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The Cryosphere Discussions

Interactive comment on "Dust from the dark region in the western ablation zone of the Greenland ice sheet" *by* I. G. M. Wientjes et al.

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We thank anonymous reviewer 2 for his extensive review with useful suggestions and detailed editorial comments, which will help to improve the paper. Below we will discuss his comments.

Specific Comments:

Comment: On p2 (abstract) the authors state that dust and cryoconite are equivalent – this is not correct (also p3 last paragraph).

Answer: The term cryoconite is often used for dust on the ice. For example, Gajda

(1958) used it to describe fine, dark windblown, inorganic and/or organic sediment, which after deposition on the ice or snow surface forms cryoconite holes; Wharton et al. (1985) explained that the term cryoconite was first used by A. E. Nordenskjöld for the sediment in holes on the Greenland Ice Cap; Maurette et al. (1987) calls it black dust (including the extraterrestrial dust); Takeuchi (2002) described it as biogenic material on glaciers, consisting of algae, bacteria, organic matter and mineral particles. We use this term to describe the surface dust on the ice and will explain this better in the text.

Comment: Provenance of dust (p2 and elsewhere) – it might be valuable to investigate the radiogenic isotope composition of the dust (Pb, Sr, Nd) for comparison with other ice core based investigations of dust provenance.

Answer: Our samples are probably a mixture of older deposited dust from different years together with recent deposition, which hampers direct comparison with ice core investigations. However, such investigations could be useful to obtain the continental origin of the dust, and we will therefore add this as a recommendation.

Comment: P3, line 2: "More knowledge. . .." – this is a very vague statement – whether or not "more knowledge" will be helpful in this regard surely depends upon the form that knowledge takes. More careful argument is needed.

Answer: With more knowledge we mean the reasons why there is a dark region. If we know what causes the dark region, we are probably able to predict how the dark region will develop in the future and therefore its future influence on Greenland's mass balance. We will extend this sentence to clarify our meaning.

Comment: P3, line 9 "showing a pattern that is typical for ice containing more dust. .. – be explicit about what this pattern is.

Answer: We mean a pattern that is typical for the outcropping of tilted, stratified layers of ice. This pattern can be seen in figure 2 of the manuscript. We will clarify this

sentence accordingly.

Comment: P3, line 17: horizontal profile represents a time-line - yes, unless (a) basal ice is exposed in the profile, or (b) there is recumbent folding within the ice.

Answer: This is true, but in our case there are no indications that exposed basal ice or recumbent folding influence the area of the dark region. Basal ice and folding are features induced by bedrock topography. The horizontal extent of the dark region perpendicular to the main flow direction is several hundreds of kilometers wide, which makes such features very unlikely.

Comment: P4, para 2 - sampling was carried out in dark region and from "brighter ice" nearer the margin – why no sampling above the dark region? Potentially important as both meltwater and katabatic winds will transport material downslope

Answer: The upper edge of the dark region is rather close to the equilibrium line as can be observed in figure 1. The small reference area between the dark region and the equilibrium line is often covered with snow and surface dust is not visible in this area. Besides, it is questionable if it is useful to sample dust near the accumulation zone, as dust there may not outcrop, but is more likely deposited with precipitation.

Comment: P4, para 2 – need to explain why grain analyses focused on mineralogy and elemental composition, as opposed to isotopic composition. Are these the optimal approaches for determining grain provenance – or just convenient?

Answer: Our main goal was to elucidate the origin and the composition of the surface dust from the dark region (compared with dust from the brighter surrounding reference ice). A logical first step in this approach is to look at the minerals and their elemental composition. In this case the elemental composition is already quite diagnostic for the origin of the dust. We agree that isotopic analyses would be a useful contribution as well and will add this as a recommendation.

Comment: P4, para 2: why not try to characterize the organic carbon, since com-

TCD
4, C1740–C1749, 2011

position likely has some bearing on its optical properties? For instance, Bhatia et al (GCA 2010) found that OM on the west Greenland ice sheet contained lipid-like and protein-like molecules, and also condensed hydrocarbons.

Answer: Bhatia et al. (2010) used their findings about lipid-like and protein-like molecules to investigate the origin of subglacial dissolved organic matter. The mechanistic link between these compounds and the optical properties of the organic material is unknown to our knowledge. This implies that a further characterization is not directly relevant for the albedo.

Comment: P5, para 2: Explain how samples were prepared for XRD analysis.

Answer: The samples were powdered and put on a sample holder; we will add this in a new version. We did no additional preparations for the XRD analysis. Composition of individual grains was investigated using electron microscopy and EDX.

Comment: P5, para 3: previously (p4, penultimate line) it was stated that it was S8 that yielded small samples, not S7

Answer: Samples from S8 were too small to use them for most of the analyses, they were only used for the optical microscopy, EDX and SEM. Samples from S7 were used for all analyses, except that they were too small for the standard decalcifications procedure, and were therefore decalcified by direct acidification within silver sample cups. We will explain this better.

