RETRIEVING BLACK CARBON ON SNOW AND ICE SURFACES IN THE ARCTIC

Rune Solberg[(1)], Carl Egede Bøggild[(2)], Borgar Aamaas[(2)], Øivind Due Trier[(1)] and Bjørn Wangensteen[(1)]

[(1)] Norwegian Computing Center (NR), P.O. Box 114 Blindern, NO-0314 Oslo, Norway, Email: rune.solberg@nr.no
[(2)] University Centre in Svalbard (UNIS), P.O. Box 156, NO-9171 Longyearbyen, Email: carl.egede.boggild@unis.no

ABSTRACT

In the last IPCC report the black carbon (BC) impact of the Arctic was recognized as an independent and recognizable contribution to global climate change. The overall objective of the project behind the work presented here is to determine whether the black carbon content in snow and glacier ice surfaces can be retrieved from satellite data. Preliminary analysis of satellite measurements shows that high concentrations of BC (from local sources) are clearly detectable in the satellite signal, both over snow and glacier ice surfaces. Chemical BC analysis of snow and ice samples taken in the field show values consistent with the satellite data. Even if the general low BC level in the snow due to long-transported aerosols might be hard to measure in the cold, dry season, we have seen a significant increase in the signal during the melting which may make BC retrieval possible during the summer months.

1. INTRODUCTION

Over the last years the importance of black carbon (BC) for the climate system has been increasingly recognized. In the last IPCC report (condensed version for policy makers) the BC impact of the Arctic was recognized as an independent and measurable contribution to global warming. However, to our knowledge, no other than this group are concerned with analysis of BC on glacier ice.

Black carbon, originating from incomplete burning of organic material or fossil fuel, form small highly solar radiation absorbing particles which have proven also to enter the Arctic [1, 2]. The smallest particles can be transported over long distances and are more frequently found in the Arctic than previously thought [3]. Though being extremely small (0.01-0.4 μm), the particles can result in warming in two ways, namely by direct radiation absorption in the atmosphere and indirectly by changing the optical properties of the snow and thus reducing the surface albedo [4]. As opposed to carbon dioxide, black carbon belongs to the group classified as 'short-lived pollutants', which are only believed to retain in the atmosphere for some days before deposition. Despite being shortly in the atmosphere, these 'short-lived pollutants' are considered as the second most important contribution to global warming [5]. And, BC is among the most important short-lived pollutants.

The feedback processes, combined with other direct and indirect effects, give a strong impact in the Arctic, despite that only around 10-20% of the global BC emissions end up in there. But an ignored effect so far is the long-term effect of BC on glaciers. Due to downward movement of accumulated snow on glaciers in combination with the ice flow – BC will become entrained in the glaciers and eventually melt free many years later further down in the melt zone. BC will accordingly accumulate on the ice surface and contribute to surface darkening. This darkening enhances the melting and contributes to thinning of the Arctic glaciers. The magnitude of this enhanced melting is not known, but the accumulated long-term effect is likely large and will continue even after a possible stop of human BC emission.

So far, BC has been measured in the field directly by taking samples for chemical or optical analysis. However, such point sampling is rather limited in providing information on the large-scale distribution and temporal variability. Furthermore, field measurements will always be limited to few samples as fieldwork in polar regions is costly. If BC retrieval from satellite data is possible, it would make large-scale monitoring of BC in snow and ice possible. This means that concentrations and variability of BC for the first time could be observed as a variable in space and time for vast regions. Operational BC monitoring would make improved energy balance modelling possible, which is in particular important for modelling the processes in the Arctic and Antarctica. In most climate models, energy balance processes in these areas are much simplified. Improved climate modelling in polar regions could potentially have a significant impact on long-term climate-change projections on the global scale.

The overall objective of the PRODEX Black Carbon project is to determine whether the black carbon content of snow and ice can be retrieved from satellite data. The experiments have so far taken place in Svalbard.

2. MEASUREMENT SITES

Two regions were chosen for satellite measurements, one on each side of the large fjord Isfjorden. One is on

Grønfjordbreen south of Barentsburg and the other on Eidembreen north of Isfjorden (Fig. 1). The distance between the two glaciers is about 60 km. The two regions should have about the same local climate. The snow sites are situated between 300 and 400 m above sea level, and the glacier sites about 150-200 m above sea level. With natural conditions without local aerosol sources, one should expect the snow development and therefore reflectance to be quite similar at the two sites.

Figure 1. Map of outer part of Isfjorden in Svalbard. The two test sites are marked by red squares. Barentsburg is situated at the eastern side of Grønfjorden, marked with an orange arrow

Coal dust concentrations are periodically quite large at Grønfjordbreen, which is less than 20 km away from Barentsburg. This situation enables more controlled sensitivity studies of a large range of soot and coal dust concentrations. On the other side, Eidembreen should hardly be affected by local sources, and therefore work well as a reference site for the satellite measurements.

