Reviewer: 1

Comments

This study investigated the black carbon (BC) mass concentration (MBC) in snow and ice samples from the ablation area of Potanin Glacier in Mongolia during the summers of 2022, 2023, and 2024. Also, this study discussed the distribution characteristics and potential mechanisms of black carbon at different altitudes and depths. This is important for understanding the deposition of black carbon in the cryosphere and climate effects. There are some details that need to be modified, as follows:

Response

We appreciate that you have agreed with our studies as we have presented them.

Comments 1

2 BC measurement using a nebulizer–SP2 system: Does dust or iron affect the determination of BC by SP2? This needs to be clearly pointed out.

Response

In reply to your question: No. Dust or iron has less effect on the determination of BC in our methods. As you know, SP2 detects the incandescence signal of FeO_x, not only BC. Therefore, we calculated the BC concentration excluding FeO_x by referencing the ratio of red-band to blue-band incandescence signals (Yoshida et al., 2016; Mori et al., 2022). This explanation was added to section 2.2 of the revised manuscript.

Comments 2

3 Mineral dust and water-insoluble organic matter: how to obtain the mass of dust? Also from Takeuchi and Li (2008)? Necessary introduction is needed.

Response

Mineral dust and water-insoluble organic matter were measured using the method described by Takeuchi and Li (2008). Sample weights after combustion at 500°C for 3 h were regarded as mineral dust mass. The sentences were revised as follows in the revised text.

Before:

"After taking samples to the laboratory, the samples were dried at 60°C for 24 h in pre-weighed

crucibles. Then we ascertained the dried impurity amounts (mineral dust and organic matter) of samples. After removing the organic matter from dried samples by combustion at 500°C for 3 h in an electric furnace, we found the amount of organic matter from the difference in weight between the dried and combusted samples. Those methods were based on those reported by Takeuchi and Li (2008)."

After:
"Using samples sent to the laboratory, mineral dust and water-insoluble organic matter were measured according to the method reported by Takeuchi and Li (2008), as modified from Dean (1974). The samples were dried at 60°C for 24 h in pre-weighed crucibles. Then we ascertained the dried impurity amounts (mineral dust and organic matter) of samples. After removing the organic matter from dried samples by combustion at 500°C for 3 h in an electric furnace, the weight of combusted samples was measured as mineral dust. We found the amount of organic matter from the difference in weight between the dried and combusted samples."

Comments 3
Lines 200-207, "However, such an order change of mass concentration with altitude was not found for mineral dust or for organic matter.": This conclusion is unclear. Dust seems to have no downward trend, but OM is also on a downward trend. Also, it needs to be clarified whether it specifically refers to filled, open, or slash results in Fig. 4.

Response
We revised the sentence as shown below, with information related to dark ice (filled result) and all ice (slash results).

"Although the OM mass concentration also shows a weak downward trend with lower altitude for dark ice and all samples, no such downward trend was found for mineral dust."

Comments 4
Lines 230-235, and Fig. 5: The figure shows that there are mega black carbons with diameter above 1000 nm, which is rare in atmospheric aerosol research. In addition, you also mentioned that the distribution is wider, which also suggested mega black carbon. I am not questioning your measurement, but I believe it is an important discovery.

Response

Thank you for your comment. In addition to our observations, some earlier studies using a nebulizer and a wide-range SP2 system (Schwarz et al., 2013; Mori et al., 2019, 2021) have also found the presence of BC particles larger than 1 μm in rain and snow samples. The results suggest that measuring a wide range of BC sizes is important for quantifying BC mass concentrations accurately and for elucidating their effects on snow/ice albedo. We have added this point to the main text.

Comments 5

Figure 5 is not clear. There seems to be a dotted line, but you haven't explained what the dotted line is.

Response

Figure 5 was reformed in the revised text, with added legends.

Comments 6

Lines 259-261 "However, the BC size distributions of surface water and surface ice were similar; the dependence of BC flow out was unclear.": It is not clear or easy for readers to understand. Besides, what is "Related to the former reason"? It is also not clear.

