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The Cryosphere
Discussions

Interactive comment on "An explanation for the dark region in the western melt zone of the Greenland ice sheet" *by* I. G. M. Wientjes and J. Oerlemans

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We thank M. Pelto, I. M. Howat and the anonymous referee for their valuable comments and useful suggestions for improvement of the paper. Below we will discuss their comments.

M. Pelto:

Comment: Additional analysis of visible imagery such as the ASTER image would be useful for analysis of dust distribution. Right now one detailed view is relied upon to tell the story, is this representative?

Answer: Because Aster works on request, the spatial and time coverage is much less than for the MODIS images. Most of the available Aster images of the dark region cover only a small part of it. For the paper we choose an Aster image that covers a relatively large part of the dark region. On this image we can see that everywhere in the dark region the wavy patterns are much more abundant than outside this region. Therefore, we think this is representative. However, we will look at more Aster images and include our findings in the manuscript.

Comment: Based on the location of the dark region in Figure 1 it would appear the dark region may intersect the albedo measurement sites JAR1, 2 or 3. Does it? If so can anything be learned from any of these sites examined by Stroeve et al. (2005).

Answer: Site JAR 1 lies near the transition from the brighter ice to the dark region, sites JAR 2 and JAR 3 lie to the west of the dark region. Therefore data from these sites does not help to explain the dark region.

Comment: Figure 1 indicates the dark region almost reaches the margin of the ice sheet just north of Jakobshavn. Looking at the debris in this region many of the debris bands in this area are parallel to flow not perpendicular to flow as most annual outcropping layers are (Fig. 1). Any explanation of this?

Answer: Because Jakobshavn is a fast moving outlet glacier, the flow of ice close to this glacier will be influenced and accelerated towards it. This will also influence the direction of outcropping layers. The darker ice will flow faster near this outlet glacier, causing the dark region to get closer to the margin at this place. We will add this point in the discussion.

Specific Comments:

Comment: 164-3: ": : :ablation zone is very wide" . Specify the range of ablation zone width. Compare that to dark zone width along a transect at the ASTER image location.

Answer: The ablation zone at this location is about 100 km. We will add this in the manuscript.

Comment: 167-12: Elevation and distance from margin of the dark region needs to be reported in more detail, focusing on a few transects to keep it meaningful. Could be a table.

Answer: We will add such a table in the manuscript.

Comment: 169-8: ": : :slush line is more to the east of: : :" To the east of the dark region I assume. What about most years where is the dark region with respect to the slush line? It would be appropriate to locate the dark region with respect to the traditional glacier zones along a transect. Nolin and Payne (2007) have already provided zone determination in the region for such a figure. It would be easiest to display in a figure like that of Figure 7.

Answer: The zone classification can differ during the summer season and for different years. As Nolin and Payne (2007) explained in their paper, the interannual differences they found could be caused by the amount of almost cloud free satellite images or by different properties of the ice surface. Our argument is that the dark region always remains at the same location, even in extreme years when the slush line migrates further to the east than the eastside of the dark region. Therefore, it can not be coupled to a slush or meltwater zone. We will try to improve this explanation in the manuscript.

Comment: 169-18: What would the reflectance spectrum be for meltwater saturated ice. A line for this if available should be in Figure 6.

Answer: As far as we know, there is no reflectance curve for meltwater saturated ice. We expect that meltwater will lower the reflectance of the ice for all wavelengths. However, we argue that because of the same location of the dark region every year and its sharp transition, the dark region reflects a property of the ice. For that reason, meltwater alone does not explain the appearance of the dark region.

Comment: 170-2: distance of dark region to margin?

Answer: This distance is in the order of hundreds of meters to tens of kilometers, depending on the latitude. We will include some distances in the table mentioned before.

Comment: 170-7: How abrupt is the transition from the dark region, give as a distance.

Answer: As can be seen from Figure 1, this transition is quite sharp. We will calculate the exact distance and add this in the manuscript.

Comment: 170-26: The assertion of the Holocene based age for the dust on an unreported distance to the margin needs additional support or simply remove it. The age of the dust is really not a focus of this paper.

Answer: The distance of the margin at this point is in the order of tens of kilometers, whereas the transition of pre-Holocene to Holocene ice is found at about 800 meters of the margin (Petrenko et al., 2005). Therefore, it seems unlikely that outcropping ice in the dark region contain dust from times before the Holocene.

Comment: Figure 1: Locate Swiss Camp on Figure 1.

Comment: Figure 2: A legend is needed for the reflectance colors.

Answer: Figure 2 does not show reflectance colors, but RGB-color compositions. These are compositions of three different planes of reflectance data combined in one figure, as explained in the text in Sect. 2. Because one color represents the ratio of the reflectances of three different wavelength bands, a legend could not be given.