Comment: P8, para 1: What is the basis for saying that the samples analysed "originate from a period within the Holocene"? Was the age of the source ice analysed – or even just characterized isotopically?

Answer: The dark region is close to the equilibrium line, where the age of the ice is (theoretically) zero. Therefore, ice from the dark region could not be very old, so a period before the Holocene can be excluded. Dust from the reference ice seems comparable to the dust from the dark region, and also not from Pleistocene origin

TCD
4, C1740–C1749, 2011

Besides, Reeh et al. (2002) and Petrenko et al. (2005) found around 69.3 °N the transition with Pleistocene ice at several hundreds meters from the margin, which is much closer to the margin as the dark region. We will explain these arguments in the revised paper.

Comment: P9, para 1: explain why aluminum is used as the reference element.

Answer: In this paragraph we are describing figure 6. We used Aluminum, because it is a general major element associated with input of non-biogenic material. We will clarify this better in the text. See also our answer on the same subject by reviewer 3.

Comment: P9, para 1: why are the results for SHR not plotted – even if there is only 1 sample?

Answer: The samples seem to cluster into two groups, with S4 and S5 in one group and S6 and S7 in the other group. As an example of this behavior, we plotted Sn concentrations against Al concentrations in figure 6. SHR behaves different, and seems to belong sometimes to the first group, sometimes to the second group and sometimes it seems to form a group on its own. If we plotted SHR in figure 6, this would suggest that SHR forms a group on its own, and this could be misleading. We will explain this better in a new version of the paper.

Comment: P9, para 2: could abundance of metals like Cs, Pb, Sb and Hg in the dark region be linked to a tendency to bind to organic matter, which is relatively abundant there?

Answer: Yes, this is indeed likely. A good correlation between TOC and the concentrations of these metals suggests adsorption to organic metal bonds. We already referred to this in the paragraph, mentioning that these elements might accumulate due to uptake by microorganisms, which are much more abundant in the dark region. We will add that these elements could bind or sorb to organic matter.

Comment: P9, para 2: what is the seasonality of dust deposition, and how might this

TCD
4, C1740–C1749, 2011

affect the extent and manner of redistribution?

Answer: We do not know what the seasonality of dust deposition is, but we also do not see how this could affect the albedo of the dark region.

Comment: P10, para1: "all these different periods" – which periods are being referred to here?

Answer: We refer to the different periods mentioned three sentences before: "*As all sites are located at different distance from the margin, the outcropping material originates from different periods.*" We will try to improve the explanation of this paragraph.

Comment: P10, para 2: "higher accumulation rates" – of what? Dust or snow? I would use the term deposition for dust and reserve accumulation for snow.

Answer: We agree that it is not clear what we mean with "accumulation rates" in this sentence and we will therefore rewrite this sentence. However, we sometimes use accumulation for dust when we mean the increase of dust amounts after several deposition events of dust. Therefore deposition of dust is not the same as accumulation of dust and we cannot avoid this verb for the dust completely, but in these cases we will state clearly that the dust is meant.

Comment: P11, para 3: What controls the abundance of P – supply or degree of biological utilization

Answer: Since we analyzed the overall bulk composition it must be the supply that controls P abundance. Even if it was taken up by biological utilization it would contribute to the P concentration which is measured on the cryoconite upon total destruction of the material. Interestingly P concentration might control the biological productivity. We found, however, no indications that this is the case, as we found higher concentrations of P at Site 4 relative to other sites, where TOC concentration were below 0.2 weight percent, indicating low microbiological activity.

Comment: P11, para 3: pH of the ice. . ..in the cryoconite holes. What is meant by the

TCD
4, C1740–C1749, 2011

“ice in the cryoconite holes”? – or do you mean the pH of the waters?

Answer: Yes, we mean the pH of the waters and will correct this.

Comment: P12, para 4: why does the sharp-edged nature of volcanic grains indicate glacial transport?

Answer: The sharp-edged nature of the volcanic grains means that they are either glacial grains or volcanic material. Volcanic material indicates glacial transport, because of the high amounts of this material, which can not originate from recent deposition only, especially at the lower sites were precipitation rates are low and wind blow much of the snow away. We have explained this in the result and discussion section, but we will extent this explanation also in the conclusion section.

Comment: P13, para 1” enrichment of dark region with elements from atmospheric sources – could this be an issue of binding to organic matter, which is more abundant in this region? (rather than evidence for localized deposition of such material)

Answer: Yes, binding to organic matter could indeed also play a role. We will look at this in more detail and change the text according to our findings.

