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Sediment concentrations and transport in icebergs, Scoresby Sound, East Greenland

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Abstract

Glaciers erode their beds and the adjacent landscape by abrasion and plucking and entraining sediment on their way downwards driven by gravity. Ice becomes a sediment transport agent. To determine glacial transport of sediment, measurements of both the ice flux and its concentration are needed. Once glaciers reach the ocean, ice and its entrained sediment is released into the ocean by calving. Further transport takes place by icebergs. Quantification of IRD (ice-rafted debris) fluxes, which upon ultimate deposition on the ocean floor is an important climate indicator, becomes even more complicated as icebergs topple and differentially melt while in transport. While the volume of tidewater glacier ice released by recent calving is quite well constrained by satellite measurements, there is a lack of measurements of the concentration of sediment within the moving ice.

Here, we describe a method to collect samples of ice from icebergs systematically for the first time in Greenland together with a strategy to obtain representative samples. Our method is tested in Scoresby Sound, East Greenland in order to describe the transport of sediment into the fjord system related to calving from known glacial source areas. Our data clearly demonstrate that biased and sparse sampling potentially produces unrealistic values of sediment concentrations. Seventy-two samples from 24 icebergs had an average concentration of sediment of 35.5 g/l of ice with a standard deviation of 97%, between the 24 individual icebergs. The origin of the sediment is related to specific source areas. Based on the samples, we present an estimate of the annual transport of sediment out of Scoresby Sound related to calving ~100 (0.3-200) million t yr⁻¹. Finally, we discuss the uncertainties of our estimate.

Introduction

A variety of geomorphic processes, e.g. Walling (1983), Milliman and Farnsworth, (2011), and Svishetski et al. (2022) drive the Earth’s sediment cycle. The relative importance of glacial erosion compared to other erosional processes, both recent and over millennial timescales is well described e.g. Hallett (1997), Antoniazza and Lane (2021), Herman et al., (2021). Whereas there are exceptions for cold-based ice sheets, and erosion rates can be variable, generally rates exceed or are on par with bedrock incision by rivers (Koppes and Montgomery, 2009; Alley et al., 2019).

In Greenland, glacial erosion is the most powerful geomorphic agent. Greenland is the largest glaciated area in the Northern Hemisphere. One example to demonstrate the efficiency of glacial erosion here is the sediment flux originating from the Watson River, which drains about 12.600 km²...
of the Western sector of the Greenland Ice Sheet, which only amounts to less than 1% of the entire 
48 ice sheet area (van As et al., 2018). This well monitored proglacial river has over a ten year period 
49 delivered 700-2300 t km⁻² yr⁻¹ of sediment derived by glacial erosion (Hasholt et al., 2018). The 
50 effects of glacial erosion are also demonstrated by the presence of hundreds of large braided river 
51 flood plains and deltas (Bendixen et al., 2017) together with large plumes of suspended sediments 
52 in fjords and coastal waters (Chu et al., 2012). Besides the output of melt-water from the rivers, 
53 Greenland is also the largest producer of icebergs by calving in the Northern Hemisphere (Enderlin 
54 et al., 2014). The average annual loss (2010 to 2017) by calving from Greenland was ~500 ± 50 Gt 
55 yr⁻¹ of water, or ~550 km³ of ice (Mankoff et al., 2020).

Moreover, sediment transported by the riverine system in East Greenland (1981) and 
56 million t yr⁻¹ of transport of sediment related to calving in the ablation zone will accumulate by surface melt and form a layer of sediment 
57 that can be from a centimetre to meter thick at the terminus. Other sources of supraglacial sediment 
58 closer to the ice sheet margin, are rock material eroded from valley sides and nunataks, forming 
59 medial and side moraines and often observed as bands of sediment in icebergs. 
60 Englacial sediment partly originates from dust deposits on the surface gradually accumulating 
61 throughout the ice column and then moving with glacial flow. This englacial component is very 
62 small. Based on ice cores, Ruth et al. (2003) found concentrations of 0.05 to 8 mg kg⁻¹ throughout 
63 the 1500 m long NGRIP ice core, originating from the ice sheet interior. Larger dust concentrations 
64 can be expected in upper ice layers formed closer to the ice sheet margin, where local outcropping 
65 rocks areas contribute to the dust deposition. 
66 The third, subglacial component originates from erosion at the glacier bed and may consist of both 
67 glacial flour from abrasion and rocks plucked from the bedrock valley bottom. Increased sediment 
68 concentrations in the basal ice are even observed in interior ice cores. Sediment entrainment is 
69 attributed to deformation at lower concentrations, regelation and freeze-on or frozen fringe 
70 processes at high concentrations (Alley, 1997; Gow and Meese, 1996; Meyer et al., 2019). 
71 Field observations show that calved icebergs can carry high concentrations of sediment at their 
72 base, but quantitative data are sparse. The first observations and measurements of sediment 
73 concentration in icebergs by the authors were from an ice-dammed lake (Nordbo Lake in Johan 
74 Dahl Land in South Greenland) intended to be used as reservoir for hydropower. Measured 
75 concentrations of 15 mg l⁻¹ up to 40 g l⁻¹ of sediment in icebergs calved into the lake demonstrated 
76 that a substantial amount of sediment can be transported by icebergs (Hasholt and Thomsen, 1981). The 
77 impact of iceberg transport was also demonstrated by the presence of IRD in bottom samples 
78 from an ice-dammed lake in East Greenland, (Hasholt, Walling and Owens, 1996). A first estimate 
79 of transport of sediment related to calving delivered to the Arctic Ocean ranged from 50 to 500 
80 million t yr⁻¹ (Hasholt et al. 2006; 2016). The estimate was based on the volume of icebergs derived 
81 from Reeh (1985a) multiplied with iceberg concentration estimates from Hasholt and Thomsen 
82 (1981) and Ruth et al. (2003). The estimated transport involved the export of icebergs from North- 
83 and East Greenland only .

