Remote Sensing of Black Carbon in the Arctic

R. Solberg[a*], C.E. Bøggild[b], A.J. Hodson[c], H. Koren[a], S.Ø. Larsen[a], Ø.D. Trier[a], B. Aamaas[b]

[a] Section for Earth Observation, Norwegian Computing Center, P.O. Box 114 Blindern, NO-0314 Oslo – Rune.Solberg@nr.no
[b] The University Centre in Svalbard (UNIS), P.O. Box 156, NO-9171 Longyearbyen – Carl.Egede.Boggild@unis.no
[c] Department of Geography, University of Sheffield, Sheffield, S10 2TN – A.J.Hodson@sheffield.ac.uk

Abstract – Black carbon ('soot'), originating from incomplete burning of organic material or fossil fuel, is widespread in the cryosphere – including the Arctic. Black carbon is stated to be the second most important contribution to global warming. In 2008, a first phase of a project was carried out in Svalbard for development of an approach using earth observation for black carbon monitoring. The overall objective is to determine whether the black carbon content of snow and glacier surfaces can be retrieved from satellite data. The project includes efforts to determine the main spectral properties of black carbon in snow and ice in the Arctic/Svalbard and to determine whether there is significant information (signal) in relevant satellite data in order to be successful in parameter retrieval of black carbon. Fieldwork included measurements of spectral properties of snow as well as ice and sampling for chemical analysis. Terra MODIS images have been analysed. A conceptual model describing the way impurities distribute on glacier surfaces is currently under development.

Keywords: Black carbon, climate change, snow, glaciers.

1. INTRODUCTION

Black carbon (BC), 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 (Ramanathan and Carmichael 2008; Koch et al. 2007). The smallest particles (a few microns in diameter) can be transported over long distances and are more frequently found in the Arctic than previously believed (McConnell et al. 2007).

Despite being extremely small (a few microns) the particles can contribute to warming in two ways, 1) by direct radiation absorption in the atmosphere and 2) indirectly by changing the properties of the snow and thus reducing the surface albedo (Flanner, Zender and Randerson 2007). The black carbon aerosols belong to the group classified as 'short-lived pollutants', which are believed to retain in the atmosphere for some days before deposition. These 'short-lived pollutants' are considered as the second most important contribution to global warming (Hansen and Nazarenko 2004). Furthermore, BC is among the most important of the short-lived pollutants.

The feedback processes and the high reflectance of the Arctic give a strong impact from BC, despite that only around 10-20% of the global BC emissions end up here. However, 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 will eventually melt free many years later further down in the melt zone of the same glacier. BC will accordingly accumulate on the ice surface and will thereby 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 presently. But due to snow ice flow the long-term effect is likely significant and well beyond termination of human BC emission.

In 2008-2009, the first phase of the European Space Agency/Norwegian Space Centre** PRODEX *Black Carbon* project for developing an approach using earth observation for black carbon monitoring is carried out in Svalbard. The overall objective is to determine whether the black carbon content of snow and glacier surfaces can be retrieved from satellite data. The project includes efforts to determine the main spectral properties of black carbon in snow and ice in the Arctic/Svalbard and to determine whether there is significant information (signal) in relevant satellite data in order to be successful in retrieval of black carbon concentrations. A combination of field measurements in field campaigns and acquisition of Terra MODIS satellite images was carried out. The fieldwork included measurements of spectral properties of snow and ice and sampling for chemical analysis.

If BC retrieval from satellite data is successful, it will enable large-scale monitoring of BC in snow and ice. Then concentrations and variability of BC for the first time could be observed as a variable in space and time. Operational BC monitoring will also enable improved energy balance modelling, which is particularly important for modelling the processes in the Arctic and Antarctica. In most climate models, energy balance processes in these areas are very much simplified. Improved climate modelling in polar areas could potentially have a significant impact on long-term climate change projections on the global scale.

2. METHODS AND DATA

Three field sites (glaciers) have been selected so far in the project: Longyearbreen, Grønfjordbreen and Eidembreen. Simultaneous satellite and field measurements are carried out a few times during the spring and summer, and possibly combined with additional information from the area, in order to obtain a better picture of what causes the temporal changes in surface albedo.

