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The Cryosphere Discussions

Brief communication: An alternative method for estimating the scavenging efficiency of black carbon by meltwater over sea ice

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Abstract. The meltwater scavenging coefficient (MSC) of black carbon (BC) is a key parameter in snow and sea ice model, as it determines the BC enrichment in the surface layer of melting snow over sea ice and therefore modulates the BC-snow-albedo feedbacks. We present a new method for MSC estimation by sampling ice layer within the snowpack and its overlying snow and measuring their physical characteristics in the snowpits in Elson Lagoon during the melting season. The bias of estimated MSC ranges from -5.4% to 7.3%, which is not exactly dependent on the degree of ablation. The average MSC value (14.5%±2.6%) calculated by this proposed method is slightly lower than that derived from the repeating sampling (RS) method in Elson Lagoon, while still is within its best estimate range. Further estimation demonstrates that the MSC in Canada Basin (23.6%±2.1%) is close to that in Greenland (23.0%±12.5%), and larger than that in Chukchi Sea (17.9%±5.0%). Elson Lagoon has the lowest MSC (14.5%±2.6%) in the study areas. It is concluded that MSC exhibited a regional difference in the western Arctic during the sampling period. The method suggested in this study provides a possible approach for large-scale measurements of MSC over the sea-ice area in Arctic.

1 Introduction

BC is among the most efficient particulate species at absorbing visible light, which can reduce the surface albedo and potentially accelerate snow melting (Flanner et al., 2007; Goldenson et al., 2012; Dou et al., 2012; 2017). Previous studies suggested an annual-mean radiative forcing of 0.1–0.3 W m^{-2} over the Arctic region from BC deposition (Flanner et al., 2009; Jiao et al., 2014). However, large uncertainties still exist in the sea ice region due to lack of field measurements and poor understanding of BC enrichment by overlying snow melting.

The enrichment of BC in melting snow largely depends on MSC, as it reflects the ratio of BC concentration in the meltwater

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departing the snow layer to the bulk concentration in the exact layer (Flanner et al., 2007). MSC which leads to enhanced concentrations of BC in surface snow has been found to be considerably less than 100% by very few previous studies (e.g., Conway et al., 1996; Xu et al., 2012; Doherty et al., 2013). In present snow and sea ice models (e.g., Flanner et al., 2007; Goldenson et al., 2012; Holland et al., 2012), MSC is valued as a constant of 20% and 3% for hydrophilic BC and hydrophobic BC, respectively, which were derived from the observations conducted at Snowdome (2050 m) of the mid-latitude Blue Glacier (Conway et al., 1996).

More recently, the MSC of BC was re-evaluated based on the field measurements in Elson Lagoon (Barrow, Alaska) and at Dye-2 station (Greenland) during the melting season (Doherty et al., 2013). They suggested a general range of 10% to 30% in the study area. The method adopted in previous studies requires continuous sampling for about 2–3 weeks at each site, and thus is laborious to be used for large-scale measurements in the polar area. Here, as an alternative, an experimental approach for calculating MSC was proposed which may provide a new way for MSC measuring, and a further comparison between the regional differences of MSCs is presented as well.

The ice layer within the snowpack results from the refreezing of meltwater that percolates into snow, and thus the concentration of BC in the ice layer can represent the BC values in the meltwater departing the snow. The BC concentrations in the ice layer and in its overlying snow layer were together to determine the MSC associately considering the thickness and density of the two layers. The field measurements and sampling were conducted in Elson Lagoon, Chukchi Sea and Canada Basin during the melt season (Fig. 1). After constraining the uncertainties of this new method, the estimated MSC was compared to the values derived from the RS method in the same area, and further the spatial variability of MSC in the western Arctic will be discussed.

2 Field measurements and sample analysis

We collected the snow samples in Elson Lagoon northeast of Barrow (Barrow expedition), in Chukchi Sea (Barrow expedition) and in the Canada Basin (1st South Korean Arctic Ocean expedition) during the late spring and summer over the past decade (2010 to 2018). The snow physical characteristics (including the snow thickness, stratification and density) were also measured during the three Barrow sea ice expeditions (year 2015, 2017 and 2018) and the 1st South Korean Arctic Ocean expedition (year 2010). In the 3rd Chinese Arctic expedition (year 2008), only snow physics (thickness, stratigraphy and density) were observed.