Comment: Figure 3: Delineate the primary dark region area on graph.

Answer: We will adapt the figure in this way.

Referee 1:

The major points are:

Comment: 1. The possible causes for the debris of the dark region have to be discussed more carefully. The authors considered only two possibilities: windblown dust and Holocene origin dust contained in the ice. However, there are some litertures that biogenic surface dust, i.e. cryoconite, covers the ablation ice, and significantly affect the surface reflectance of the Greenland ice sheet (e.g. Gajda, 1958). That would also be another possibility.

Answer: Dust on the ice surface is often called cryoconite, after A. E. Nordenskjöld, (Gajda, 1958; Takeuchi, 2001). The word cryoconite does not say anything about the origin of this dust. Part of the dust might be biogenic, but we think that there are in principal two main sources for the dust on the ice sheet. It could be outcropping dust from the inner part of the ice sheet or it could come from outside the ice sheet. We agree that we are too specific in naming these two possibilities. For example, the dust could not only be wind blown material from the tundra area, but it could also come down with precipitation. In the revised manuscript, we will name these possibilities more clearly.

Comment: 2. Spatial variation of cryoconite coverage on an Alaskan Glacier has been shown in Takeuchi (2009). According to the paper, cryoconite is abundant on the surfaces near the margin and snowline. The abundance cryoconite near the snow line is due to high biological (snow algal) production. This pattern seems similar to the case of this paper. Authors may mention this possibility.

Answer: Takeuchi (2009) found different spectra for wet snow, for red snow due to snow algal bloom and for ice contaminated with dust. When comparing our results with these three spectral types, the spectrum of an exposed ice surface corresponds best with our findings. This is logical, as our dark region is on the ice surface; it becomes visible after the snow disappears. Additionally, Takeuchi (2009) found higher absorptions at wavelength ranges of 400-600 and 670-680 nm for the red algal bloom. This is not the case for the spectra of the dark region.

Comment: 3. Gajda (1958) also describe stripes (wavy pattern) on the ice surface based on in situ observation. He concluded the stripes were due to deposition of cryoconite by wind action, which is different interpretation from that of this paper. Authors should mention this difference of the interpretation.

Answer: The stripes that Gajda (1958) described does not have a wavy pattern. They are long thin lines parallel to the margin and seem to be a completely different phenomenon. Besides, these stripes are only about 10 cm wide, whereas the wavy patterns seen on the Aster image are in the order of tens to hundreds of meters. We will add a scale bar in Figure 8c, to make the differences between these orders of size more clear.

Comment: 4. Cryconite hole development may also affect surface reflectance. If the holes significantly developed on the ice surface, reflectance would become higher even if abundant dust exists on the glacial surface. Development of the holes is physically determined as shown by e.g. Gribbon (1979). Spatial variation in such physical factor may cause the reflectance variation.

Answer: We agree that the formation and characteristics of cryoconite holes might have an effect on the albedo. But in both situations, either dust spread out on the surface or dust collected in holes, the albedo will be much lower than the albedo of ice without any dust. If comparing the spectral information of ice from the dark region and from a brighter region with literature values, there seems to be a significant difference in the amounts of dust in both regions. Gribbon (1979) found that the depth of the holes is determined by the bulk extinction coefficient of the ice and the albedo of the ice surface. He also found that characteristics like the diameter and the number of holes seems only to be influenced by the amount of dust available. Because the albedo in the dark region is lower and dust is more abundant, the depths and other characteristics possibly increase the effect of the darkening. This feedback mechanism needs more investigation; we will mention this in the manuscript.

Minor comments:

Comment: P.169 L.10 The dark region seems to remain in the same location in Fig. 4, however, it is not clear in 2001, 2004, and 2006. Authors should explain why.

Answer: This is probably due to less melt in these years. We will examine this as suggested by I.M. Howat and discuss this in the manuscript.

Comment: P.169 L.19 Takeuchi et al. (2001) is probably wrong citation. The spectral reflectances of ice with cryoconite and clean bare ice is not shown in the paper, but in another paper shown below (Takeuchi et al., 2001).

Answer: This will be corrected.

Comment: P.169 L.23 If authors want to conclude that the melt water does not caused the darkening in the area based on the spectral reflectance, authors should show spectra of glacial surface with meltwater and show that it differed from the spectra obtained from the image.

Answer: As far as we know, there is no spectral information of glacial ice containing meltwater. However, we conclude that meltwater is not the only source for the dark region, because of the same location of the dark region every year and because of the sharp transition on both sites of the dark region. Of course, a dark region means more energy absorption and therefore more melt. Therefore, the dark region will probably also contain more meltwater, but this does not seem to be the only reason for the darkening. We will try to explain this argumentation better in the manuscript.