84 Overeem et al. (2017) attempted to quantify sediment transport from Greenland with a focus on 
85 riverine suspended sediment transport assessed from remote sensing imagery. Beside calculation of 
86 the proglacial river sediment transport, based on calibrated LandSat-derived fluvial suspended 
87 sediment concentration, the paper also presented a preliminary calculation of the amount of 
88 sediment transported by calving icebergs. The combined estimate of fluvial and glacial sediment 
89 transport suggest that Greenland is the largest exporter of sediment in the Northern Hemisphere. 
90 Moreover, if the maximum estimate of the sediment transport by calved icebergs is used, this 
91 component of the sediment transport from Greenland could account for up to 17% of the total flux
of sediment from the continents to the oceans worldwide. However, very few field measurements of
the thickness of sediment-rich basal ice or the concentration of sediment in icebergs from
Greenland have been available for these calculations. Thus, an improved knowledge of the range of
concentration of sediment in icebergs and quantification of the spatial variability across different
calving source areas are required.
IRD plays an important role in paleoceanographic research to describe past ice sheet activity and
to identify Heinrich layers in the North Atlantic (Andrews, 2000). Recently IRD investigations in
Upernavik Isfjord, NW Greenland has demonstrated that IRD deposition can be related to recent
glacier proximal locations (Vermassen et al. 2019). Therefore, collection and analysis of samples
from icebergs from a known source area may be useful to fingerprint IRD in ocean bottom cores.

Here we aim to: 1) develop a method and strategy to obtain representative samples of calved ice. 2) determine the sediment concentration and its variability in ice samples collected in front of known
source areas (calving fronts). 3) investigate if the sediment in the ice samples can be related to the
geology of specific source areas. and 4) discuss the applied methodology in relation to the
calculation of sediment transported by calved ice.

Fieldwork
An obvious reason for the lack of measured concentrations of sediment in icebergs is the difficult
access to tidewater glaciers with calving fronts along the remote coasts of Greenland. Other reasons
are the harsh weather conditions and the difficulty of boat travel within the melange of sea ice,
which includes growlers, bergy bits and icebergs choking up the fiords near calving fronts.
Moreover, the potential for sudden toppling or fracturing of icebergs makes in-situ sampling of
larger icebergs unsafe. Yet, there is boat access to fiords with tidewater glaciers in their fiord heads
near many Greenlandic communities and coastal research stations. In addition, potential for
sampling during research cruises or other investigative efforts exists.
The Danish Navy regularly patrol the waters around Greenland to control illegal access and fishing
and to carry out Search and Rescue (SAR) missions. An agreement between The Danish Centre for
Sea-research (DCH) and the Danish Navy provides the possibility for scientific projects to obtain
logistical support and help from the Navy after an application and a positive evaluation of the
quality and relevance of a given project. This agreement has allowed the first author to join a
mission in Scoresby Sound, East Greenland in August 2018 (Fig. 1). Beside the normal tasks e.g.
SAR, which have absolute priority, the main scientific objective of the expedition was to investigate
the impact of seismic booming and ship traffic on narwhal behaviour. However, the first author
was allowed to use the Man Over Board (MOB) rubber dinghy with crew for sampling of ice at a
distance of up to 4 nautical miles from the vessel HDMS I/F Lauge Koch.

