditions to maintain battery power. Lake Hoare Camp is in close proximity to Commonwealth Glacier, about 10 km farther upvalley and closer to the polar plateau. Thus, we expect that the wind events and associated rBC aerosol observations at Lake Hoare Camp would follow similar trends in deposition of rBC aerosols in the accumulation area of Commonwealth Glacier. The instrument was calibrated using mobility-selected Aquadag particles, corrected for effective density and instrument response using recommended parameterizations (Gysel et al., 2011; Laborde et al., 2012). We estimated an effective detection range from approximately 90 nm to 500 nm (Schwarz, Spackman, Gao, Perring, et al., 2010), based on detector gain settings, and laboratory tests performed prior to the field deployment.

2.4. Aerosol Transport Modeling

Smoke aerosol optical thickness (AOT) from biomass burning comes from the Navy Aerosol Analysis and Prediction System (NAAPS) reanalysis (Lynch et al., 2016). The NAAPS model is used to demonstrate that there is no large-scale biomass burning smoke transport event during the study period. NAAPS was recently developed and validated at the Naval Research Laboratory. It is a global $1 \times 1°$ decade-long 6-hourly 550 nm AOT reanalysis product. It utilizes a modified version of the NAAPS as its core and assimilates quality-controlled retrievals of AOT from Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua and Terra and the Multiangle Imaging SpectroRadiometer (MISR) on Terra (Hyer et al., 2011; Shi et al., 2014; Zhang & Reid, 2006). NAAPS characterizes anthropogenic and fine biogenic aerosol (including primary and secondary organic aerosols and sulfate), biomass burning smoke, dust, and marine sea-salt aerosols. Biomass burning smoke is derived from near-real-time thermal anomaly satellite-based data used to construct smoke source functions (Reid et al., 2009), with orbital corrections on MODIS-based regional tunings and emissions. The fine- and coarse-mode reanalysis AOT at 550 nm is shown to be in agreement with the ground-based global-scale Sun photometer network Aerosol Robotic Network AOTs (Holben et al., 1998).

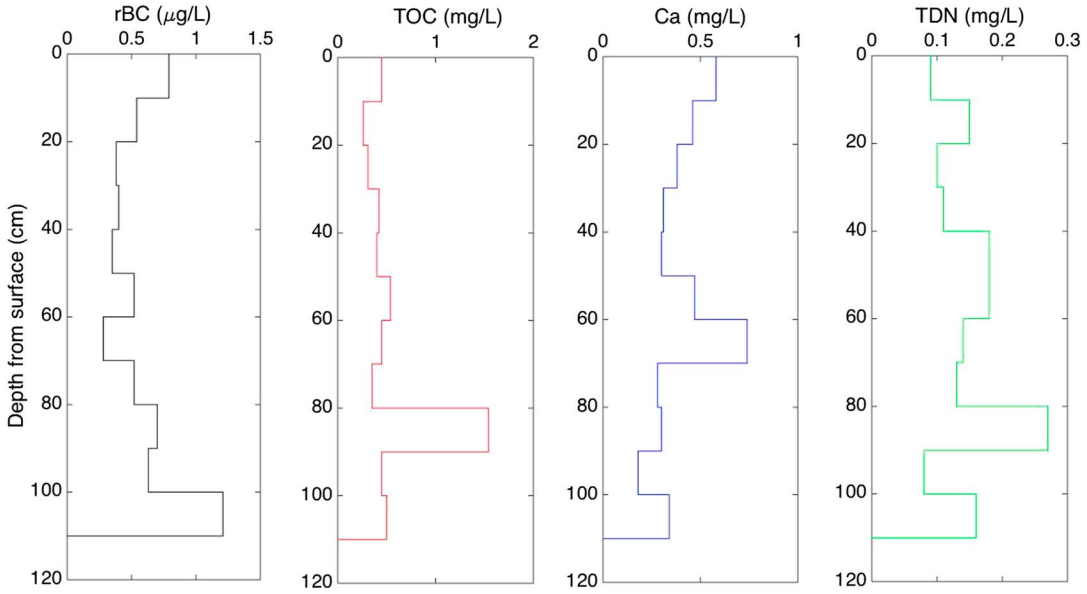

Figure 2. Snow depth profiles from a snow pit in the accumulation of Commonwealth Glaciers, Ca^{2+}, refractory black carbon (rBC), total organic carbon (TOC), and total dissolved nitrogen (TDN).