The sample collection was performed at three stages in Elson Lagoon and Chukchi Sea during the expeditions in 2015 and 2017. At the stage before snow-melting onset, we collected snow from 4 cm above the sea ice up to the snow surface. At the early stage of melting, the upper snow layer was firstly collected, and then the underlying ice layer was sampled separately

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in the same snow pit. The newly fallen snow was also collected during the snowfall. In order to study the spatial distribution of BC, we dug up three snow pits to sample parallelly at each site (50 meters apart from each other). Observations show that the differences in BC concentrations of the three snow pits are negligible, as the standard deviation value was one order of magnitude lower than the mean concentration. We took the average BC concentration from all three pits as the BC concentration at that exact site. In the end of snow-melting season and when most of the snowpack had melted, we collected the top 4-cm layer of snow to analyze the BC concentration in the melted snow. In 2018, we just collected samples of melting snow in the Chukchi Sea. More details are showed in Table S1.

Sampling was performed using a pre-cleaned plastic shovel and single-used vinyl gloves. Samples were stored in polyethylene bags that had been thoroughly washed with abundant deionized ultrapure water in the laboratory prior to use. In the laboratory, the snow samples were allowed to melt in ambient temperature (18–20 ºC) and immediately filtered through quartz-fibre filters (25 mm, Whatman® QM-A). The filters were stored in an insulated cabinet with blue ice and kept in low temperature avoiding any bacteria to produce and transited to the laboratory in University of Chinese Academy of Sciences for analysis.

We used two analytical methods to measure the concentration of BC. The quartz filters were firstly dried between 60 ºC and 70 ºC and then measured using an optical transmission analytical method (Model OT-21, Magee Scientific, California USA). The OT-21 is widely used in the measurement of atmospheric BC aerosol. Thereafter, a 1.0 cm^2 punch was cut from each filter, and was analyzed for elemental carbon (EC) using the "Thermos-optical NIOSH 5040" method (Sunset Laboratory Inc., Forest Grove, U.S., which has been applied to measure EC in Svalbard snow (Forsström et al., 2013). A comparison between EC and BC in a previous study (Dou et al., 2017) showed that the values obtained from two different methods are highly correlated (R^2 = 0.97). For consistency, we adopt BC referring to BC and EC. Five blank filters were processed following the same analytical procedure as the samples, except that they were filtered with ultrapure water. The measured BC background of the filters (0.03±0.02 ng g^{-1}) are an order of magnitude lower than the concentration of the ice layer. The values in Table S1 and Table S2 have been corrected by excluding blank contributions.

3 Results and discussion

During two Arctic Ocean Expeditions (the year 2008 and 2010), ice layers developed in almost all snowpacks over sea ice in the measurement area, and the snow stratigraphy and thickness exhibited highly spatial variabilities. The observed thickness of ice layers ranges from ~0.3 cm to ~2.5 cm. During the field measurements in Elson Lagoon in 2015, we recorded that the ice layer came into being on May 18th and May 22th, the early stage of sea-ice melting season. The ice layer was observed in Chukchi Sea on May 25th–28th, 2017, and on May 30th –31th, 2018.

The ice layer results from the refrozen meltwater that percolates into cold snow along layer-parallel capillary barriers by heat conduction into surrounding subfreezing snow (Pfeffer et al., 1998; Massom et al., 2001; Colbeck et al., 2009). It detains BC particles in the meltwater leaving the upper snow layer. Except for the formation mechanism mentioned above, ice layers could also generate from the radiation crust or liquid precipitation re-freezing (Massom et al. 2001). However, the BC concentrations in these two types of ice layers are in the same order of magnitude as those of new or recently-fallen snow. Besides, the radiation crust usually forms on the snow surface (Colbeck et al., 2009; Dou et al., 2013). The ice layer frozen from liquid precipitation is mostly formed during winter season before the snow-melt onset (Sturm et al., 2002; Langlois et al., 2017). These two types of ice layers cannot reflect the BC scavenging with meltwater, and thus were not considered in this study.

By measuring BC in the selected ice layer and its overlying snow, it can be drawn that the concentration of the ice layer is 0.42±0.08 ng g^{-1} in the measurement area, meaning that ~0.42 ng of BC particles can be carried away from the snow layer by 1 gram water. Before estimating MSC, the BC concentration of the ice layer is also compared with those of other snow layers in the measurement area at different ablation stages. The BC concentration increased from 1.32±0.20 ng g^{-1} in the new snow to 2.42±0.63 ng g^{-1} in the generally melting snow (Fig. S1), and the concentration in the surface layer increased up to 15.91±1.12 ng g^{-1} in the end of snow ablation.

