CryoCarbon

Expedition final report

Zackenberg River Catchment (ZRC)
NE Greenland 78°28′N; 20°34′W
July to August 2019

Dr Emily Stevenson
University of Cambridge

Dr Mel Murphy
University College London

Zackenberg river catchment, NE Greenland. Dr Murphy recording field notes in the bottom right corner. Photo credit Dr Stevenson.

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Correspondence to eis22@cam.ac.uk

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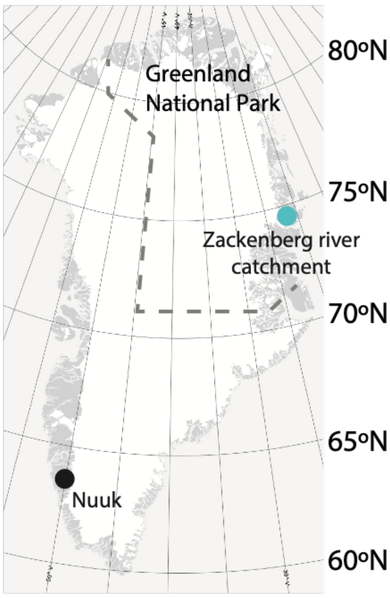
Summary: In the summer of 2019, Stevenson and Murphy undertook three weeks of fieldwork in remote northeast Greenland in the pristine Zackenberg River Catchment. During this time Murphy and Stevenson monitored and sampled from a Glacial Lake Outburst Flood (GLOF) event. The GLOF stems from the A. P. Olsen Glacier flowing downstream into the Zackenberg River causing massive river bank erosion, vast sediment deposition and the delivery of up to 90% of the catchments annual sediment budget in ~32 hours. The sediment contains highly reactive minerals which, when weathered, can either sequester or release CO_2 into our atmosphere causing either a negative or positive climate feedback into the Earth-climate system. As climate instability increases, it is vital we determine the impact such events are having on Arctic landscapes, climates and ecosystems as GLOFs and other large erosive events become more common.

Aim: Determine the impact of Glacial Lake Outburst Flood events on the inorganic carbon budgets of high arctic rivers.

Expedition members:

Dr Emily Stevenson
Department of Earth Sciences, University of Cambridge
+44 (0) 1223 764368
eis22@cam.ac.uk

Dr Mel Murphy
Department of Earth Sciences, University College London
+44 (0) 2031 056349
melissa.murphy@ucl.ac.uk



Expedition location:

Zackenberg River Catchment (ZRC),
northeast Greenland 78°28′N; 20°34′W

Dates of expedition:

15th July until the 5th August 2019

1: Introduction:

Greenland's ice is melting much faster than scientists previously thought, with the pace of ice loss increasing fourfold since 2003[1]. And it's not just the ice; there is substantial export of suspended sediment to the global oceans from glacial erosion in Greenland (Figure 1). Although runoff from Greenland represents only about one percent of the Earth's freshwater flux, the Greenland ice sheet produces approximately 8% of the modern export of suspended sediment to the global ocean[1].

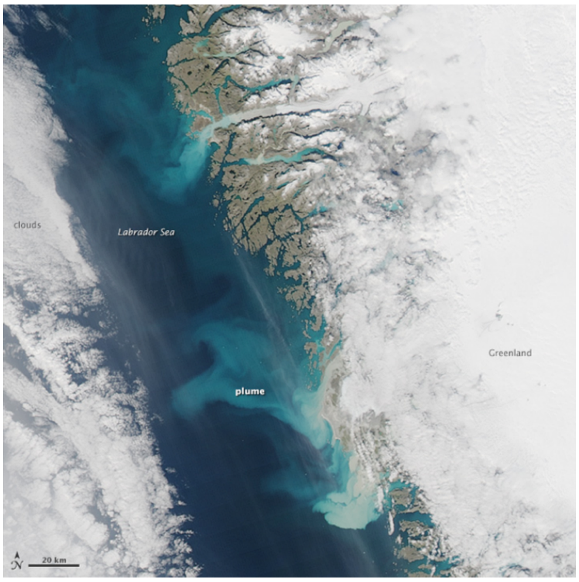


Figure 1: Massive sediment plumes from Greenland into the Labrador Sea, here you can see the sediment being taken into ocean currents . Photo credit NASA Earth Observatory

The present-day sediment flux to the ocean from Greenland is approximately 56% higher than during the baseline period of 1961-1990, and it's increasing[1]. This sediment is finely ground, and contains highly reactive minerals that, when weathered, can both *release* and *remove* carbon dioxide (CO_2) from the atmosphere[2], and we don't know which of these processes dominates overall in Arctic river systems. This has huge implications for understanding whether Arctic rivers are acting as a *source* or *sink* for atmospheric CO_2, and therefore, how weathering in the Arctic impacts the long-term carbon cycle and climate.