2.1 Field campaigns

In each field campaign, a set of spectral reflectance samples are taken. Samples are also collected for material compositional analysis in a laboratory, i.e. determining the fractions of black carbon (BC), organic material and lithogenetic material. In order to improve the understanding of the evolution on the snow and ice

* Corresponding author
** The project is funded by the Norwegian Space Center as part of ESA's PRODEX programme

surfaces, an automatic time-lapse camera was set up for taking daily pictures of a glacier surface during the spring and summer period.

The first series of field measurements were carried out in the summer of 2008, and field campaigns for the 2009 season started in March. The combination of spectral measurements, photos and samples were taken of the glacier surface at Longyearbreen in August 2008. Spectral measurements were taken with an Analytical Spectral Devices Fieldspec Pro spectroradiometer measuring in the electromagnetic interval 350–2500 nm.

2.2 Satellite measurements

The most relevant satellite data are Terra MODIS and ENVISAT MERIS. Supplemental sources could be NOAA AVHRR and ENVISAT AATSR. MODIS data (of 250 and 500 m pixel size) and MERIS data (of 300 m pixel size) are regularly downloaded from data providers. Automatic cloud detection is run for MODIS, while manual screening is carried out for MERIS. The data is then geometrically corrected to a common map projection. At the end of the measurement period, time series of satellite data are composed for the pixels corresponding to the sites.

Two sites have been 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 (Figure 1). The distance between the two sites is about 60 km. The two sites should have about the same local climate. They are situated between 300 and 400 m above sea level, and both have a small gradient facing towards north, though somewhat more westerly on Eidembreen. With normal conditions without local aerosol sources, one should expect the snow reflectance to be quite similar at the two sites.

One of the applications of these sites is for satellite algorithm development, calibration and validation. Coal dust concentrations are periodically quite large in the area, as around other coal mines in Svalbard. Grønfjordbreen is less than 20 km away from Barentsburg. This situation enables more controlled satellite data sensitivity studies of a large range of coal dust concentrations when field measurements are taken simultaneously with satellite measurements. On the other side, Eidembreen should hardly be affected of local coal dust, and therefore function as a reference site for the satellite measurements.

At each site an area of 500 m × 500 m has been chosen. The 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 to compare the reflectance. A number of images taken between 3 April and 26 June 2007 have been studied.

2.3 Time-lapse camera monitoring

A camera located on Lars Hiertafjell acquired photos of Longyearbreen at three hour intervals, from 7 July to 15 August 2008. Unfortunately, the summer season of 2008 was short. Longyearbreen was covered by snow most of the time. The glacier was fully covered by snow at the start of the time-lapse photo series and almost through July. Some patches of ice were visible in early August, but shortly after, fresh snow had covered the glacier.

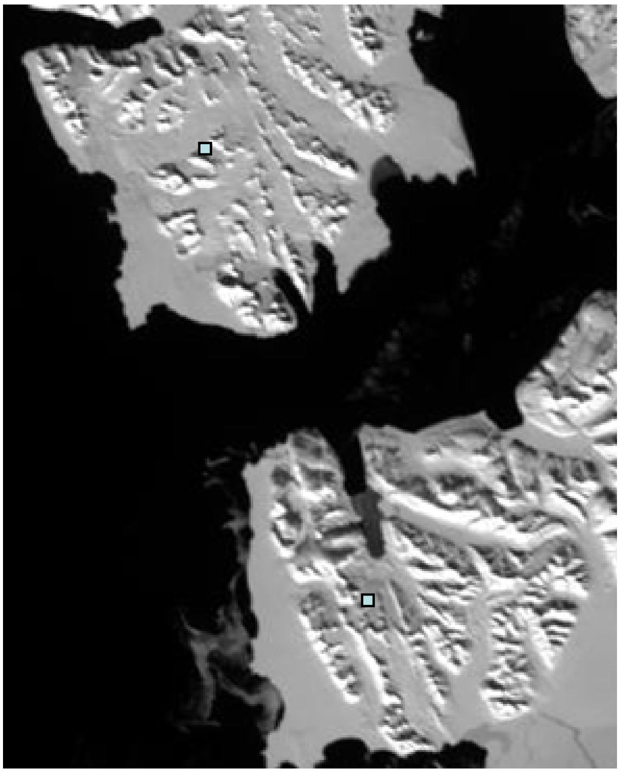

Figure 1: MODIS image (band 1) of 28 April 2007. The two test sites are marked with rectangles. Barentsburg is situated at the eastern side of Grønfjorden (north of the lower rectangle)