Methods

Sampling strategy: Sampling sites were chosen as close to the calving front of the selected source
area as possible, depending on weather and ice conditions. The iceberg to be sampled was chosen to
be the one closest to sample position pre-selected on a map. The intention was to distribute samples
evenly along the calving front. In order to obtain samples for describing the geology of the
sediment and to get an idea of the “maximum” transport, supplementary sampling was carried out
from icebergs with an observed large content of sediment, the so-called “dirty icebergs”.
Sampling procedure: For safety reasons only small icebergs in the WMO (World Meteorological
Organization) size categories growlers (<1m freeboard, <10m waterline) and bergy bits (< 5m
freeboard, 10-30m waterline) were selected for sampling. The first sample was taken at a random
location where the boat bumped up to the iceberg. The following two samples were picked
“systematically” within a fixed distance of 2-6 m (multiples of a used yardstick length) from the
previous sample. This systematic sampling was used to avoid subjective choices of sample
locations, while the triplicate samples helped to assess variability within a selected iceberg. At each
sampling point, the ice was loosened by chopping with a mountaineering ice axe with a long shaft.
If samples are intended e.g. for analysis of englacial sediment concentration, the surface must be
cleaned before chopping and if the sample is destined for analysis of trace elements e.g. iron
content, a brass hammer must be used instead of a steel ice pick. The shards of ice (0.3-1.7 kg) were
collected in a collapsible fishing net held underneath the sampling point or picked up from the
water. The pieces of ice were put into a pre-labelled plastic bag, which was carefully inspected for
leakage. In case of potential leakage due to sharp shards, double bagging of the sample was
employed. To avoid leakage by sharp shards a bottle or container with thicker walls was also used
when available.

The location of the sampling points and time of sampling was recorded with a handheld parallel
multi-channel GPS or the boat GPS receiver, with a typical accuracy of 5-10 m, and date and time
of sampling were noted. A description in the field of the iceberg is given according to the WMO
classification. An overview photo of the iceberg and photos of each sample location were taken, if
possible with a standardized colour calibration, or grey scale calibration card within the photo view.
A full field description includes notes on the ice matrix, i.e. blue ice/white ice, bubbly/broken/dense, visible layering or stratification, evidence for algae, red or green, and any
alternative light-dark bands. Sediment sorting, angularity, grain size distribution, layering or
stratification visible, and presence and abundance of pebbles or cobbles must also be recorded in
field notes. Environmental conditions, such as air- and water temperature were measured together
with wind speed and direction. If available, water depth from the boat sonar system was noted.

After returning to the ship, the samples were allowed to melt, and in the case of observed leakages,
new plastic bags were applied. Then all samples were weighed with a resolution of ± 1 g. Freeze
storage was not used because of lack of available freezing capacity during all steps of the normal
transport route from Greenland to the laboratory.

Analysis: In the laboratory, all samples were again controlled for leakage, visually and by weighing
and comparing against field weights. In a few cases, the outer bags were damaged due to heavy
handling during transportation, but it was observed that no sediment had been lost from the inner
bags. First, a subsample of 50-100 ml, which was used for analysis of the isotopic content, was
filtered through Millipore CEM 0.45 micron filters. Then the sediment was separated from the
water by filtering through Whatman GF/F mass fibre filters with a retention diameter of 0.7 microns
(to avoid lengthy duration of the filtering); larger grain sizes were poured into porcelain crucibles or
metal containers. Filter papers, crucibles and metal containers were dried at 65°C and weighed with
an accuracy ± 0.1 mg. Loss on ignition was determined after combustion at 550°C.

Geology: Lithic fragments down to gravel size were used in a blind test. A geologist, who has
carried out geological mapping of Greenland with special experience in the Scoresby Sound area
was asked to characterize the fragments, and, to the extent possible, to identify the rock types and
their possible source areas without being informed about the sampling location.

Isotopic analysis: Measuring the stable isotope ratios of oxygen and hydrogen (δ18O, δD)
was mainly carried out to distinguish between thick accumulation or sea ice (with high δ18O) or
glacial ice, from icebergs originating by calving (with low δ18O). We also explored whether
isotopic signatures provide information about the local origin of the glacial ice. Isotopic analysis
was performed at the Niels Bohr Institute (NBI), Denmark using Cavity Ring Down Laser
Spectroscopy with a Picarro L2140i analyser. Measurements were reported on the international
VSMOW-SLAP (Vienna Mean Ocean Water Standard Light Antarctic Precipitation) isotope scale
after calibration with local water standards. Methodological details on the instrument calibration
and accuracy are described in Gkinis et al. (2021). The accuracy of the results are within ±- 2‰.
Calculation of the sediment transport: The 2018 volume of calved ice delivered from 15 individual calving glaciers was determined by measuring the velocity of the ice from satellites and multiplying the velocity with the cross section area of flux gates based on updated bedtopography from BedMachine v4. Details of the methodology and accuracy of this approach are described in Mankoff et al. (2020). Uncertainty ranges from 6-44%, with a mean of 24%. Uncertainty for the total discharge is ~10%. The concentration of sediment from each of the 15 glaciers was determined as the average concentration of the samples collected in the present investigation that were closest to each glacier. The annual transport was determined by multiplying volume of ice from a glacier with the corresponding concentration.