The MSC is estimated based on the observations of BC, snow density and thickness. According to the definition by Flanner et al. (2007), MSC can be given by:

$$MSC = h_i \cdot \rho_i \cdot C_{bi} / h_1 \cdot \rho_1 \cdot C_{b1} \qquad (1)$$

where h_i (cm), ρ_i (g cm^{-3}) and C_{bi} (ng g^{-1}) are respectively the thickness, density and BC mass concentration of the ice layer (Fig. S2); h_1 (cm), ρ_1 (g cm^{-3}) and C_{b1}(ng g^{-1}) are the same variables but for the snow layer before the melt event (Fig. S2). Note that determining scavenging efficiency with this method requires measuring the above factors at a given site at least twice, before and after the melt event.

If the snow physics and BC concentration were not measured before the melt event, we would choose another method to calculate MSC. We assumed that as the surface snow melts, BC particles scavenged by meltwater are refrozen in the ice layer, that is, $h_1 \cdot \rho_1 \cdot C_{b1} = h_i \cdot \rho_i \cdot C_{bi} + h_2 \cdot \rho_2 \cdot C_{b2}$, where h_2 (cm), ρ_2 (g cm^{-3}) and C_{b2} (ng g^{-1}) are respectively the thickness, snow density and BC mass concentration of the melting snow overlying the ice layer (Fig. S2). By determining the loading of BC per unit area (ng cm^{-2}) in the ice layer and in the partially melted snow layer above it, the scavenging efficiency (MSC) is given by:

$$MSC = h_i \cdot \rho_i \cdot C_{bi} / (h_i \cdot \rho_i \cdot C_{bi} + h_2 \cdot \rho_2 \cdot C_{b2}) \qquad (2)$$

In fact, the assumption behind the proposed new method also implies that all of the melt water generated from the original

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snow column is conserved in the ice layer and its overlying snow. Thus, $h_1 \cdot \rho_1$ is also equal to $(h_i \cdot \rho_i + h_2 \cdot \rho_2)$ in the assumption.

Since the new method largely depends on the conservation of snow mass and BC content before and after the ablation event, we validate the above presumption using the observations that involve snow sampling both before and after the melt event at 6 sites during the Barrow expeditions (Table S2). The average of the snow density and BC concentration of the whole layer of snow were used to represent the situation (ρ_1, C_{b1}) of the upper part (h_1) of the snow layer before ablation. Here, deviations from 100% conserved is used to measure the conservation of BC $((h_i \cdot \rho_i \cdot C_{bi} + h_2 \cdot \rho_2 \cdot C_{b2})/\ h_1 \cdot \rho_1 \cdot C_{b1}$-100%) and snow $((h_i \cdot \rho_i + h_2 \cdot \rho_2)/\ h_1 \cdot \rho_1$ -100%), and to evaluate the uncertainty in the derived scavenging efficiencies. The loss of snow mass and BC content after the ablation event are both smaller than 7.0% (Fig. 2a), indicating that most of the meltwater and BC within it was re-frozen in the ice layer and the BC content was substantially conserved. The assumption of the proposed new method is valid in the measurement area during the sampling period.

According to Eq. (2), we estimated the MSC (MSC_2) in the measurement area and compared it with the MSC_1 calculated based on Eq. (1). The result indicates that there is a slight difference in the MSCs calculated separately by the two methods. The bias of MSC ((MSC_2-MSC_1)/MSC_1) caused by the deviation of snow and BC from 100% conserved before and after melt is small than 7.2% (Fig. 2b). Further analysis showed that there is no obvious correlation between the estimated bias of MSC and the degree of snow melting (Fig. 2b).

With the new method, we calculated the MSC in Elson Lagoon and compared it with that estimated by Doherty et al. (2013) in the same area. The result indicates that the MSC in Elson Lagoon is 14.5%±2.6%, close to the average estimation (16.2%±8.5%) by repeated sampling (RS) introduced by Doherty et al. (2013) and is still within its best estimation [14.0%-20.0%]. Our estimation of the MSC is also broadly consistent with that adopted by Flanner et al. (2007) in their model study. They assumed that the MSC is 3% for the hydrophobic BC and 20% for hydrophilic BC, given that the total BC is a combination of the two types of BC.