3. SATELLITE MEASUREMENTS

At each site an area of 500 m × 500 m were chosen. The Terra MODIS sensor has pixel resolution of 250 m × 250 m in channel 1 (620–670 nm) and channel 2 (841–876 nm). Each of the areas is covered by four MODIS pixels in these channels. Channel 1 has been used for radiance comparison. Envisat MERIS data of 300 m pixel size has been made available to the project through an ESA Category-1 agreement. MERIS channel 6 (620 nm) has been used for comparison with MODIS channel 1.

Automatic cloud detection (NR's k-NN algorithm [6]) has been run for MODIS, while manual screening has carried out for MERIS. The data was geometrically corrected to a common map projection. The data was then converted to top-of-atmosphere (TOA) radiance values.

4. FIELD MEASUREMENTS

In situ measurements have been carried out at three field sites: Longyearbreen, Grønfjordbreen and Aldegondabreen. Longyearbreen is easily accessible directly from Longyearbyen, while Grønfjordbreen and Aldegondabreen are situated south and south-west of Barentsburg, respectively. The field measurements were coordinated with the satellite measurements in order to achieve a number of simultaneous measurements. The measurements were carried out in the spring and summer.

4.1. Snow sites

The measurements and sampling were limited to the surface (upper 10 cm) except for the early spring campaign where measurements and sample collection were also done at various depths in about 1.5 m deep snow pits. Snow samples were collected for material compositional analysis (including BC). On-site analysis included spectral measurements, snow characterisation (including grain size and shape) and measurements of snow and air temperatures, wetness, density and depth (as far as a stick could be driven down). Samples and measurements were taken at 4–5 positions at each site in order to achieve an overview of local variability. The spectral measurements were done with an ASD Fieldspec Pro spectroradiometer measuring in the electromagnetic interval 350–2500 nm.

4.2. Glacier ice sites

Samples were taken at a total of 14 locations at three sites at Grønfjordbreen and Aldegondabreen in a campaign in July 2009 (Bøggild et al. in prep). A campaign was carried out at Longyearbreen in September 2009 were samples were taken at a total of five locations. At each measurement point an ice sample was retrieved together with spectrometer measurements. The rationale for taking multiple samples at every location as well as many samples on each glacier is to document and possibly quantify the high spatial variability of glacier surface albedo and aerosol accumulation.

4.3. Meteorological station data

A HOBO weather station was set up at an altitude of 180 m.a.s.l. at Grønfjordbreen and was running from April until September 2009. The station measured, relative humidity, wind speed, wind gust, wind direction, incoming solar radiation and outgoing solar radiation (300-1100 nm).

5. RESULTS

5.1. Satellite measurements

Snow sites

Looking at the radiance values for the accumulation area ('snow') sites on both glaciers (Fig. 2, top panel), the sun elevation is causing an increase in early summer and decrease after summer solstice. One can also see that there is an increasing difference in the radiance values recorded at the two glaciers, with Eidembreen having the larger values. This hints at a hypothesis of Grønfjordbreen having the albedo lowered by local pollution, and that the effect is increasing through the melting seasons. Measurements from MODIS and MERIS seem to be quite consistent.

Glacier ice sites

For the radiance values for the ablation area ('glacier ice') sites (Fig. 2, lower panel), one can see that the values are quite similar to the accumulation area sites in the first part of the period (which could be expected as all sites are snow-covered in this period). From early summer and for the rest of the period the ablation area sites show lower radiance values than the accumulation area sites on both glaciers. Looking at the relative difference between the ablations area test sites on the two glaciers, the differences is not increasing as much as the difference between the two accumulation area sites, but there is still a trend showing increasing differences during the period. For both the ablation and the accumulation area the relative differences show quite high deviations. Measurements from MODIS and MERIS seem to be quite consistent.