***The objective of this project was to determine the impact increased physical erosion in High Arctic environments has on carbon dioxide (CO_2) removal and release to the atmosphere, and the implications for our current climate*.**

More specifically we are looking to investigate the role of hugely erosive Glacial Lake Outburst Flood (GLOF) events in the High Arctic landscape of the Zackenberg River Catchment (ZRC)[3]. The ZRC is located in the remote Northeast Greenland National Park, a pristine region unspoiled by human activity and global pollution (Figures 2 & 3) This glaciological, geographical and geochemical expedition set out to sample the pristine rivers within the ZRC and the A.P. Olsen glacier GLOF. Glacial lake outburst floods can singlehandedly deliver a catchments yearly sediment export in less than 48 hours[3], causing massive riverbed erosion, and the exposure and mobilisation of vast amounts of sediment. In turn, this will influence mineral, elemental, nutrient and carbon fluxes into the ocean and atmosphere. As the polar regions are changing so rapidly, it is important to understand the impact climate change has on the long-term carbon cycle in these environments. To date, there is a major gap in our understanding about how climate-driven changes in the Arctic will affect biogeochemical- and carbon- cycling in Arctic terrestrial and marine ecosystems.

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[1] Overeem et al., 2017: Substantial export of suspended sediment to the global ocean from glacial erosion in Greenland. Nature Geoscience 10, 859-863
[2] Torres et al., 2017: Glacial weathering, sulfide oxidation, and global carbon cycle feedbacks. Proceedings of the National Academy of Sciences of the United States of America 114 (33) 8716-8721
[3] Søndergaard, et al., 2015: Mercury exports from a High-Arctic river basin in Northeast Greenland (74°N) largely controlled by glacial lake outburst floods. Science of The Total Environment 514, 83-91

2: Original objective of expedition: Scientific

The overall objective of the project was to determine the impact increased physical erosion in High Arctic environments has on carbon dioxide (CO_2) removal and release to the atmosphere, and the implications for the evolution of our current climate. Our aim is to understand the role and impact of a hugely erosive GLOF event on the High Arctic landscape of the ZRC (Figures 2 & 3), and how such an event may transiently alter the silicate, carbonate and sulfuric acid weathering fluxes, such that weathering reactions may release CO_2 directly to the atmosphere, counteracting that from the long term drawdown of CO_2 via silicate weathering. To do this we sample water and sediment from throughout the GLOF event, and from the river tributaries that drain into the Zackenberg river, and measure hydrochemical parameters such as pH, conductivity and discharge. At our respective academic institutions we will then geochemically and isotopically characterise the samples using new and established techniques[4,5] to determine the chemical reactions happening within the river water and ZRC, and if the reactions result in an overall net release or sequestration of CO_2.