Results

Sampling and sampling conditions

Sampling was carried out from the 26th August to 1st September 2018, when the sea-ice had disappeared from the Scoresby Sound. The weather was fair with light winds that allowed the MOB to operate far from the fjord coast. The ship sailed north through Hall Bredning (fig. 1), where several large icebergs originating from the Daugaard-Jensen Gletsjer were drifting southwards along the east coast of Jameson Land. Then we sailed through Ikaasakajik (Ojord) and further south west through the sound east of Storo because the passage westwards was blocked by a melange of ice possibly originating from the Eielson Gletsjer. The route went south through ice from Rolige Bræ and Vestfjord Gletsjer, and then eastwards through Ujuaakajiip Kangertiva (Fonfjord), where the first samples (no. 1-2) were taken. Samples 3-5 were taken directly south in Nertiit Kangersivat (Gasefjord). We then turned back to a whaling station closer to the fjord head of Rødefjord, and iceberg samples no. 6-11 were collected nearby. Then we sailed east to the waters along the south coast of the fjord (fig. 2 and 3) where samples no. 12-21 were collected. Because of the melange of ice originating from Nertiit Kangersivat (Gasefjord) it was not possible to sail closer to the calving fronts here, the nearest samples were at the location of iceberg 17 and 18. When the whale observations along the south coast were finished, we turned northwards through Hall Bredning again and had opportunity to collect the last samples at location 22, 23 and 24 (fig. 1), downstream of the Daugaard-Jensen Gletsjer calving front. A total of 24 icebergs were sampled.

Sediment concentration

We have assumed a density of 0.9 g cm$^{-3}$ for ice and 2.65 g cm$^{-3}$ for sediments in order to calculate the sediment concentration in mg l$^{-1}$ for icebergs. An overview of the calculations and the results of the 72 single samples (three from each iceberg) are available in a table in the Isaaffik data portal https://isaaffik.org. Sample weight varied from 0.3 to 1.7 kg with an average of 0.7 kg. The average concentration was 36.6 g l$^{-1}$ with a maximum of 692 g l$^{-1}$ and a minimum of 0.8 mg l$^{-1}$. The standard deviation was 400% of the average. The variation in sediment concentration between the single iceberg triplicate samples is several orders of magnitude. The sample with the maximum concentration was not able to float because the density was larger than one.

Results from the 24 individual icebergs, shown in figure 1, are calculated as the average of the three subsamples and are reported together with the standard deviation in table 1. The average of all 24 concentrations is 36.6 g l$^{-1}$ as above; the median is 6.6 g l$^{-1}$, and standard deviations varying between 42 and 173% with an average of 97%. Maximum sediment concentration is 442 g l$^{-1}$ and minimum 4 mg l$^{-1}$. The distribution of concentrations is shown in figure 2A and B. Figure 2A shows the concentration of the samples sorted after size, the x-axis displays the number of the iceberg with a certain concentration. Figure 2B shows the number of icebergs within intervals of 2500 mg/l ice. Figure 2 clearly demonstrates a skewed distribution of the concentrations, with
eleven icebergs in the two lowest intervals (0-5000 mg/l). The rest of the samples are spread within the interval (7500-60000 mg/l) with a minor concentration between 20000 and 400000 mg/l. Two outliers with respectively 120 and 442 - g l⁻¹ are found because of the “biased” sampling from “dirty” icebergs. An example of the variation within a single iceberg (7) is shown in fig. 3 A, B and C.

Considering concentration as function of distance from nearest source area reveals a very large spread of values at distances out to 80 km. Some icebergs can have several possible source areas. A similar survey revealed a large variation out to 60 km from source. In both cases, low concentrations are found once the iceberg has travelled more than 100 km from any possible source, indicating an expected loss of sediment from source to the mouth of the extensive fiord system.

Geology

The locations of the 24 sampled icebergs are plotted on a lithological map, fig. 3 (Harrison et al., 2011, Moon et al., 2021). Two main groups of rocks were identified as shown in table 2. Basaltic rocks originate from the southern coastal area of the fjord. Samples 3-5 and 14-18 represent Nertit Kangersivat (Gåsefjord) as a source draining part of the Greenland Ice Sheet, whereas samples 12 and 13 are sourced from a local glacier (Syðlhre) draining from the basaltic area, and samples 19 - 21 also represent a local glacier, the Brede Gletsjer. Gneissic rocks are found in samples 6-8 and 9-11 representing the geology of the western part of the fjord. They originate from Rolige Bræ or the Vestfjord Gletsjer. Samples 22, 23 and 24 also contains gneiss, and they either originate from local glaciers, such as Eielson Gletsjer, small glaciers calving from Renland or Milne Land or are broken off from larger icebergs originating from the Daugaard-Jensen Gletsjer. Overall, the results confirm that a sample of rock fragments from an iceberg often can be traced back to a distinct calving front. If the geology at the calving front is unique, the samples can be used to track the travel route of the supraglacial component of ice rafted debris. On the other hand, samples from an iceberg originating from a well-defined source area may provide useful information about the unknown geology of the source area if the geological surveying has been less intense than in the present area.