The MSC exhibits significant spatial variability due to the different particle sizes and hydrophilicity (Flanner et al., 2007). From the observations in this study (Chukchi Sea, Elson Lagoon and Canada Basin) and the results of Doherty et al. (2013) (Elson Lagoon and Dye-2, Greenland), we investigated the spatial differences of MSC in western Arctic. The average of the MSCs in the Canada Basin (23.6%±2.1%) is basically the same as that at the Dye-2 site, Greenland (23.0%±12.5%), while is larger than that of Chukchi Sea (17.9%±5.0%); and Elson Lagoon has the lowest MSC (14.5%±2.6%) (Fig. 3). The average of the MSCs in western Arctic is 18.0%±3.8%.

The observations in this study are narrowly distributed in the Elson Lagoon, Chukchi Sea and Canada Basin. We reviewed

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the snow stratigraphy records obtained during the 3rd Chinese Arctic expedition and during the expedition hiking through the North Pole from 88 ºN to 90 ºN in late spring 1995 (Xiao et al., 1997), separately. The records show that the ice layers were widely developing over high latitudes of the Arctic Ocean (Fig.1), consistent with the observations in Svalbard in late spring 2007–2009 (Eckerstorfer et al., 2011). This suggests a broader applicability for the new method in estimating the MSC of BC in the Arctic, and shows a potential applying in conducting large-scale observations of MSC, for example, along the cruise lines where it is not pragmatic to carry out long-term continuously sampling.

3 Conclusions

The MSC of BC has been found to be much less than 100% in few previous studies, leading to enhanced concentrations of BC in surface snow, lowering albedo and accelerating the rate of snow melting. This study proposes a new experimental approach to determine the MSC by sampling the ice layer and its overlying snow in the snowpits during the melting season, assuming the complete conservation of snow and BC content before and after the ablation event. The method is different from the established methods which require repeated sampling (RS method) over an extended period. The present observations confirm that the theory adopted in the proposed method is valid in the study area and the estimation bias of the calculated MSCs is not dependent on the melting degree during the ablation.

Further estimation with the new method demonstrated that the MSC exhibits regional differences in western Arctic. In the measurement period, the average MSC in Canada Basin is the largest, which is close to that estimated in Greenland, followed by those in the Chukchi Sea and in Elson Lagoon. The spatial difference is suggested to be considered in the future simulation of BC-in-snow over the sea ice, rather than setting MSC as a constant in the snow and sea ice model. Combined with all available observations, we estimated an average of MSC in western Arctic of 18.0%±3.8% ranging from 13% to 30%.

Data availability. The observations of snow thickness, snow density and BC concentrations applied in this study are available as the Supplement.

Supplement. The supplement related to this article is available online at:

Author contribution. TD designed the experiments and performed the analyses. TD, ZD, SL, YZ, QZ, MH and CL conceived field measurements and snow sampling. All authors participated in the writing of the paper.

Competing interests. The authors declare that they have no conflict of interest.

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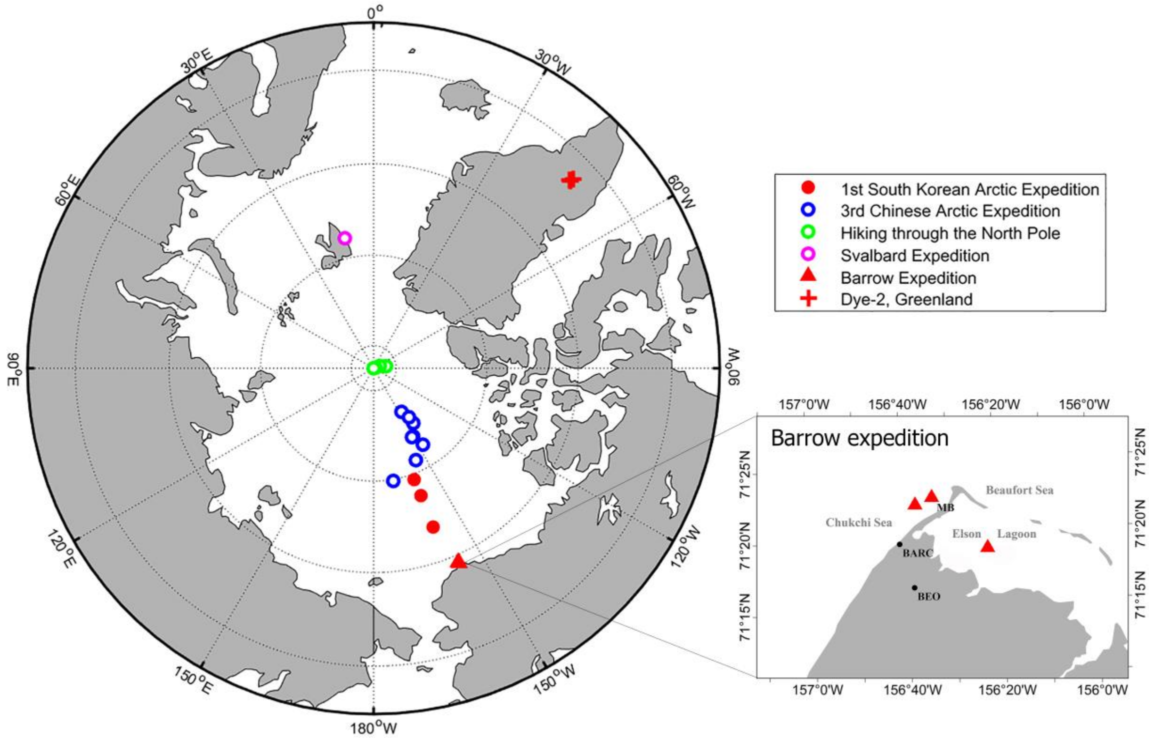