Comment: P13, para 2: organic matter in cryoconite has a high light absorbency – here is where there should be more detailed description of optical properties of OM cf those of the various minerals detected.

Answer: That organic matter in cryoconite affects its light absorbency is well known and already investigated by other researchers. References for this (Takeuchi et al., 2001 and Hodson et al., 2010) are named in the introduction. Our statement that the dark region is not only caused by dust, but also by organic matter is based on the presence of (opaque, not transparent) organic matter in the material. The exact quantitative contribution of organic matter to the dark region is not known yet.

Comment: P13, para 3: by “meteorites” do you mean micro-meteorites?

TCD
4, C1740–C1749, 2011

Answer: Yes, we will change this.

Comment: P13, para 3: can't the elemental analyses help you determine whether there is volcanic material present? Isn't volcanic glass pretty diagnostic under an optical microscope? Doesn't it have distinctive optical properties? Is it really only Icelandic volcanoes that deposit material on Greenland?

Answer: Yes, we used the elemental analyses to argument that the material is unlikely to have a volcanic source.

The morphology of the grains corresponds to a volcanic source or transport of grains through the ice. Volcanic glass can be identified under an optical microscope using crossed nickels, but we did not unambiguously detect glass under the microscope. Still, this does not imply that it is not there, as (part of) the volcanic material might have some crystalinity. Hence, the absence of fully amorphous material does not imply that the material is not volcanic. Therefore, based on only the microscopy, we cannot exclude that (part of the) material has a volcanic origin.

No, not only Icelandic volcanoes deposit material on Greenland, but as we explained in the text, volcanic material from single events, like big volcanic eruptions, could be excluded, based on the equal REE patterns for five different sites and therefore from five different periods (a horizontal transect can be seen as a time line, as explained in the introduction). Greenlandic volcanoes are the only ones that are close enough and erupt often enough to contribute to the material for all these sites, but their REE pattern is different from the REE patterns of our samples and therefore they seem unlikely to provide the material on the ice. We will try to explain this argument better.

Comment: P13, para 3, penultimate line: "outcropping" seems to imply an origin from within the ice sheets as opposed to from local atmospheric deposition. Is this intended, and, if so, why? "multiplying rapidly" – I don't see any basis at all for this statement.

Answer: This sentence is: "*Together with this dust, microorganism could have settled*

on the ice sheet, outcropping at present in the dark region and multiplying rapidly."

Ultimately the microorganisms on the ice have to originate from somewhere, often they originate from wind-blown organic matter. In this case, it could be recent wind blown material, but it might also be possible that some organic material was blown on the accumulation zone of the ice sheet together with the high amounts of dust, in a period when much more dust from local sources was transported to the ice sheet. This organic matter consequently travelled through the ice, together with the dust. Algae might survive for some time in the ice. After outcropping, they become exposed to the sunlight and can start multiplying rapidly (in contradiction to when they are at depth in the ice). We will change this sentence.

Comment: P14, para 1: "age of the outcropping dust" – do you mean the age of the dust, or the age of the ice it came from? I suspect the latter – if so, wouldn't it be worth at least analyzing the stable isotope composition of the source ice to see if it is of Holocene or Wisconsinan age? If you mean the dust – how could it be dated? By OSL or TL perhaps – or would the dust be re-zeroed following surface exposure?

Answer: We mean the age of the outcropping ice, and will change this in the revised version. This recommendation is meant to find out more about the period in which higher dust has settled on the ice sheet, causing the dark region. Stable isotope composition seems not sufficient to achieve this goal. Besides, we know already that the dark region must be of Holocene ice, because of its position close to the equilibrium line.

Editorial Comments:

Answer: We will change the text according to these 72 points, with exception of:

Comment: 2.3: "higher" than what?

TCD

4, C1740–C1749, 2011

Answer: . . . higher relative to the brighter surroundings.

Comment: 3.1 “enhaced” – relative to what? The abstract says melt rates here are lower than at the ice margin.

Answer: “*The dark appearance implies lower albedos and therefore enhanced melt rates.*” We mean enhanced with respect to the case if there would be no dark appearance and therefore no lower albedos.

Comment: 12.13 Takeuchi (2001)

Answer: We already cited Takeuchi (2001) in this line, so we have no clue what the reviewer means.

Comment: 12.15: We only found green algae in abundance at the higher elevations, suggesting that they could have been flushed away from the glaciers at the lower sites due to the higher melt rates and runoff.

Answer: This sentence does not say exactly what we meant, but we will change our sentence.

Comment: 14.1: dust from the outcropping ice, ice cores from several metres below the surface need to be analysed to avoid. . .

Answer: We meant that the ice cores should be several meters in length, to obtain enough material for analyzing, at some depth (does not necessarily be several meters) below the surface. We will change this sentence accordingly.

Interactive comment on The Cryosphere Discuss., 4, 2557, 2010.