Response

Regarding "the BC size distributions of surface water and surface ice were similar", figures for surface ice and water were added to Figure 5 for comparison. Considering your comments and the other comments related to section 3.1.3, the TEM analysis results were moved to the subsequent section (3.1.4). The text on which you have commented has been revised as shown below.

Before: "Major factors of change in BC size distributions for ice and snow samples after deposition are coagulation of BC particles and size-dependent out flow with melted water, depending on the particle size. However, the BC size distributions of surface water and surface ice were similar; the dependence of BC flow out was unclear. Related to the former reason, Figure 6 shows STEM images and elemental maps of water-insoluble particles collected at the smallest particle stage for a snow sample and two surface ice samples."

After: "The reason for the broader BC size distributions in ice and water samples that experienced melting and refreezing, compared to those in snow samples, remains unclear. Possible reasons include size-dependent outflows of meltwater from ice and coagulation of BC particles during melting. For

outflow with melted water, if smaller (or larger) BC is more easily scavenged out as ice melts and flows out, then differences in the BC size distribution can be expected between surface ice and surface water. However, the BC size distributions of surface water and surface ice on the same day were similar (Figure 5a, right column); the dependence on BC size in the flow-out was unclear. For coagulation, because the BC concentration was higher in the surface ice samples, we infer that BC particles can contact and coagulate more easily in snow/ice meltwater around surface ice. Although sample vials were sonicated before BC measurement, strongly connected BCs might remain."

Comments 7

Line 262: What is 50 nm in Figure 6a? Or is it a typo of 500 nm?

Response

No, it is not a typographical error. The size is not for the aggregation particle diameter but for the primary globules which constitute the aggregation. We added scales and information related to the globule size to Figures 6a and 6b. In addition, we revised the relevant text as presented below.

Before:

"Aggregations of globules of less than 50 nm diameter, which are characteristic of soot particles"

After:

" Aggregations of small (less than 50 nm diameter) monomer globules, which are characteristic of soot particles "

Comments 8

Line 267, "Although their shape is similar to that of soot, the individual spherules in the aggregation had a larger diameter (>100 nm) and were O-rich compared to soot, indicating organics": Why can't it be a mixture of OM and Soot, add relevant literature, such as iScience 26, 108125, (2023), 10.1016/j.isci.2023.108125. npj Climate and Atmospheric Science 7, 65, (2024), 10.1038/s41612-024-00610-8.

Response

Based on morphological features (monomer size) and the compositions, we classified the majority of the particles as OM and silicate. However, this particle might contain soot, as you have noted. If BC was covered by such abundant insoluble OM, then this would be consistent with the fact that soot

cores were not observed despite the high BC concentrations in the samples. We revised the relevant text in section 3.1.4.

Thank you for recommending the interesting literature related to atmospheric soot and OM mixing. These reports also indicate that soot cores are abundant in atmospheric aerosols. OM parts on atmospheric soot appeared to be thin, small, or less abundant than in our samples. The solubility of their OM could not be ascertained. On the other hand, we regard the aggregation in surface ice samples as likely sediment formed in snow and ice samples because the mixing states and morphological features of the aggregations differed from insoluble cores in atmospheric aerosol particles at the site and in several observations, including your recommended literature. We address that point in the next comment 9. Please see revised 3.1.4, too.

Comments 9

"However, in general, submicrometer atmospheric aerosols are rarely composed only of such organics or mineral dust in internal mixed states": This sentence is not scientific enough. You prepared the TEM sample through water and cannot compare it with the mixing state of atmospheric aerosols.

Response

We well understand that the mixing state of samples prepared through water cannot be compared directly with that of air samples. Therefore, we selected the referenced reports of the related literature related to microscopic analyses that specifically examined inclusions such as soot and metals in secondary materials. Particularly, we earlier observed multiple TEM samples of urban, polluted, and clean air using water dialysis (Ueda et al., 2011ab, 2018, 2022, 2023). Water dialysis is used to observe atmospheric aerosol particles before and after removing soluble substances. The water-insoluble materials after water dialysis can be compared with those for samples prepared through water. In addition, we also collected several air samples in 2024 for reference. For illustrative purposes, we have included electron micrographs of aerosol samples in revised Supplemental materials (Fig2. S1 and S2). The water-insoluble residues after removing soluble materials using water dialysis did not consist mainly of dust or organic particles, such as those observed in the surface ice samples.