2.4 Black carbon and dry mass analysis

During the field campaigns snow and ice surface samples are taken for determination of impurity concentrations and composition. The concentrations can be determined by bringing samples back to laboratory and melted. The analysis consists of measuring the total and fractional dry mass of each sample and comparing this to the surface area of each sample. The compositional analysis quantifies fractions of organic material, fractions of lithic material and finally fractions of BC from the samples. This is the minimal analysis in order to isolate the BC fraction of the surface impurities.

2.5 Image analysis of surface samples

Digital image analysis algorithms have been implemented for detection of cryoconite at the glacier surface. The processing can be divided into three steps: pre-processing, segmentation, and feature extraction. The methods are implemented in Matlab. The features have been further analysed for studies of the structure and distribution of cryoconite.

3. EXPERIMENTAL RESULTS

The BC chemical analysis data are studied together with the other field and satellite data. Spectral measurements in the field document the spectral properties of black carbon and other impurities under changing conditions through the snowmelt season (from winter to summer). Digital photos of the sample sites document visible surface components. Field spectra are compared with the satellite data in order to determine whether there is significant information (signal) about black carbon in the satellite data.

Surface measurements

A glacier surface photo is shown in Figure 2. When the cryoconite nodules have been detected by the pattern recognition algorithm, statistics for a number of features can be calculated. We have so far calculated nodule histograms of minimum distance to neighbours (Figure 3), area, eccentricity, elongation and intensity.

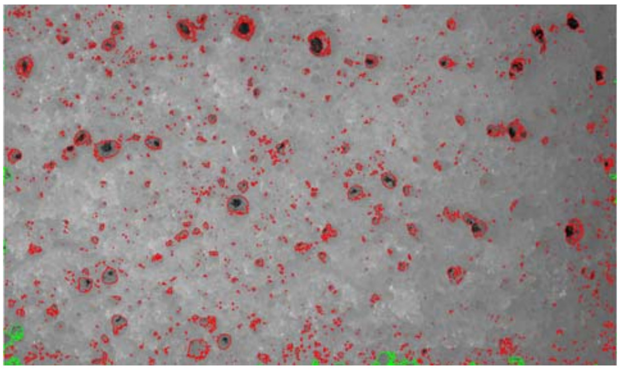

Figure 2: Photo of glacier surface with detected nodules shown by red border lines

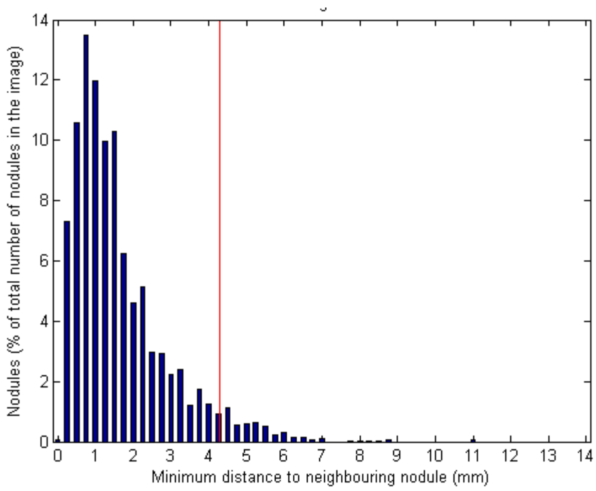

Figure 3: Histogram of minimum distance to a neighbouring nodule

The high variability in dry-mass distribution, as seen by the statistical analysis of surface photos and apparent high variability of surface reflectance, calls for an explanation on how impurities collect and distribute on a melting glacier surface.