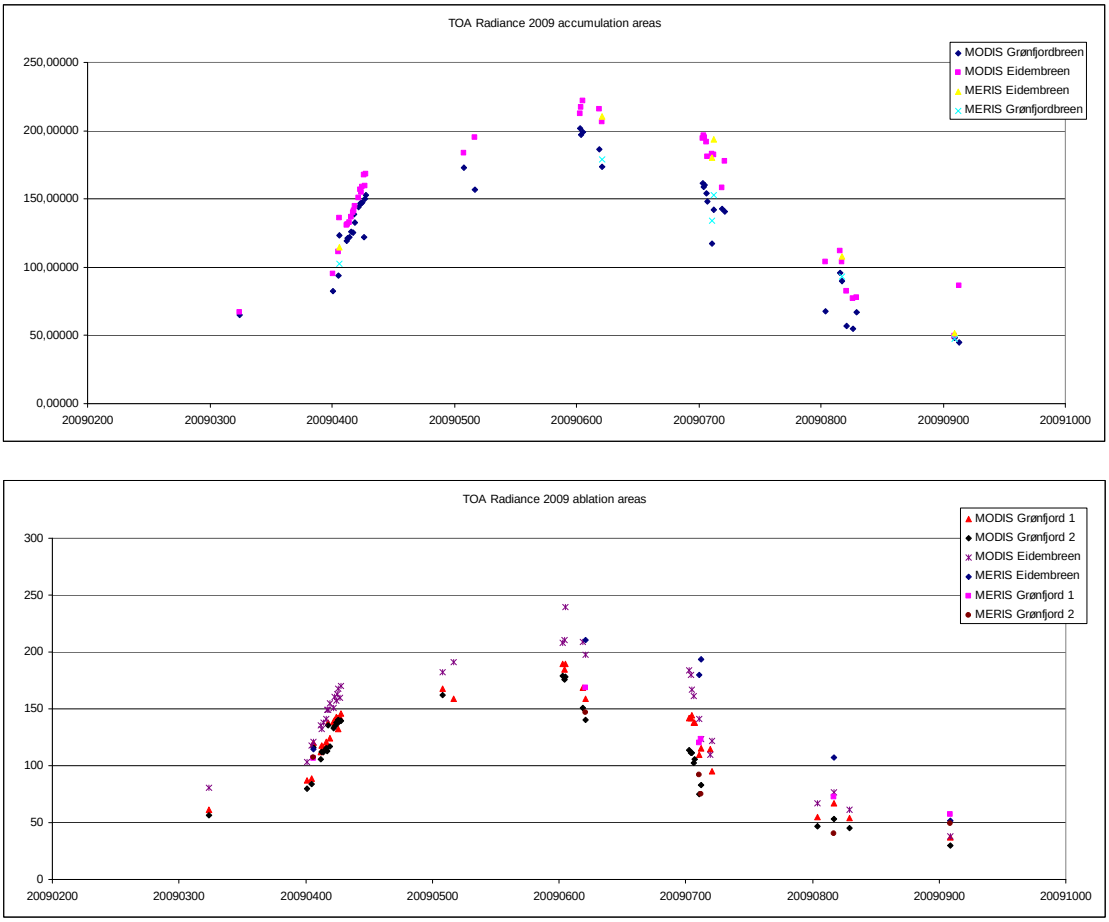

Figure 2. Top panel: Top-of-atmosphere radiance from the MODIS and MERIS image data in the accumulation area ('snow sites') of the glaciers. Lower panel: Top-of-atmosphere radiance from the MODIS and MERIS image data in the ablation area ('glacier ice sites') of the glaciers

5.2. Field measurements

Snow sites

The results of the chemical analysis for Grønfjordbreen in April show that BC concentrations were highest in the surface snow layer (Fig. 3). A maximum in BC concentration for the upper site was measured for an ice lens that contained dark particles, probably soot, seen visually at site. The mean BC concentration for the upper 5 cm in the snowpack at the two sites was 162 µg/l and 39.5 µg/l at the upper site. The BC concentration increased at least by one order of magnitude during the spring and summer melt. At the upper site of Grønfjordbreen, the BC concentration was about 764 µg/l in July. The snow samples from the lower site contained too much BC to be analyzed by the applied chemical method.

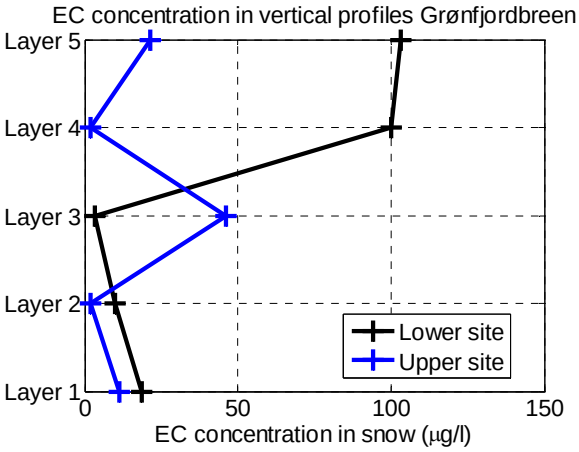

Figure 3. The vertical profile of the EC concentration at two sites on Grønfjordbreen in April 2009

Glacier sites

The cryoconite burden per unit surface area on the glacier was determined from the measurements. Since the surface area of each sample is known, a cryoconite burden per square meter was calculated.
Preliminary results show that the surface loading of impurities from aerosols can vary from 84 g/m² to almost 4300 g/m² on Grønfjordbreen and Alagondabreen. The cryoconite burden observed is much larger than what was observed on Longyearbreen in 2008. This high loading measured on Aldegonda-breen and Grønfjordbreen is also in line with visual observations which show patches of extra high cryoconite content.