3. Results and Discussion

3.1. Snow Pit Chemistry

Previous research demonstrated that between 1993 and 2004 the mean snow accumulation rate in the accumulation zone of the Commonwealth Glacier was between 14 and 16 cm/yr snow (Witherow & Lyons, 2008). Therefore, given the depth of our 110 cm pit, we assume that this shallow snow pit represents about 7 years, for example, 2006–2013. This period includes two especially warm sunny summers of high streamflow (2008/2009 and 2011/2012). Due to the expected relatively low accumulation rates of rBC and large volume of snow needed for the analyses, the sampling depth interval was chosen to integrate ~0.5 year of snow accumulation. rBC concentrations in the snow pit ranged from 0.2 μg/L to 1.3 μg/L, with an average ± standard deviation of 0.35 ± 0.3 μg/L, (Figure 2). This result illustrates that rBC is present in the accumulation area of MDV glaciers, but at very low concentration. The rBC component of rBC-containing particles ranged in size (VED, assuming 1.8 g/cc void-free density) from 0.1 μm to larger than the SP2 detection limit at 0.75 μm. Assuming diminishing rBC mass above this upper threshold, we estimate a mass median diameter in the 0.3–0.4 μm range (Figure 3). The particle peak is higher than typical ambient air rBC, which normally peaks below 0.2 μm (Schwarz, Spackman, Gao, Watts, et al., 2010), indicating substantial mass contributions from large BC particles. This large rBC size distribution could be due to the following: (1) large/uncontrolled sources (e.g., Southern Hemisphere biomass burning events), (2) atmospheric processes influencing size-dependent removal or freeze/thaw in the aerosol phase, or (3) postdeposition processes, for example, freeze/thaw at the snow surface. There was no apparent difference in the size of the rBC particles on the surface layer and deeper in the snow pit; therefore, an average size is reported across the 11 samples.

Given the coarse sampling depth intervals within the snow pit, there is no clear interannual trend observed for any of the inorganic chemical constituents. There were, however, some relatively strong correlations among Cl^- and both Mg^{2+} and SO_4^{2-} and negative relations between TOC and Ca^{2+} (Figure S). Furthermore, a moderate correlation between Ca^{2+} and Cl^- may be due to salty local soil being deposited on the glacier (Lyons et al., 2007) during high wind events. The positive relationships between Cl^-, Mg^{2+}, and SO_4^- suggest that these constituents are related to an input of marine aerosols onto the glacier. This is consistent with previous work (Lyons et al., 2003, 2007). In general, the rBC concentrations do not follow trends in the other constituents, including TOC deposition, except Ca^{2+} in the upper 50 cm of the profile.

The lack of relationship between the rBC and both Cl^- and Ca^{2+} concentrations may be due to the coarse sampling interval or may reflect sporadic input of rBC onto the glacier surface. This may be due in part to

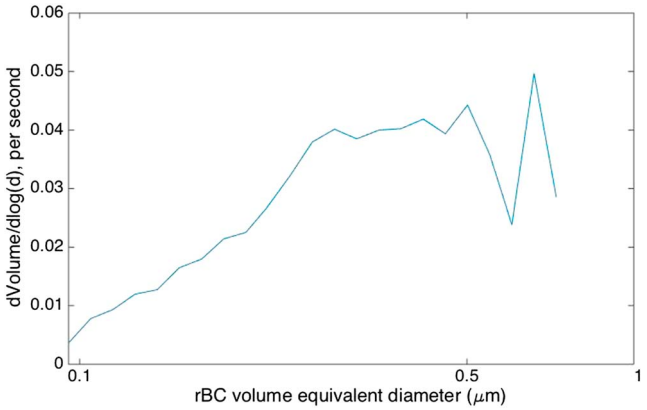

Figure 3. Average refractory black carbon (rBC) size distributions for 11 samples in a 1.5 m snow pit in the accumulation region of the Commonwealth Glacier in the McMurdo Dry Valleys, Antarctica.

both the local combustion of fossil fuel throughout the austral summer and long-range atmospheric transport of Southern Hemisphere wildfires. Such episodic Southern Hemisphere smoke events have been previously observed in two ice cores (Bisiaux et al., 2012). These events can also be observed in the MDV region (Figures S3–S5). Such episodic events could cause more rBC deposition in the austral summer than the winter, or vice versa, for some years depending on climatic patterns and Southern Hemisphere smoke transport events during a given year. When the ratio of TOC/rBC is compared to monthly mean biomass burning smoke AOT from the NAAPS model (Figure 4), it appears that the high TOC concentrations may be a result of long-range transport of Southern Hemisphere wildfires.