Isotopic analysis

Results from the analysis of selected samples are shown in table 3, where A, B and C refer to a subsample from a given iceberg. A certain grouping appears. The δ¹⁸O from the northern and western part of the fjord system are grouped around -32 per mil, while the samples from the south coast are grouped around -22 per mil. Similarly, for δ Deuterium the northern and western samples group around -250 per mil and from the south coast around -180 per mil is found. No clear pattern is found for the D-O (Deuterium excess) values. Results from the Grandjean Fjord (Reeh et al. 2002) and from Renland (Joensen et al. 1992) confirm that δ¹⁸O values in glacier ice in the Scoresby Sound are expected to have values in the range of -24 to -37 per mil. Only one sample (11A) has a high value of -8.14 per mil that may indicate an erroneous sample.

Transport of sediment by calving

We assume that the average concentration of samples from a source area represents the true average concentration of sediment in the ice calved from that source area. The mass of transported sediment is then calculated by multiplying the measured volume of ice calved from the source area over the year 2018 with the average sediment concentration. Here we use the measured ice flux from the 15 glaciers based on work by Mankoff et al. (2020). Our calculation of the ice transport out of Scoresby Sound is shown in Table 4, together with the coordinates of the glacial flux gates. The entire volume of calved ice is 19.5 km³, of which the Daugaard-Jensen Glacier alone accounts for
53%. In comparison, modelled simultaneous meltwater flux from this region amounts to 10 km\(^3\) yr\(^{-1}\)
(as calculated from analysis of runoff predicted by RACMO, in Overeem et al., 2017). The

calculation in Table 4 reveals a transport of 234 (~200) million tons per year with an uncertainty of
100%. The average concentrations of sediment in ice from the 15 source areas are determined as an
average of concentrations from 3-10 icebergs. The average concentrations and the resulting
transport of sediment are also shown in Table 4. Small local glaciers on Milne land and Renland are not
included because measurements of calving volume are lacking. In addition, these glaciers would
have been represented only by one sample of sediment concentration (22). Only three icebergs (22,
23 and 24) are measured at locations that could represent ice from the Daugaard-Jensen and Charcot
source areas. The two samples closest to the Daugaard-Jensen Glacier have concentrations of only
12 to 40 mg l\(^{-1}\); whereas the inclusion of sample 22 brings the average up to 14066 mg l\(^{-1}\). This
clearly demonstrates the large uncertainty resulting from the use of only a few samples of sediment
concentration. The accuracy of the volume of calved ice is reported as ± 10% of the average of the total
output of 500 Gt yr\(^{-1}\). However, the accuracy of estimates from single glaciers can be less
favourable as seen from table 4. Using the 10% on the calved volume and the lowest standard
deviation on our average concentrations of 97%, then the combined uncertainty will be the square
root of 10\(^2\)+97\(^2\) equal to ± 97.5 %. The uncertainty is dominated by the uncertainty of the
concentration average. The transport calculation excludes two outliers, iceberg 3 (442486 mg l\(^{-1}\))
and iceberg 9 (121256 mg l\(^{-1}\)), because they were selected specifically to obtain samples of
sediment. Including these two samples, the transport would have been biased towards high
concentrations and our calculated transport would be larger than the “true” transport, perhaps
representing an “upper limit”. However, if we assume that the rest of samples with high
concentration represent the right proportion of “dirty ice” in the melange of icebergs, then our
estimate of 234 (~200) million tons could be correct. Iceberg 11 is also included, although the
isotopic analysis indicates that it could consist of sea-ice. This iceberg is still included because the
sediment concentration was 1693 mg l\(^{-1}\), which is considered unlikely for sea-ice from the open sea.
However, at the beginning of the sampling, the distinction between sampling aimed at geological
origin and sampling aimed at determination of sediment transport was not strict. The limited access
to the MOB resulted in sampling biased towards sampling “dirty” icebergs to get at least one
sample from a source area. Here we compensate for this bias by omitting all icebergs used for
g eo logy description in Table 2. The average concentration of sediment in the remaining 12 icebergs
(4973 mg l\(^{-1}\)) is multiplied with the volume of calved ice, giving a transport of 97 million ton yr\(^{-1}\)
(~100) as our best estimate. An estimate of the “minimum” transport is found by multiplying the
average concentration (14.4 mg l\(^{-1}\)) from the 5 icebergs with the lowest concentration with the
volume of calved ice, only 0.3 million tonnes, as shown in Table 4. The spatial distribution of
calved ice and ice-transported sediment is shown in figure 5 A and B. The distribution of the
sediment transport is governed by the transport of ice while differences in concentration have a
minor impact. The transport is dominated by the Daugaard-Jensen Glætsjø (53%) and glaciers
connected to the Ice Sheet, while the transport from the south coast is low.

Drift velocity and temperature

In some cases, it was possible to calculate drift velocity and direction from the GPS observations.
We recorded velocities of up to 6 km hour\(^{-1}\). Most often, we found that the drift direction followed
the wind direction when the wind speed was more than 5 m/sec. The maximum air temperature was
10\(^\circ\)C and water temperature ranged from 3 to 8\(^\circ\)C indicating that the melt rates at the surface can be
high.