Figure 1: Locations of snow and ice layer sampling and the measurements of snow thickness and density in this study. Barrow Expeditions include the field measurements carried out in the Elson Lagoon in 2015, and in the Chukchi Sea in 2017 and 2018; the 3rd Chinese Arctic Expedition was conducted over the Canada Basin and the center region of Arctic Ocean in 2008; the 1st South Korean Arctic Expedition was conducted over the Canada Basin in 2010; the North Pole Expedition refers to the first Chinese expedition hiking through the North Pole from 88 ºN to 90 ºN in 1995 (Xiao et al., 1997); the Svalbard Expedition was conducted by Eckerstorfer et al. (2011) in the field observations in 2007-2009. The open circle indicates the point at which the ice layer is observed. Solid triangles and squares mark the locations for both sampling and on-site measurements. Cross marks the location of Dye-2 where the MSC was estimated by Doherty et al. (2013).

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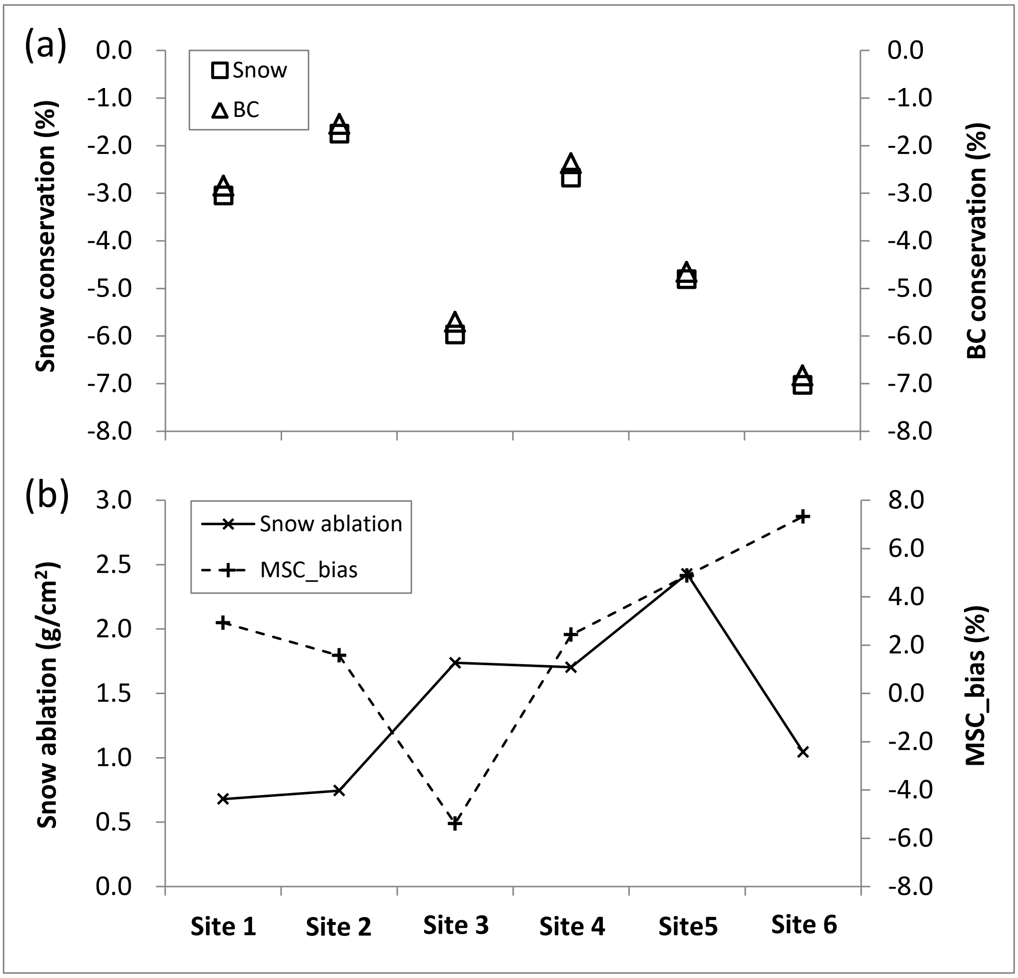