For surface ice, a long time has passed since deposition. Therefore, we rather think factors other than atmospheric deposition have had a strong influence, such as the separation of small mineral parts from coarse dusts and the precipitation of organic matter in snow water. Particularly, the almost homogeneous mixing states of aggregation containing C and Si (not external mixing states) at st5r imply that they were sediments formed in samples. This study is intended for readers in the fields of snow and ice and atmospheric science. We are concerned that researchers who have not observed atmospheric samples might mistakenly believe that the particles in the sample are solely of

atmospheric origin. Therefore, we explained that it is a characteristic of melting ice samples by comparison to insolubles in atmospheric aerosols. We have revised the related explanation above in section 3.1.4.

Comments 10

1.3 BC size distributions and particle mixing states: The author seems to emphasize the impact of coagulation on particle size distribution, and hopes to explain the differences in black carbon relative to atmospheric aerosols. Unfortunately, the role of the coagulation mechanism has not been clearly explained or involved in data analysis or discussion. Add the latest references, and reconstruct this section to improve readability and the scientific nature of the discussion, i.e., Nature Communications 16, (2025), 10.1038/s41467-025-65079-2. Geophysical Research Letters 46, 8453-8463, (2019), 10.1029/2019gl083171.

Response

The references you have recommended include discussion of the atmospheric aggregation process associated with snow, which was very interesting. However, because our study measured only deposition samples rather than atmospheric aerosol BC, the differences between fresh snow, accumulated snow, surface ice, and meltwater are attributed primarily to processes within the snow after deposition. Therefore, we revised the discussions presented in 3.1.3 and 3.1.4 to suggest post-deposition processes based on our results. In addition to the response to comment 6, please see details of the revision in the main text.

Comments 11

Figure 10: Why is there a downward trend of 2023 in Figure (a)? Also, at the same altitude, only one sample was collected in 2023?

Response

We are unable to present an adequate explanation for the downward trend of 2023. However, because the differences among the three points were small, we regard the values as similar rather than representative of a downward trend. In 2023, there was only one surface ice sample at each altitude because we mainly used vials for samples of different types, such as snow, rain, and water.

Reviewer: 2

Comments

Ueda et al., 2025 "Concentration and size distribution of black carbon over the ablation area of Potanin glacier: Enrichment ability of surface weathering granular ice of water-insoluble particles with snow/ice melting" presents BC in various materials, snow, ice, and water, which were took from Potanin Glacier. TEM analysis was conducted to investigate fine particle composition of inpurities in snow and ice. They discussed comprehensive observation results of BC deposition, residual, and outflow and estimated BC remaining fration on ice with melt water out flow. This study will contribute to extending understanding of BC dynamics in cryosphere science and more detailed understanding on BC climate effects. The methods and analysis support well the conclusion of this study. There are some parts to be revised.

Response

We would like to thank you for the many constructive comments, which have helped us to improve the manuscript.

Major comment

1. FBC was obtained by CAM-ATRAS to estimate BC remining fraction. The idea is interesting and challenging. However, CAM-ATRAS is a global model with spatial resolustion of 1.9° × 2.5° and I wonder this resolution is sufficient or not for estimation FBC in cases where significant spatial heterogeneity is anticipated, such as in ablation glacial regions.

Response

We also think that actual differences in F_{BC} can affect R estimation when meteorological conditions are heterogeneous. However, the surrounding terrain is flat. The ablation area of this glacier has a gentle slope (about 7 degrees). In fact, according to the precipitation parameter (based on accumulation data estimated with pollen content) observed in our earlier study (Khalzan et al., 2022), precipitation between the st2–st5 altitudes was similar (about 11% difference). Considering this similarity and the contribution of F_{BC} to the R calculation formula, it is unlikely that actual F_{BC} would be sufficiently different to alter the conclusion about the altitude difference of R. We added a relevant explanation for the stability of precipitation in 3.3.2 and for the terrain in 2.1 to the revised text.