Discussion
Here we discuss strategy and limitations to our sampling approach, relate the sample descriptions to different modes of glacial sediment transport, provide discussion on provenance and possible identification of source area and put the estimated sediment transport into perspective of suspended sediment flux.

It is not possible to measure the volume of an ice sample in the field and it is difficult and expensive to bring the sample to the laboratory in frozen state. Therefore, we use given densities of 2.65 and 0.9 g cm$^{-3}$ for sediment and ice respectively to calculate the volume of ice. As basalt is heavier than gneiss, it could be advocated that actual densities should have been used. However, using a range of density for rocks from 1.74 to 3.3 g cm$^{-3}$ would result in a change in ice volume of ~2 per mil. We do not know the actual density of ice. Our density of ice differs slightly from the density (0.917 g cm$^{-3}$) that has been used to calculate the measured volume of calved ice to water equivalent, a difference of 1.9% that is considered negligible compared to the other uncertainties.

We collected samples with an average weight of 0.7 kg with a maximum of 1.7 and minimum of 0.3 kg. It appears that small samples can result in anomalous results, as for instance iceberg number 3, which would not be able to float, as the density of its smallest sample, is larger than that of water. This iceberg also has a very high standard deviation of 173% of average concentration, and this inhomogeneity is caused by the biased selection of this iceberg for collection of rock pebble and sediment sample to determine rock type and mineralogy. Another iceberg, number 9, also has a very large concentration, but with a standard deviation of only 78%, showing that the sediment can be more homogenously distributed within an iceberg.

For safety reasons we chose only to collect samples from icebergs within the WMO size classes bergy bits and growlers. It could be argued that icebergs of this size do not represent the population of icebergs drifting around on the way from the calving front to the open sea. Hypothetically, small iceberg size could be the result of melting of a larger iceberg, with the implication that has lost its surface sediment while melting and tumbling around and therefore has concentrations below average. From our field observations, we have seen very large icebergs drop off bergy bits and growlers so a tail of these along their travel route follows them. We have also observed large icebergs suddenly disintegrate into minor bits and pieces because of inner tensions or after capsizing. Remote-sensing based observations (e.g. Sulak et al., 2017) and theory on iceberg size distribution show that initially icebergs follow an exponential or power-law distribution (Kirkham et al., 2017) which is resulting from elastic-brittle fracture processes (Åström et al., 2020). Over periods of transport this size distribution evolves reflecting the grinding and crushing processes in an ice mélange (to a power-law distribution with a different exponent), (Åström et al., 2020). These studies support the assumption that large toppled icebergs can still generate growlers or bergy bits by grinding and crushing, even after a substantial period of melt in the mélange. Considering melt-rates, even minor icebergs have enough mass to persist all the way to the open sea. Therefore, we assume that sampling growlers and bergy bits will not result in an entirely biased estimate of the concentration of sediment in icebergs travelling from the calving front to the open sea.

We collected three samples from each iceberg in order to quantify the variation of concentration within an iceberg. We find that the standard deviation can be up to 173% of the average concentration, a better measure of the average concentration could be obtained by collecting more samples. However, storing, transportation and analysis would have been too costly in this pilot-study. A solution could be to randomly collect e.g. 10 subsamples, store them in one container and analyze only the bulk sample.

To obtain samples representing the true distribution of concentrations we used random sampling to avoid subjective choices of icebergs and sampling positions as recommended by Yates (1960). We use the term “quasi random” to describe the fact that we collect samples with an equidistant
distance of multiples of ruler length, claiming that our samples are true random samples because no

known processes could distribute the sediment systematically over this spacing.

The iceberg chosen to be sampled is found as an iceberg of the correct size closest to a GPS

position pre-chosen as a sampling position on a map. We endeavored to get as close to the calving

front of a source area as possible. Looking at the UAV photo fig. 6, it appears that a number of

“dirty” icebergs are floating around between a much larger numbers of “clean” white icebergs. By

collecting our samples from randomly chosen icebergs, the “dirty” icebergs should theoretically

occur in our samples in proportion to their occurrence within the whole population of icebergs.

Accidentally we can either collect too many or too few “dirty” icebergs resulting in either an over-
or an underestimation of the average population concentration. In future UAV imagery, such as

shown in fig. 6, may serve to calculate the proportion of “dirty” icebergs, and allow stratified

random sampling by collecting samples of a smaller number of “dirty” icebergs and a larger

number of the “clean” ones according to their actual proportion. Similarly, Anderson et al. (1980) in

a study from Antarctica observed icebergs from a helicopter and found four “dirty” icebergs out of

370.

In the Scoresby Sound catchment, the Daugaard-Jensen Gletsjer is the largest single producer of

calved ice, responsible for more than half of the total ice flux. Because of logistical constraints, we

were only able to collect two to three samples that likely represent the concentration of sediment

from this source. To obtain a transport value from this source with a narrower band of uncertainty,

the number of randomly chosen icebergs should ideally be taken proportional to the output of ice

from the single source areas.