Using the mean annual snow accumulations from above the equilibrium line on the Commonwealth Glacier tabulated by Witherow et al. (2006) and the mean concentration of rBC in the snow pit presented within, we calculated an annual rBC mass flux of ~27 μg/m^2/a. This should be considered an estimate because of the lack of a direct accumulation rate information from this particular snow pit. This flux is considerably higher than those recently observed in more remote locations of Antarctica by Bisiaux et al. (2012). These investigators calculated fluxes from more remote Antarctica of 16 and 13 μg/m^2/a for coastal West Antarctica (the WAIS site) and Law Dome, respectively, and between 3.6 and 7.8 μg/m^2/a in snow since 1963 at elevations >2,500 m in Dronning Maud Land, East Antarctica. Our higher flux value for the Commonwealth is reasonable given its closer proximity to the coast, to the large-scale science operations and human presence discussed above, and potential for the influence of resuspension from bare ground during events followed by deposition.

3.2. rBC Aerosol Concentrations

Atmospheric rBC aerosol mass concentrations (excluding local contamination) were low (0.09–1.3 ng/m^3 at ambient conditions) throughout the MDV. These concentrations are some of the lowest reported values from Antarctica (Table 1), which could also be due to the sensitivity of the SP2 to BC. An early estimate of total aerosol light absorption (not merely that of rBC) based on measurements made over three field seasons from 2000 to 2003 suggested higher loads than we find. Concentrations at the remote sites were extremely low, 0.09 ng/m^3 at Mt. Flemming, the farthest west measurement on the edge of the EAIS and 0.11 ng/m^3 in Alatna Valley, the farthest north measurement. All remote site measurements were collected during normal wind patterns, that is, not during foehn wind events. Our synoptic sampling at the remote sites suggests that there were no sporadic long-range smoke events transported from the Southern Hemisphere during this time. An average concentration in the Miers Valley, which is rarely visited, was 1.3 ng/m^3. This site was the most southerly measurement, and concentrations were similar to average concentrations at Lake Hoare Camp, 1.3 ng/m^3, when the predominant wind direction came from McMurdo Sound. At the Lake Hoare Camp, local contamination from generators, rocket toilets, and helicopters caused detectable spikes up to approximately 200 ng/m^3 about three to five times per day during normal workdays Monday to Saturday. These high emission events are expected to produce rBC, which is deposited somewhere in the MDV.

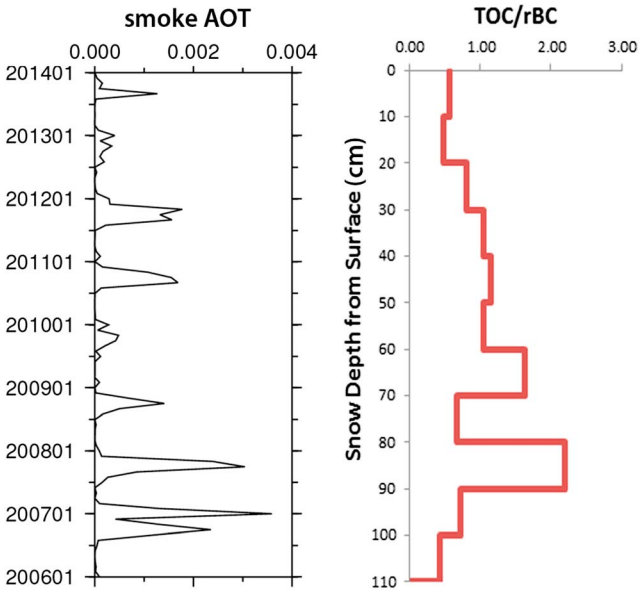

Figure 4. The ratio of TOC to rBC compared to smoke aerosol optical thickness (AOT), unitless from the NAAPS model over the same time scale as the snow pit.