2. It was difficult to understand the connection between the argument presented at the end of Section 3.1.3 regarding the mixing state of particles and the comparison with atmospheric aerosols. Detailed

comments are written in specific comments.

Response
We revised the explanations in 3.1.3 of the revised text in line with your specific comments and with the other reviewer's comments. Please see related details in response to the specific comments.

3. Does the explanation of BC enrichment on the snow surface discussed in 3.1.1 and 3.1.2 contradict BC enrichment in melted water discussed in 3.1.3? I think it would be better to organize the discussion again.

Response
We did not discuss BC enrichment in 3.1.3 before the revision, although we did address the size distribution and coagulation process. We do not think that there was a contradiction. As presented in section 3.1.1, BC enrichment is slight in surface snow (sublimation and evaporation are the main processes), but intense in surface ice (enrichment through snowmelt, detailed in the later section 3.3.1, is the main process). The BC size distributions were also similar and sharp in fresh snow and surface snow, but they exhibited some broadening in surface ice, suggesting a relation to BC enhancement with melting. During revision, the discussion was reorganized into sections 3.1.3 and 3.1.4 in the submitted text.

Spcific comments
L53: I think either 'fresh' or 'new' would be fine.

Response
We deleted 'new'.

L69: Add more specific methods for sampling method and sample treatment, such as amount of snow sampled, area of the sampling points, melting techniques, etc. Glacier might have a large spatial discrepancy of BC in snow, and strong heating can decrease measured BC concentration by SP2.

Response
We added some sample information to the second paragraph of section 2.1 of the revised text. We collected an approximately 10 cm × 10 cm area, as added to the revised text. The weights of the BC

samples were not measured. The surface granular ice depth was added in Tables S3 and S4. In 2024, considering the spatial discrepancy, we collected multiple samples for each stake. The samples were melted under ambient temperature (about 7 °C) at the base camp.

L75: Since glaciers are flowing, and sampling points are marked by stakes, does this mean the ground position of the sampling points is changing? If so, wouldn't the amount of snow fall and sediment deposited from surrounding weathered rock change over time?

Response
As you have said, the stakes move. However, because the glacier has a gentle slope (7 degrees) and a slow flow velocity (Table 1), the elevation changes little during a few years. In response to major comment 1, we added that the glacier has a gentle slope in this section of the revised text.

L90: It is preferable to indicate that a blank field has not been analyzed, such as by labeling it "N.A.," rather than leaving it blank.

Response
"N.A." was added to Table 1.

L115: How much air flow rate of the nebulizer?

Response
The air flow rate was 0.8 L min^{-1}. That information was added to the explanation in the revised text.

L124: I can understand sonication is needed to minimize BC wall loss, but I wonder the sonication is really effective to mitigate the possible change of the BC size? If yes, sonication may also change original BC size distribution. If there are appropriate references, it should be added.

Response
Because the primary objective is to measure the total amount, the samples were sonicated. Sonication is probably an efficient method for dispersing BC particles that adhere weakly to wall surfaces and to the other particles, including coarse particles that are unable to pass through the nebulizer system. The

sentence was revised as shown below.

Before: “Before measurement using the nebulizer-SP2 system, liquid samples in glass vials were sonicated for 10 min to minimize the loss of BC particles attached to the vial wall and to mitigate the possible change of the size distribution by the coagulation of BC particles in the samples.”

After: “Before measurement using the nebulizer-SP2 system, liquid samples in glass vials were sonicated for 10 min to minimize loss of BC that is unable to pass through the nebulizer system, such as BC attached to the vial wall and BC on the coarse particles.”

For the sonication size distribution, we decided that this should be considered for each sample feature. Therefore, the description was deleted here. In our earlier test experiments conducted using snow collected from Greenland and Sapporo (0.2–60 ng g^{-1} BC concentration), the concentration recorded immediately after sonication and melting slightly increased, but the particle size distribution changed less (Ueda et al., 2025). However, for samples containing high-concentration impurities, such as the surface ice samples in this study, we think greater care should be taken to account for the possibility of aggregation, as discussed in sections 3.1.3 and 3.1.4 of the revised text.

