Interactive comment on "Brief Communication: Light-absorbing impurities can reduce the density of melting snow" by O. Meinander et al.

Reply to the Anonymous Referee #2

We are thankful to the Anonymous Referee#2 for all the valuable comments. Our reply is given below.

Referee:
"This study presents measurements indicating a correlation between snow BC content and snow density. The findings are based on a small number of measurements, preventing any robust conclusions. Because this connection has not been previously drawn, however, the study seems of sufficient novelty, interest and importance for publication, despite the preliminary nature of the conclusions. Importantly, the authors also propose three physical mechanisms that could potentially explain the relationship."

Our comment:
We thank the Referee for this positive evaluation and are pleased to bring out the fact that after we had submitted our manuscript to TCD, we made a small laboratory experiment. These new experimental data were found to support our hypothesis, presented in our Brief Communication TCD-paper, that BC may decrease the liquid water retention capacity of melting snow. We found that snow with added soot released melt water sooner than snow without added soot.

For this new experiment, we added a known amount of soot to a snow sample, mixed the soot and snow, and let the snow melt indoors, while measuring the melt water on a drip pan as a function of time. The results showed that while the control snow started to release melt water after 40 minutes, the snow with added soot released melt water already after 12 minutes. When cold water was added on snow, the control snow released water after 29 minutes, while the same amount of water in sooted snow caused water to release already after 7 minutes. All the snow samples were of the same size (same weight and volume) representing the same natural snow, and mechanically treated the same way whether soot was added or not, e.g., the control snow was also mixed although no soot was added.

In consequence, we'd like to suggest the following new sentences to be added in the Discussion and conclusions of our revised manuscript (p. 264, after line 24):

"Furthermore, according to our recent laboratory experiment (unpublished data), we found that snow with artificially added soot released melt water sooner than snow without added soot. For this experiment, we added a known amount of soot to a snow sample, mixed the soot and snow, and let the snow melt indoors, while measuring the melt water on a drip pan as a function of time. The results showed that while the control snow started to release melt water after 40 minutes, the snow with added soot released melt water already after 12 minutes. When cold water was added on snow, the control snow released water after 29 minutes, while the same amount of water in sooted snow caused water to release already after 7 minutes. All the snow samples were of the same size (same

weight and volume) representing the same natural snow, and mechanically treated the same way whether soot was added or not; e.g., the control snow was also mixed although no soot was added. Hence, these new experimental data were found to support our hypothesis that BC may decrease the liquid water retention capacity of melting snow."

Referee Comments:

Referee:
Abstract: The authors should mention that no relationship was found between density and BC content in natural non-melting snow (without the artificial addition of impurities).
Our reply:
We agree and suggest a new sentence to the abstract (following the sentence "In our experiments, artificially added light-absorbing impurities decreased the density of seasonally melting natural snow."):
"No relationship was found in case of natural non-melting snow."

Referee:
It would be helpful to indicate more clearly throughout the paper, and especially in Figure 2, which samples were subject to artificial addition of impurities, and of those, which samples were subject to volcanic sand versus chimney soot. In Figure 2 and elsewhere in the paper, it is unclear whether the samples were taken from different snowpack locations (potentially all in the same general vicinity) or different times from the same snowpack. Please clarify.
Our reply:
We totally agree and the revised Fig. 2 is now color-coded. For the cold snow samples, the places were three different ones: Lake "Orajärvi" for the SR campaign, several SNORTEX sites around the Sodankylä area for the SNORTEX data, and for SoS-2013 one area inside the fenced Sodankylä airport field (here: spot S7 and reference). For the melting snow, it was only one area of the SoS-2013, inside the fenced Sodankylä airport field (spots S5, S12, S13, and reference). The years and dates are shown in Table 1. To clarify, we suggest the following new sentence to be added in Materials (p. 261, line 14):
"The cold snow samples were: snow on a lake (17 March 2009); various sites around the Sodankylä area (18-19 March 2009 and 23-24 March 2010); and a fenced experimental field (6 and 10 April 2013). The melting snow data were from the experimental field only (17-18 April 2013 before and after rain)."

Referee: p.261, 26: The meaning of the superscripts are unclear.
Our reply: The subscripts refer to the institutes of the authors of this paper. To clarify, we suggest replacing the superscripts with the names of the institutes in parenthesis after the names.

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Referee: p.262, 14: "One density measurement for each location was made." - This implies that density at each location was only sampled one time. Was this also true of the BC measurements? (i.e., are any of the data points shown in Figure 2 taken from the same snow column, but at different times?)

Our reply: Some of the BC samples of Fig.2a. for cold snow pack were from the same place but at different times (i.e., different month or year). For the melting snow, the number of BC samples varied depending of the sampling plot, as mentioned in the text (p. 263 line 22).

Referee: p.262,18 and p.264,21: "consequent" -> "subsequent"
Our reply: Now corrected.