The average concentration at F6 Camp was higher than the other sites, 4.6 ng/m^3. Although this site is near Lake Hoare Camp, it is closer to McMurdo Station and receives more flyover helicopter traffic and generally more wind from McMurdo Sound than Lake Hoare Camp, which is sheltered by the Canada Glacier. The decreasing concentrations

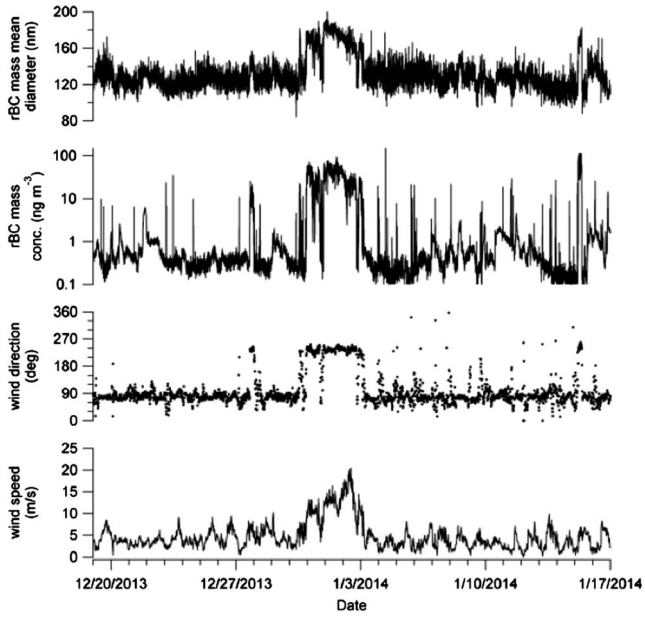

Figure 5. Time series rBC aerosol results from Lake Hoare Camp with foehn wind event.

toward the polar plateau suggest that local anthropogenic activity does have a small measurable impact on rBC concentrations in the MDV.

4. Results and Discussion, rBC Aerosol Trends With Foehn Wind Event

The average background level of rBC concentrations at Lake Hoare Camp over the summer 2013–2014 season, 1.3 ng/m^3, was calculated for periods when the prevailing wind direction was from McMurdo Sound and excluded local contamination spikes (Table 1). This is well below previous findings of 5 ng/g (Hansen, 2003); however, an appreciable decrease in aerosol BC cannot be confirmed due to the differing analytical techniques, rBC by SP2 (this study) versus eBC by aethalometer (previous study), which is more susceptible to interference from non-BC particles. These background concentrations are also lower than previous observations at McMurdo Station (Hansen & Nazarenko, 2004). The foehn wind event captured at Lake Hoare Camp over the 2013–2014 New Year (Figure 5) brought strong downvalley winds and warm air from the East Antarctic Ice Sheet (EAIS) polar plateau. During this event when the wind direction changed (the predominant wind direction is from McMurdo Sound toward the EAIS polar plateau) and the air temperature and wind speed increased, the average rBC concentration also increased to approximately 35 ng/m^3, during the period: 12:30 30 December 2013 to 00:00 3 January 2013. During this time the concentrations reached the range of previous observations at McMurdo Station. The mass mean volume equivalent diameter of the rBC particles also increased from close to 130 nm to more than 170 nm. Reanalysis from the NAAPS model shows that aerosol loadings and speciation did not change during this time period (Figure S6a), nor was smoke transported to the continent during this time (Figure S6b). Therefore, the increased rBC load during the foehn wind event was independent of air parcel history on regional scales. No difference was observed in the ratios between the detectors during the foehn wind event and nonfoehn wind periods, and ratios were consistent with rBC calibration aerosol, indicating that particles measured during both periods were consistently rBC (Figure S7). Although the cause of the rBC increase is unknown, our measurement period is relatively brief, and available supporting aerosol data are lacking, we can infer that rBC concentrations do significantly increase at Lake Hoare Camp during foehn wind events. These findings are contrary to conclusions from Weller et al. (2013) at Neumayer Station, which is located on the Ekstrom Ice Shelf on the other side of the continent. This could be due to production of more local rBC particles in the MDV during summer field seasons, which remain on the soil surface until resuspended during high wind events. As a result, the MDV are a unique location to study resuspension of aerosols deposited on soil due to the ice-free nature of the region.