L143: Is this a handmade instrument?

Response
Yes, this is a handmade cascade impactor.

L196: 'fresh' may be more accurate than 'fresher'. Please check.

Response
That was revised to be “fresh” in the revised text.

L214: Compared to what is it ‘lower’?

Response
The sentence was revised as shown below.

Before: “However, they decreased in areas of lower elevation, which is the inverse of trends reported for accumulation areas in earlier studies.”

After: “However, they decreased with lower elevation among stakes 5r, 4c, 3c, and 2c, which is the inverse of trends reported for accumulation areas in earlier studies.”

L258: Is there any reference?

Response

No, we have not found reference material including discussion of the BC size distribution for surface ice samples. Although it was difficult to ascertain the reasons for differences in BC size distributions in snow and ice samples, we revised the paragraph (third paragraph in section 3.1.3) and added a discussion based on our results.

L270: I could not understand what this sentence is trying to explain. BC is affected post-deposition process, thus comparison with atmospheric BC is meaningless. In addition, while BC sources are remote site from observation area, mineral dust sources are assumed to be local. What are you trying to explain by bringing up atmospheric conditions from entirely different environments shown in these references? Please reconsider.

Response

As you have commented, we also think that BC in surface ice affected the post-deposition process because the feature in submicrometer water-insoluble particles in the surface ice samples (organic-only or silicates-only states) differed clearly from general water-insoluble materials in aerosol samples. We clarified the distinction with atmospheric insoluble particles to avoid misleading readers into thinking that the particles in the sample are solely of atmospheric origin in revised section 3.1.4.

In the revised version of the text, the references were limited to representative atmospheric states around the Asian atmosphere or to water dialysis. We also added information related to atmospheric aerosol samples to the supplement. Most major aerosol particles are sulfates, with occasional soot-containing particles. However, the submicron water-insoluble matter remaining after water dialysis did not consist predominantly of OM and silicate particles, such as those observed in the surface ice samples. We revised sections 3.1.3 and 3.1.4 of the revised text considering your comments.

L272: As I pointed above, the source of dust is expected to be neighboring exposed rock area. I think that the mineral dust simply emitted from neighboring areas into the air by saltation and sand blast process, and was deposited on the snow and ice surface (just dry deposition).

Response

As we have explained in an earlier comment, we also think most of the original dust particles in the glacier originate from the local environment. We agree with that. In addition, silicate, carbonate and other minerals in such dust particles can partially melt and re-form poorly soluble sediment with submicrometer particles such as calcium silicate and calcium carbonate.

L274: This sentence also fails to clarify what authors expected to explain and its evidence. Why does the presence of other particles promote BC aggregation? If TEM analysis showed advanced BC aggregation or internal mixing with others in the case of samples rich in minerals or organic, this contradicts previous explanations. Furthermore, considering the nebulizer orifice diameter, the droplets formed during atomization should be quite large. Can the agglomeration occurring within droplets really be ignored for these particle rich samples? In any case, I believe this section of the discussion, including this part, requires reorganizing what authors expected to show and their supporting evidence.

Response

We revised the descriptions and structures of sections 3.1.3 and 3.1.4 to address inconsistencies related to ultrasonic dispersion. Although we sonicated sample vials, some particles, such as strongly connected BCs, might remain connected. The surface ice sample contained high concentrations of impurities: minerals, organic matter, and BC. Therefore, it is thought that particles readily contact one another in melt water before refreezing. In addition, aggregates containing C and Si were found in the TEM sample of the st5r surface ice. Silicates and calcites can be formed as sediment in aqueous solutions and might bond BCs and cover.

We cannot completely rule out that coagulation in the nebulizer might have affected BC high-concentration samples. However, this effect is thought not to be a major factor in the difference in size distributions between snow and ice samples because such highly concentrated samples were measured after dilution by pure water, as explained in section 2.2. In addition, the BC size distribution of surface water with low BC concentration also showed a wide distribution, as shown in Figure 5, suggesting a weaker relationship between the wide distribution and the BC concentration of the samples.