6. DISCUSSION AND CONCLUSIONS

The field-measured BC concentrations of snow on Grønfjordbreen in April are well above the average for Svalbard. The BC background level is about 4.1 µg/l [7]. The reason for this is the proximity to the coal mining settlement of Barentsburg, about 15 km north of the glacier. The weather station showed that the wind comes from the direction of Barentsburg about 15% of the time for the period April–September. A large share of the BC particles accumulates and/or stays in the snow during the spring melt, resulting in an increase in BC concentration through the melting season. Extremely high BC concentrations are measured in the snow at the end of the melt season in later summer. Aldegondabreen is closer to Barentsburg than Grønfjordbreen, and is, thus, likely even more influenced by the BC emissions in Barentsburg.

A number of ‘dry mass’ samples were collected at the glacier ice sites on Longyearbreen, Alagondabreen and Grønfjordbreen. Besides determining the mass of the impurities on the glacier surface, referenced digital photos were taken at exactly the same location of sample retrieval. The results so far have shown that a relationship can be derived between the mass of the aerosol impurities and the percentage of surface coverage, which again relate to surface albedo.

The representativeness of our results needs to be verified by results from other glacier types at other locations where wind deposition and climate is different. We have so far focussed on small valley glaciers near settlements which are only a fraction of all glaciers on Svalbard. The observed impurity loading and high spatial variability is in line with similar observations from the Greenland ice sheet.. This despite on large glaciers the ice crystals are also larger, which favours development of cryoconite holes where the impurities become concentrated. These holes are only visible vertically and can contain much cryoconite. Due to the low solar angle in the high Arctic the impurities entrained inside the deep cryoconite holes have little effect on the melting.

The satellite-measured radiance from snow sites (‘accumulation sites’) and glacier ice sites (‘ablation sites’) varies through the 2009 spring-to-summer season. The seasonal variation due to solar elevation is obvious in the data. No solar elevation and atmospheric correction have been done in this preliminary data analysis. However, since quite a number of observations are available, some trends are clear. There is a systematic, significant difference between Grønfjord-breen and Eidembreen with Grønfjordbreen exhibiting the lowest radiance values. This difference was expected as the local concentrations of BC and soot in general are high in the Grønfjorden area. There seem

also to be an increase in the difference between the two glaciers during the spring, but one should be cautious with interpretation until further corrections have been done to the data followed by a statistical analysis.

The data patterns are quite similar for both accumulation and ablation sites for this season. The main reason is probably the strong summer melt that resulted in disappearance of snow from both upper and lower sites quite close in time. The difference between the two glaciers is larger for the lower sites than the upper sites, which is probably due to snowmelt at the lower sites being ahead of the upper sites by a few weeks, resulting in more surface impurities at the sites ahead in development.

As no field measurements were taken at Eidembreen (which is much less accessible that Grønfjordbreen), we assume in the following that the BC concentrations at Eidembreen are rather close to the background level at Svalbard in general. This is conformant with field measurement done in [7], which also have quantified the average background level to 4.1 µg/l.

Field measurements of BC concentrations in snow show an increase during the snowmelt season. The surface samples of the upper site at Grønfjordbreen showed BC concentrations in April about 10 times higher than the background level. In the beginning of July the concentration had increased to 185 times higher than the background level. The increase in BC concentrations at the surface confirms general experience by BC fieldworkers that the amount close to the surface increases in the melting season. This was expressed in the discussions at the Black Carbon Workshop in Trømsø, 13-14 August 2009. It was also stated that much is still unknown to how BC is transported in the snow during the melting process. Some of the surface increase might also be due to precipitation as rain in the summer season.

There is good consistency between the albedo measurements taken by the climate station at Grønfjordbreen and the satellite-measured radiance. There is a gradual decrease in the albedo from late May until late July.

In conclusion, the satellite measurements show a clear difference between Eidembreen and Grønfjordbreen, including the early spring season with dry snow when there are approximately 10 times higher BC concentrations at Grønfjordbreen than Eidembreen (upper sites). At Grønfjordbreen the BC concentrations have increased approximately 20 times until beginning of July. If this concentration-increase rate during the melting season is representative in general, we can conclude that there is a measurable satellite signal from BC in the snow in Svalbard during the melting season. This should hint towards a retrieval algorithm based on an approach of analysis in a time series of satellite observations where the snowmelt season is included.

7. REFERENCES

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