Observations at exposed glacial margins indicate that a basal layer with extremely sediment

concentrations can be 1 to 5 m thick. Large concentrations of sediment in the basal layer have also

been found in Greenland e.g. 46% to 61% by mass at the Russel Gletsjer (Yde et al. 2010) and 35%

on a glacier on Qeqatarsuaq (Disko Island) (Larsen et al. 2010). In Antarctica, icebergs have been

observed with 12-15m thick sediment-laden ice (Anderson et al.1980). Samples at exposed basal

ice along the margin of a tidewater glacier in Baffin Island indicated an average volume

concentration of 35% (Dowdeswell, 1986). In the present study, we clearly found evidence of both

supraglacial and englacial deposits within the sampled icebergs, and possibly some that represent

basal ice. We observed one iceberg, see fig. 7, that most likely represented the basal layer, but

unfortunately, we were not able to collect samples. Because of the basal position and the density of

this layer, it will only be exposed after toppling of the icebergs during calving, or later because of

iceberg capsizing due to imbalance because of underwater melting. The calving regime of the

Daugaard-Jensen Gletsjer appears to be generating more tabular icebergs, and is perhaps less

affected by toppling, and because of this, it may be difficult to obtain samples from this basal

sediment-laden ice.

Sampling could also be based on collecting the right proportion of ice of different glaciological

origin in order to obtain a concentration that represents the concentration at the calving front. The

preliminary calculation of the sediment transport by calving in Overeem et al. (2017) is based on a

volume of englacial ice with a volumetric concentration of sediment found from a few

measurements. Such “clean” ice is described in cores from the Greenland Ice Sheet, (Ruth et al.

(2003)). The englacial ice represents the “clean” white ice originating far from ice sheet boundaries

and mainly receiving its sediment as windborne dust. More importantly, calculations account for a

volume of ice from a bottom layer of ice with 20% of sediment by volume and an estimated average

thickness of 3 m (Andrews et al., 1994). However, in East Greenland on its way from the drainage

divide to the calving front the moving ice erodes at its boundaries with the valley bottom and

mountain sides as demonstrated by the thick supraglacial debris layers originating when the ice
passes around nunataks (fig. 7). Closer to the calving front the glacier can receive sediment input from rock fall and dust blown in from neighboring out-wash plains. Due to the melting at the surface sediment is accumulated on the surface in the ablation zone of the glacier. This surface sediment may enter crevasses by slumping or through transport by supra-glacial meltwater. The fast flow of the ice and the formation and closing of crevasses result in a chaotic distribution of sediment in the uppermost ice column at the calving front where it is very difficult to distinguish between ice of different origin. However, at least in our study, this supraglacial component appeared to be a significant additional source term.

In particular, it is difficult to obtain samples representing the bottom layer (fig. 8). Growlers and bergy bits are formed at the terminus during the calving or produced from larger icebergs by calving. However, they could also be remnants of a large iceberg after transport, melting, grinding, and crushing in the melange. Collapse of ice tongues may also produce a large amount of smaller icebergs as described by Vermassen et al. (2020).

Syvitski et al. (1996) describe the complicated transport patterns in Kangerlussuaq Fjord, East Greenland. There is an annual cycle of iceberg transport. During the winter, icebergs cannot leave the fjord because of the formation of sea-ice that has closed the fjord. The calving forms a melange of broken ice termed sikussak in front of the terminus, where the icebergs can have a residence time of up to two years. When the sea-ice gradually disappears during summer, the icebergs escape the sikussak and transit the fjord in about 68 days. In this study, the sampling was carried out in late August. At that time, sea-ice had totally disappeared, but the samples were confined to areas outside the sikussak both in Gåsefjord and in Rodefjord. Along the north coast of the Geikie Plateau, we could get closer to the calving fronts. Nordvestfjord was dominated by large icebergs from the Daugaard-Jensen Gletsjer while rather few bergy bits and growlers occurred. Calving from a big iceberg was observed in this area but the sampled icebergs 23 and 24 were not observed as being recently broken off from a large iceberg. Tidewater glaciers further to the north of Scoresby Sound may lose most of the sediment from the bottom layer, because it is locked up in the sikussak where it is exposed to melting by the seawater, (Reeh et al. (1999), Bigg (1999), Enderlin et al., (2018)).

The effect of this residence time in the melange and melting is that any icebergs released from the sikussak will contain less sediment to be transported long distances. Several authors have described the problems of trying to predict the occurrence and frequency of calving, and subsequent transport routes e.g. Benn et al. (2017), Bond and Lotti (1995), Choi et al. (2018), Death et al. (2006), Meire et al. (2017) and Todd et al. (2017). They point to the importance of basal topography, bottlenecks in fjords, trapping and bouncing into valley sides and meteorological factors.