Referee: Equation 1: Please report 95% confidence intervals of the slope of this equation. This calculation could be done exclusively using the midpoint values shown in Figure 2b.
Our reply: The 95 % confidence interval of the slope of the Eq. 1 is from -0.46 to -0.08, i.e., we are 95 % confident that the true slope of this equation is in the range defined by -0.27±0.19. This we suggest to be added in the revised version, after the Eq.1 (p.264, line3):
"The 95 % confidence interval of the slope of the Eq. 1 is from -0.46 to -0.08, i.e., we are 95 % confident that the true slope of this equation is in the range defined by -0.27±0.19."

Referee: p.264, 5: "previous FMI Sodankyla snow density data" - Was this snow subject to artificial addition of impurities? If not, what are the implications for extending these data to high-BC-content snow?
Our reply: These "previous FMI Sodankylä snow density data" were for natural snow without artificial addition of impurities, and provided the best available standard deviation estimate for Sodankylä snow. This snow density data set does not have impurity information, but the concentrations can be assumed to belong to 9-106 ppb (Table 3 in Meinander et al. 2013, ACP, http://www.atmos-chem-phys.net/13/3793/2013/acp-13-3793-2013.pdf). In the future, we plan to make more density measurements on high-BC-content snow, too. As our results presented in Fig 2, and our new data set, both suggest that BC might decrease the liquid water retention capacity, we would estimate that a change (an increase) in the standard deviation of the snow density would not have significant implications to our results.

Referee: p.264, 9: The use of "natural snow" here and elsewhere is a bit confusing because some of this snow was presumably subject to the artificial addition of impurities. I suggest that the authors try to clarify these descriptions. (This is related to the point above about the need to clearly distinguish between unperturbed and artificially contaminated snow).
Our reply: By natural snow we refer to snow that has the origin of snowfall, and has not been affected by snow clearing etc. manmade disturbances, and on the other hand is not produced by a snow cannon either. We agree that we have not defined "natural snow" clearly, and to clarify we suggest to include the following definition in the revised manuscript (p. 261, line 12):
"By natural snow we refer to a snow pack that has formed from snowfall, i.e. has not been produced by a snow cannon, and has not been affected by human activity, e.g. snow clearing".

Referee: p.265, 2: "evaporation" -> "sublimation"
Our reply: We'd like to suggest *"evaporation from the liquid phase and sublimation from the solid phase of the surrounding snow"*

Referee: **p.265: Process #3: Earlier in the paper, snow grain size measurements are reported. Is there any relationship between BC content and snow grain size? Please comment here on this.**
Our reply: This is a very good point made by the Referee. Process#3 refers to our suggestion on the possibility of soot in snow to result in larger snow grain sizes via increased melt and metamorphosis.

For cold snow SoS data: The grain sizes of the non-sooted snow were indeed a bit smaller (0.25-0.75 mm in diameter), compared to sooted snow grains (0.25-1.5 mm in diameter). Furthermore, some metamorphosis had taken place in this sooted snow resulting melt-freeze crust grains (as a result from melting and refreezing), while at the same time, the control snow grains were precipitation particles, under the same environmental conditions of the homogeneous experimental field. Hence, these results would suggest that the assumed process could exist.

For seasonally melting SoS-data: i) 16 April, two of the sooted spots (number 9 and 11) had larger grains in surface snow than the other examined sooted spots or the reference snow. Spot 9 was wood-burning soot (EC=1026 ppb), and spot 11 (EC=159 ppb) was soot from peat-burning power plant. *ii)* However, the next day (17 April) only one sooted spot (number 8, wood-burning soot, EC=489 ppb) had larger grains than any other spots. On the other hand, the reference snow did not have the largest grains on 16-17 April, before the rain. *iii)* 18 April, after the rain had stopped, we have snow grain data for the reference, and two sooted spots (number 12 and 13). Then the reference had on average the same size grains as the other two impurity spots, but also the largest grains and the largest variability in grain sizes. We would assume (ref. our latest experiment) that the cleaner snow could hold the incoming rain water better than the snow containing impurities, and larger grain sizes could result right after rain.

We'd like to conclude that our data showed some slight indication for the possibility of soot in snow to result in larger snow grain sizes via increased melt and metamorphosis, and our data did not show clear evidence against this possibility. Obviously, more data are needed. This information we'd like to suggest to be included in the revised manuscript (p.265, line 17):

"Here our data showed some slight indication for the possibility of soot in snow to result in larger snow grain sizes via increased melt and metamorphosis, and our data did not show clear evidence against this possibility."

Referee: **Table 1: It would be helpful to remind readers here about which campaigns included the artificial introduction of impurities to the snow.**
Our reply: We have now included one new column in Table 1, indicating whether artificial introduction of impurities to snow took place or not.

Referee: **Fig 2a: Is the "reference spot" indicated with only one point on this plot? What distinguishes the reference spot from the other "natural snow" points shown in this figure?**
Our reply: The "reference spot" in Fig 2a is only one point (EC=126 ppb). This SoS-2013 point is the one that is closest to the sooted SoS spot (EC=1465 ppb). The "reference spot" is by its properties basically equal to all the other natural snow spots, but it is a SoS experimental spot. That is why it is included inside the circle. The reader can compare the sooted spot result with the "reference spot" (= same place and time for these two points), and also with all the spots inside the circle (= various places and times). In the revised manuscript, a color-coding to the Fig 2a was added to clarify these results.