Remote sensing of black carbon at snow and glacier ice surfaces - first results of a modelling approach

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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 sufficient information (signal) in relevant satellite data in order to be successful in retrieval of black carbon concentrations.

The feedback processes and the high reflectance of the Arctic give a strong impact from black carbon, despite that only around 10-20% of the global black carbon emissions end up here (Koch et al. 2007; Flanner, Zender & Randerson 2007; Hansen & Nazarenko 2004). However, an ignored effect so far is the long-term effect of black carbon on glaciers. Due to downward movement of accumulated snow on glaciers in combination with the ice flow, black carbon will become entrained in the glaciers and will eventually melt free many years later further down in the melt zone of the same glacier. Black carbon 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 ice flow the long-term effect is likely significant and well beyond termination of human black carbon emission.

Three field sites (glaciers) are studied 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.

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, organic material and lithogenetic material. In order to improve the understanding of the evolution on the snow and ice surfaces, an automatic time-lapse

camera was set up for taking daily pictures of a glacier surface during the spring and summer period.

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.

Two sites have been chosen for satellite measurements of snow, one on each side of the large fjord Isfjorden. One is on Grønfjordbreen south of Barentsburg and the other on Eidembreen north of Isfjorden, 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 snow albedo algorithm development, calibration and validation. Soot concentrations are periodically quite large in the Grønfjordbreen area, as around other coal mines in Svalbard. This situation enables more controlled satellite data sensitivity studies of a large range of soot concentrations for field and satellite measurements. On the other side, Eidembreen should hardly be affected of local soot, and therefore functions as a reference site for the satellite measurements.

The satellite-measured top-of-atmosphere (TOA) reflectance values of the two sites are supposed to increase during the spring due to increasing solar elevation. So they do in our observations from the 2008 season, but they start to decrease at the end of the period. This may be caused by melting snow. 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 then been calculated. The values at Eidembreen increase until 12 June and then start decreasing. At Grønfjordbreen the top is reached already 24 May. This could indicate that more impurities at Grønfjordbreen affect the albedo as measured from the satellite. 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. As no fieldwork took place at these glaciers in 2008, we have repeated the satellite measurements in 2009 together with field measurements. The black carbon analysis of the field samples is expected to be available by the end of the year.

Glacier ice surfaces have been measured and sampled in the summer seasons of 2008 and 2009. The high variability in dry-mass distribution on the glacier ice surface, as seen by 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. 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. 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 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 diameter at millimetre scale.

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 ultraviolet radiation of the sun behind the particles and hence cannot be detected spectrally.

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. We therefore need to develop a model which can correct for the directional effects associated with cryoconite hole formation.

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 black carbon, 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 has been development. A black carbon retrieval algorithm for glacier ice surfaces will need to include an albedo model taking into account the albedo variability contributors and the associated processes.

If black carbon retrieval from satellite data is successful for snow and glacier ice surfaces, it will make large-scale monitoring of black carbon in polar regions possible. This means that concentrations of black carbon for the first time could be observed as a variable in space and time. Operational black carbon 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.

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