The isotopic analysis confirmed that nearly all samples were from icebergs. In table 3 subsamples from an iceberg indicate significant differences in the deposition temperature of up to 2 °C. This can be explained by our sampling procedure that can result in at least a 2 m vertical distance between the sampled layers of ice, so that the time of deposition of the ice is different. The spatial grouping of the isotopic content may be explained by the different origin of the icebergs. The icebergs from north and west originate from several fast flowing glaciers with large source areas connected to the Ice Sheet, while icebergs from the south are calved from local glaciers with minor source areas. Meltwater data from the Mittivakkat Gletsjer, S.E. Greenland (Yde et al. 2016) confirm that it is unlikely to find glacier ice with a δ¹⁸O value of -8.14 per mil in the Scoresby Sound area. However, because of the large sediment content (xxxx mg/l ice) we assume that the sample is from an iceberg, this is supported by the fact that there was no coast with loose sediments where the sediment could be picked up nearby. A possible explanation is that the sample was contaminated by seawater after it has fallen into the water during sampling and then picked up with...
the net. It is therefore recommended only to use samples fallen directly into the net for isotopic analysis.

**Conclusions and perspectives**

In this pilot project, we have developed a new procedure and protocol to obtain un-biased samples from icebergs in order to evaluate their role and share of the total sediment transport from Greenland to the Atlantic Ocean.

We have discussed problems related to the sampling procedure and to the complicated transport routes of the icebergs from the calving front to the open sea.

We demonstrate large variations in the concentrations of sediment, both within any individual iceberg and spatially between icebergs in Scoresby Sound.

We present an estimate of the transport related to calving of ~100 million tons per year with a range from 0.3 to 200 million tons. We are fully aware that 12 samples of icebergs are not sufficient to constrain the transport of sediment reasonably accurate, but we have performed the calculation to illustrate the effects of biased sampling. The simultaneous meltwater-driven suspended sediment fluvial contribution is 21-30 million tons (from Table 1 in Overeem et al., 2017).

We have also demonstrated the potential of collecting samples from icebergs to describe the travel routes of IRD and/or to obtain new knowledge about the geology of the land underneath the calving glaciers. However, this sampling should be more focused in the selection of distance of sampling from calving front and in obtaining larger amounts of fine sediments for more sophisticated geological and mineralogical analysis, including quantification of the angularity of the coarse sediment fraction.

The utility of isotopic analysis is demonstrated, but probably the interpretation of the analysis and the information that could be extracted from the analysis could be improved significantly by comparing samples collected simultaneously from the glaciers upstream of their calving fronts.

It is important to state that this pilot study was of short duration and had only limited access to a major calving front (Dauggaard-Jensen Gletsjer). Thus, this dataset has limitations when extrapolating the results in time and space. In particular, we recognize the complexity related to trace the travel route of any sampled icebergs. Larger icebergs are nowadays tracked by satellite by for example the Danish Meteorological Institute (DMI), but the smaller bergy bits and growlers are not. We envisage the potential of the use of UAV’s to fill this gap in knowledge, as also shown in Ryan et al. (2015).

In relation to climate change, this component of the Global Sediment Cycle will diminish or disappear when the global amount of ice capable of calving diminish during warm periods. In cold periods, this component will increase, as the calving fronts move closer to the open sea, so that the icebergs do not lose their sediment load in fiords. This effect is clearly demonstrated by IRD deposits found far south in the Atlantic Ocean.

This pilot study focus on methodology intended to be used in the study of the transport of sediment by calving in Greenland. It clearly demonstrates the importance of systematic unbiased sampling. In the future we intend to utilize the experiences from this investigation by using a clear definition of sample aim, a relevant stratification of samples to secure unbiased representative sampling and a sufficient number of samples. The results of our studies of the sediment content of icebergs calved from Greenland are published in the Isaaffik data portal (see references), where also future data will be published.

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WMO Iceberg classification


List of Figures and tables:

Fig. 1 Map of sample locations in Scoresby Sound, East Greenland.

Fig. 2 A. View of calving front at Sydbrae. Calving front 300 m high, surrounding mountains 2000m. Observe high concentration sediment stripes, medial moraines on the surface and within the calving front, photo location close to iceberg 12 in figure 1 (photo B. Hasholt). B. Satellite image of Sydbrae Glacier (USGS) illustrates how local rockwalls and nunataks source abundant supraglacial sediment.

Fig. 3 A “dirty” iceberg with likely exposure of sediment-laden basal ice layer, close to the location of iceberg 12 (photo courtesy Bettina Ovgaard).

Fig. 4 Example of triplet samples from iceberg 7, perhaps a part of an ablation surface.

Fig. 5 Lithology of the Scoresby Sound area with sample locations included. Data from Harrison et al., 2011, geological map made available through QGreenland (Moon et al., 2021).

Fig. 6 Planview photo from an altitude of 100 m taken from an UAV (drone). Observe the proportion of “dirty” icebergs and the size distribution of the icebergs. The dinghy is 7 m long.

Table 1: Average sediment concentration in 24 icebergs

Table 2: Geological evaluation of sample origin

Table 3: Isotopic analysis

Table 4: Transport of calved ice from the Scoresby Sound catchment.