Although there is no local production of rBC in the winter because field activities are limited to the austral summer with the exception of very limited polar night fieldwork that may extend into March or April, rBC, produced locally in the summer months, remains present on the valley floors. Resultantly, foehn/katabatic wind events, which change the predominant wind direction 90°, increase wind speed by more than 6 m/s and occur more frequently during the winter (Nylen et al., 2004) and may resuspend and transport rBC aerosols, therefore depositing them on snow and ice surfaces in the winter months in the MDV as well. Long-range atmospheric transport is also possible year round from Southern Hemisphere industrial pollution and biomass burning from wildfires.

5. Summary and Conclusions

The rBC-snow concentrations reported here from the accumulation region of the Commonwealth Glacier are not currently high enough to lower albedo, change the radiative forcing, or enhance meltwater generation, such as in the Arctic (Keegan et al., 2014; Pedersen et al., 2015; Tedesco et al., 2015). The large rBC particle concentrations in snow may be due to the episodic wildfire events that are transported from the Southern Hemisphere to the MDV (Figures 3 and S5) and from postdeposition freeze-thaw processes. Although not

directly comparable, the very low rBC concentrations in the snowpack reflect the low background atmospheric concentrations observed on the MDV valley floor (Table 1). As mentioned earlier, there was a slight trend between rBC and Ca^{2+} (Figure 2) in the upper 50 cm of the snow profile. This could be due to thawing permafrost, which may enable more soil transport to the glacier or more frequent foehn wind events that could have transported both soil and rBC to the glacier accumulation area over the past several years. However, the overall lack of correlation between rBC and Ca^{2+} (Figures 2 and S2) suggests that rBC deposition over the past 7 years has not been associated with soil deposition from the valley floor. This is also likely a function of elevation, rather than transport given that the elevation change from the valley floor to the sampling site is ~360 m. This finding combined with the low rBC concentrations observed in the snow pit suggests that across the average of the 7 year snow profile, the larger particle sizes of aerosol rBC measured at Lake Hoare, which are resuspended during foehn wind events, have not been transported to the accumulation area of Commonwealth Glacier where the snow pit was located (Figure S8a). Thus, the rBC observed in the snowpack is likely transported and deposited via long-range transport, mostly likely scavenged from the atmosphere as snow precipitation. However, the larger rBC particles observed during the foehn wind event could be deposited on the ablation region of the glaciers, such as the rough area near the terminus of the Canada Glacier down valley of Lake Hoare Camp (Figure S8b). More research could be conducted to look at the frequency and intensity of foehn wind events and the relationship to rBC deposition in the MDV glaciers. This would be similar to a previous study that explored the impact of sediment from the Wright Valley floor that is transported by foehn winds to Wright Lower Glacier and results in a reduction of surface albedo, leading to earlier melt onset, as well as an overall longer melt season (MacDonell et al., 2013).

Refractory BC aerosols are present in the boundary layer of the atmosphere at low concentrations throughout the MDV, except near fairly limited local sources. The background aerosol loading from long-range transport appears steady over our measurements and is currently too low in the accumulation region, <1 μg/L, to change the broadband albedo of the Snow and Ice Aerosol Radiation online model (Flanner et al., 2007). Therefore, it currently does not have a significant impact on surface albedo on nearby glaciers and snowpacks at higher elevation. NAAPS reanalysis shows that sporadic inputs occur as a result of Southern Hemisphere wildfires. The resuspension of local rBC sources, associated with foehn winds, also appear to be sporadic.

This study raises a point of consideration that rBC produced in the MDV remains there and could be transported around the surface of the valleys by foehn events. This is confirmed by the combination of spikes above 200 ng/m^3 concentration, due to local sources, as well as the increased concentrations that were measured during the foehn wind event. While the rBC concentrations measured in this snow pit are not sufficient to reduce surface albedo, there is potential for accumulation of rBC on snow and ice surfaces at low elevation throughout the MDV, which were not measured as part of this study.

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