Comment: P.171 L.4 Authors should present an ASTER example of the brighter ice as well as dark region in Fig.8 to show the wavy pattern is less clear on the brighter ice. Also, it is not clear that why the wavy pattern can be evidence of dust from colder periods. Authors should explain this logic more carefully.

Answer: If Figure 8b is large enough, it can be seen that the wavy patterns are more abundant in the dark region. Nevertheless, we will show an intersection from

the brighter ice as well, to make the differences more clear. In ice cores from the accumulation zone of the Greenland ice sheet, layers containing abundant dust are found. This dust has settled on the ice sheet during colder periods, because of dryer and windier circumstances. It can also originate from volcanic eruptions. Due to the flow pattern in an ice sheet, the ice, including the dustier layers, will flow through the ice sheet towards the margin and after some time melt out in the ablation zone. Because of this flow, these layers will outcrop in wavy patterns, just as the patterns observed in the dark region. We therefore conclude that these patterns are evidence for dust from an older period. We will extend this explanation in the manuscript.

I. M. Howat:

Comment: Please cite the sources for your imagery data.

Answer: We will add these sources.

Comment: The discussion of the variations in the time series data is very unsatisfying. The 2 main sources of variance hypothesized - satellite position and surface accumulation - can be tested. Positioning data is distributed with the L1B metadata and surface accumulation or SMB timeseries does exist from multiple data sources, for example:

Box, J.E., D.H. Bromwich, B.A. Veenhuis, L-S Bai, J.C. Stroeve, J.C. Rogers, K. Steffen, T. Haran, S-H Wang, 2006: Greenland ice sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output, 2006: Journal of Climate, Vol. 19, No. 12, pp. 2783–2800

Burgess, E.W., R.R. Forster, J.E. Box, L.C. Smith, D.H. Bromwich, 2010: Greenland ice sheet annually-resolved accumulation rates (1958-2007), a spatially calibrated model, Journal of Geophysical Research,

Van den Broeke, M. R., J. Bamber, J. Ettema, E. Rignot, E. Schrama,W. J. van de Berg, E. van Meijgaard, I. Velicogna and B. Wouters, 2009: Partitioning recent Greenland mass loss, Science 326, 984-986.

I suggest testing these hypothesis by comparing your results with the satellite positioning and the SMB variations. If I remember correctly 2002-3 was a high accumulation year, so that would support your conclusion, but this should be referenced.

Answer: We will test if the mass balance data correspond with our conclusions and extend the manuscript with our findings. We will also try to calculate the satellite position from the ephemeris and altitude data from the L1B products. We will adapt the discussion of the manuscript, depending on the outcomes.

Comment: As pointed out by reviewer 1, it would be nice to see more than one aster image to establish that these waves are temporally and spatially persistent and unique to this region (i.e. as opposed to the "control" region).

Answer: In the revised manuscript, we will give a more detailed image of the control region, like the detailed image of the dark region in Figure 8c, to show that the wavy patterns are much more abundant in the dark region. We will also describe our observations from other Aster images in the discussion of the manuscript.

Comment: Clearly the fact that they bend to parrallel with flow at Jakobshavn, as pointed out by M. Pelto is due to increased flow rates - this could be discussed.

Answer: See our answer at the mentioned comment of M. Pelto. The fact that the dark region seems to be influenced by increased flow rates near Jakobshavn, is another argument that the dark region is a property of the ice. We will add this point in the manuscript.

References

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Nolin, A. N. and Payne, M. C.: Classification of glacier zones in western Greenland using albedo and surface roughness from the Multi-angle Imaging SpectroRadiometer (MISR), Remote Sens. Environ., 107, 264-275, 2007.

Petrenko, V. V., Severinghaus, J. P., Brook, E. J., Reeh, N., and Schaefer, H.: Gas records from the West Greenland ice margin covering the Last Glacial Termination: a horizontal ice core, Quat. Sci. Rev., 25, 865–875, 2005.

Takeuchi, N., Kohshima, S., Shiraiwa, T., and Kubota, K.: Characteristics of cryoconite (surface dust on glaciers) and surface albedo of a Patagonian glacier, Tyndall Glacier, Southern Patagonia Icefield, Bull. Glaciol. Res., 18, 65–69, 2001.

Takeuchi, N.: Temporal and spatial variations in spectral reflectance and characterisitics of surface dust on Gulkana Glacier, Alaska Range, J. Glaciol., 55, 701-709, 2009.

Interactive comment on The Cryosphere Discuss., 4, 163, 2010.