Many combinations of distributions of cryoconite on the glacier surface are possible, see Figure 4. If the airborne impurities were homogenously distributed on the surface, then thickness of the layer would be more than the diameter of each aerosol particle (Figure 4A). Since, the aerosol particles are opaque; this would lead to an albedo of pure cryoconite material, i.e. an albedo of ~4%. At the other extreme we know that the albedo of clean ice with no impurities is around 60-65%. Many measured surface albedo values deviate from this, and commonly measured abedo values are around 55%. These albedos are significantly higher than for the cryoconite material but lower than for pure ice albedo. Detailed surface observations have revealed that the cryoconite material tend to cluster in nodules which appear to have a spherical shape with a diameters at millimetre scale (Figure 4B).

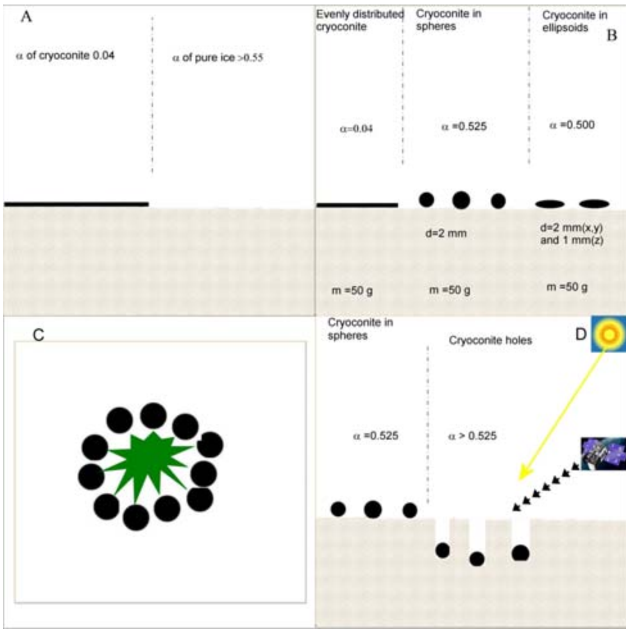

Figure 4: Conceptual model for how impurities distribute on glacier surfaces. A: Effect of evenly distributed A/BC; B: Effect of nodule formation; C: Effect of 'glue' from microorganisms; D: Effect of cryoconite holes on solar illumination and satellite albedo

The most likely reason for such nodules to form is bonding by microorganisms living near the nodule surface (see e.g. Hodson et al. 2007). An experiment was performed where microorganisms were removed using potassium hydrogen peroxide. The comparison of albedo from natural cryoconite material and material cleaned from microorganisms did reveal no significant difference. We conclude that the micro organisms "hide" from the UV radiation of the sun behind the particles and hence cannot be detected spectrally (see Figure 4C).

A known phenomenon on glacier surfaces is the formation of cryoconite holes. Such holes form when solar radiation does penetrate the ice and absorbs in the cryoconite material inside the ice. A cylindrical or conical shape hole is established upon melt-down of the material. Looking from above (nadir) the optical effect of such a hole is observable. But with increasing angles from zenith the albedo of pure ice becomes dominating. So, if the zenith angle of a satellite is different from the zenith angle of the sun, the surface albedo measured by the satellite is not the surface albedo for solar radiation (Figure 4D). We therefore need to develop a model which can correct for the directional effects associated with cryoconite hole formation.

Satellite measurements

The satellite-measured top-of-atmosphere (TOA) reflectance values of the two sites at Grønfjordbreen and Eidembreen are supposed to increase during this period because of increasing solar elevation. So they do, but they start to decrease at the end of the period. This may be caused by melting snow. The MODIS images show higher reflectance values on Eidembreen in general. This may be caused by the difference in slope angle and direction.

Without impurities, the temporal development of the TOA reflectance should be quite similar for the two sites. The measured values have been calibrated by subtracting the minimum value in each image. The differences in absolute values and relative to the value on Eidembreen have been calculated. The results for days without clouds at the two sites (mean value of the four pixels) are shown in Table 1. (The reflectance values have not been scaled to percentage units.)

The values at Eidembreen increase until 12 June and then start decreasing. At Grønfjordbreen the top is reached already 24 May. This could indicate more impurities at Grønfjordbreen. The values at Grønfjordbreen then decrease more than at Eidembreen and the difference is increasing. One explanation is an increasing amount of impurities in the snow at Grønfjordbreen.