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Figure 2: Deviations from 100% conserved for snow and BC after ablation (a), snow ablation ($h_1 \cdot \rho_1 - h_2 \cdot \rho_2$) during the melt event and the bias ((MSC_2-MSC_1)/MSC_1)*100% of estimated MSC based on Eq. (2) (b). The ticks on the X-axis are matching sites given in Table S2.

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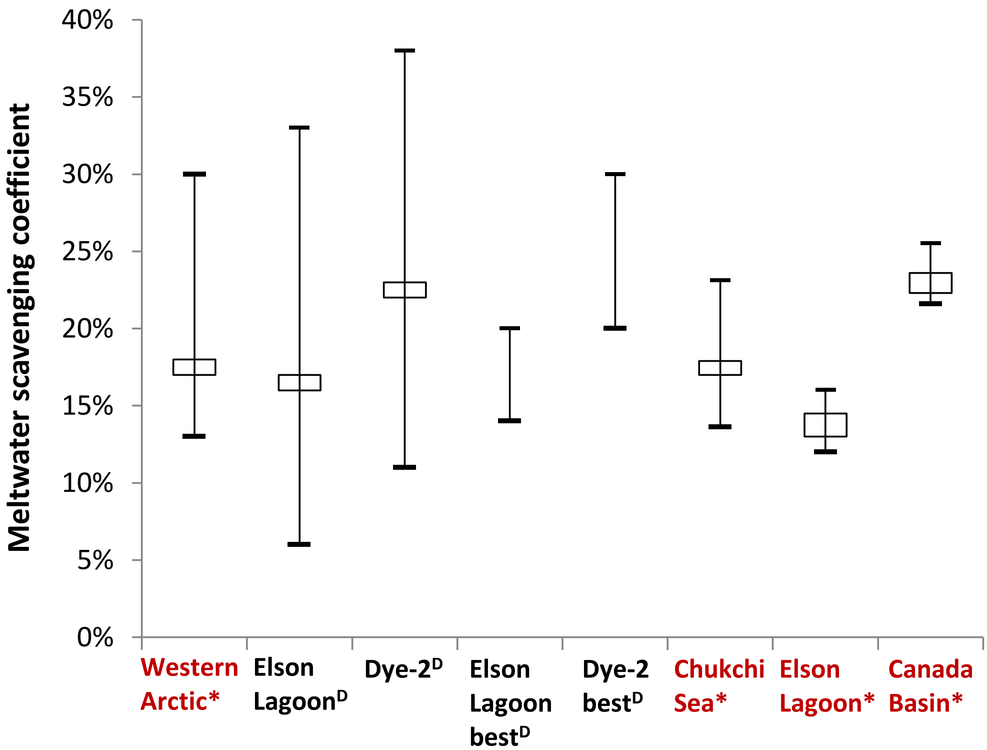

Figure 3: MSC of BC in different regions over the western Arctic. Superscript '*' indicates the results of this study (red), and '^{D}' indicates the results of Doherty et al. (2013). Elson Lagoon best^D and Dye-2 best^D indicate the best estimated range of MSC respectively in Elson Lagoon and Dye-2, Greenland published in Doherty et al. (2013). The values of the western Arctic were estimated based on the observations in all measurement regions, and the best estimated values in Dye-2 and Elson Lagoon were employed in the estimation. The box indicates the mean (upper) and median (bottom) values, and the whiskers depict the extent.