Table 1 Mean measured values of MODIS channel 1 at the test sites, and a comparison of the two. (The TOA reflectance values have not been scaled to percentage units.)

Date/Time	**Eidem (E)**	**Grønfjord (G)**	**E-G**	**(E-G)/E**
2007.04.03 11:55	3843	3092	752	0.196
2007.04.11 12:45	4437	3529	908	0.205
2007.04.28 11:50	6245	5480	766	0.123
2007.05.05 11:55	6589	5848	741	0.112
2007.05.24 12:25	7778	6478	1300	0.167
2007.06.12 12:55	7846	6342	1504	0.192
2007.06.18 12:20	7589	5515	2074	0.273
2007.06.26 11:30	7545	5173	2372	0.314
2007.06.26 13:10	7271	5016	2256	0.310

4. DISCUSSION AND CONCLUSIONS

If BC retrieval from satellite data is successful, it will 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. Operational BC monitoring will enable improved energy balance modelling, which is of particular importance for modelling climate change effects in polar regions. In most climate models, energy balance processes in these areas are crudely described. Improved climate modelling in polar areas could potentially have a significant impact on long-term climate-change projections on the global scale.

There are several sources of impurities which reduces the albedo of snow and glacier surfaces. Mineral dust is the major source of aerosols. A small fraction of the aerosols constitute of BC, which due to its strong radiational effect even at small concentrations affects the Arctic radiation balance. The aerosols vanish with seasonal snow when it melts away, but they do accumulate on glaciers over time. We have illustrated that storage processes of aerosols controls the ice albedo, and hence the melt rates on glaciers. Therefore, a better understanding of storage/release processes is a key to understand the past, present and future albedo of glaciers.

The results of our initial studies have shown that a model approach is needed to discriminate between various surface material (organic and lithic) and black carbon. A concept for such a model is under development. If the aerosols accumulated on the glacier surface were evenly distributed, the surface albedo would be around 4%. Two processes increase ice albedo: 1) cryoconite holes (at the margin of glaciers), and 2) formation of nodules by microorganisms (local glaciers and high on ice sheets). Newly exposed ice of both ice sheets and glaciers will develop a low surface albedo. A BC retrieval algorithm for glacier surfaces will need to include an albedo model taking into account the albedo variability contributors and the associated processes.

For snow, top-of-atmosphere reflectance was studied using Terra MODIS satellite data. Seasonal local variability at two sites, one affected with coal impurities from a local source (a cold mine) was studied. The results are too premature to conclude whether an algorithm for retrieval of BC in snow can be developed, but they indicate that temporal analysis (time series analysis of frequent observations) may obtain robust and accurate results.

REFERENCES

Flanner, M.G., C.S. Zender and J.T. Randerson, 2007, "Present-day climate forcing and response from black carbon in snow," *Journal of Geophysical Research*, Vol. 112, doi:10.1029/2006JD008003.

Hansen, J., and L. Nazarenko, 2004, "Soot climate forcing via snow and ice albedos," *Proc. Natl. Acad. Sci.*, 101, 423-428, doi:10.1073/pnas.2237157100.

Hodson, A., A.M. Anesio, F. Ng, R. Watson, J. Quirk, T. Irvine-Fynn, A. Dye, C. Clark, P. McCloy, J. Kohler and B. Sattler, 2007, "A glacier respires: Quantifying the distribution and respiration CO_2 flux of cryoconite across an entire Arctic supraglacial ecosystem," *Journal Of Geophysical Research*, 112, G04S36, doi:10.1029/2007JG000452.

Koch, D., T.C. Bond, D. Streets, N. Unger and G. van der Werf, 2007, "Global impacts of aerosols from particular source regions and sectors," *Journal of Geophysical Research*, 112, D02205, doi:10.1029/2005JD007024.

McConnell, J.R., R. Edwards, G.L. Kok, M.G. Flanner, C.S. Zender, E.S. Saltzman, J. R. Banta, D.R. Pasteris, M.M. Carter and J.D.W. Kahl, 2007, "20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing," *Science*, 7 September 2007: Vol. 317. no. 5843, pp. 1381 – 1384.