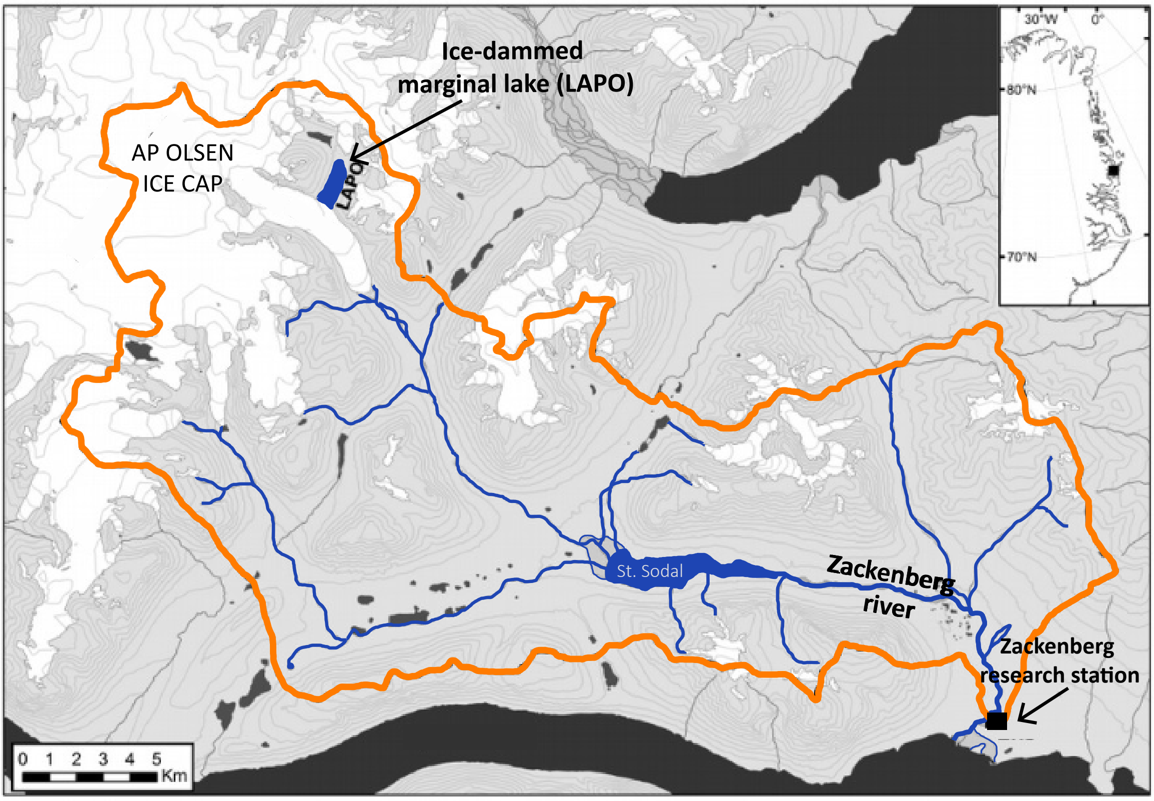


Figure 2: Location of the Zackenberg River Catchment (ZRC) in Northeast Greenland (map insert). Orange outline shows the limits of the Zackenberg water shed ~500km^2 and catchment. The Zackenberg river is fed predominantly by the glacial outflow from the A. P. Olsen ice cap. A marginal ice-dammed lake fills with ice and snow melt during the melt season, and when it reaches a maximum volume and pressure the ice dam fails and the lake drains sub-glacially causing a massive Glacial Lake Outburst Flood event (GLOF). This vast amount of water and sediment flows catastrophically downstream through St. Sodal in the Zackenberg valley, and into the Zackenberg river. A monitoring station located on a bridge nearby the Zackenberg Research Station records river stage height and discharge. We proposed to sample the GLOF from this location (as monitoring has occurred here since 1997[6]), as well as other rivers draining into the Zackenberg river to also determine the impact of changing geology throughout the catchment on the chemistry of the river.

[4] Torres et al., 2016: The acid and alkalinity budgets of weathering in the Andes–Amazon system: Insights into the erosional control of global biogeochemical cycles. Earth and Planetary Science Letters 450, 381–391
[5] Camels et al., 2007: Sustained sulfide oxidation by physical erosion processes in the Mackenzie River basin: Climatic perspectives. Geology 35 (11) 1003-1006
[6] http://g-e-m.dk

3: Expedition Member Biographies:

Dr. Emily I Stevenson, British
Postdoctoral Researcher at the University of Cambridge, in the Earth Sciences Department

Stevenson has worked in Arctic and high Arctic environments for more than seven years; studying glaciated landscapes and rivers that flow from them. Field seasons as long as three months have given her an unrivaled experience of camping and living in remote Arctic locations and with it an insurmountable respect for the landscape, weather and wildlife. From most recent, Stevenson has conducted fieldwork and geochemical research in the following Arctic locations:

2017 & 2018:	NE **Greenland**: Field leader, reconnaissance and geochemical sampling of Zackenberg River system (total three weeks over two years).
2016:	**Svalbard**: Ny Alesund: Field assistant, GPS surveying, and ice penetrating radar surveying (one week)
2015:	South **Greenland**: Field leader, geochemical sampling of glacial system (three months).
2014:	**Alaska**: Field assistant/faculty member for the Juneau Icefield Research Program (three weeks)
2013 & 2014:	**Canada**: Field leader, Studying and sampling the Athabasca and Saskatchewan Glaciers, **Canadian Rockies** (total five months over two years).
2013:	**Greenland** Field leader, sampling from glaciers around West, South and East Greenland continent (three weeks)
2012:	**Alaska**: Field leader sampling the Lemon Creek Glacier, (three months).
2010:	**Iceland**: Field assistant, soil, water and ground water sampling (one week).
2009:	**Iceland**: Field assistant, collection of samples from Hekla volcano (one week).

High Altitude Fieldwork: In 2005 Stevenson mountaineered in the Cordillera Real, **Bolivian Andes**, summiting Nevado Sajama (6,542 m) and Chacaltaya (5,375m)

Stevenson has also undertaken fieldwork in tropical locations, sampling from some of the World's largest rivers:

2019:	**Myanmar**: Field assistant, Irrawaddy and Salween river sampling (one week)
2019:	**India**: Leader, sampling the Hooghly river in lower Bengal (two one-week trips)
2018:	**Myanmar**: Field assistant, Irrawaddy and Salween river sampling (two two-week trips)

Stevenson has completed 'Polar Bear and Weapon for Protection Course' in Ny Ålesund, Svalbard, (valid until Oct 2019), and undertakes rifle training prior to any High Arctic fieldwork. She has both wilderness and outdoor first aid training certificates (valid until May 2021) and is a member of the Cambridgeshire Search and Rescue team (CamSAR). CamSAR requires rigorous training, and continual professional development in navigation, first-aid, radio communication and search skills, monthly.

Dr. Mel J Murphy, British & Australian
Postdoctoral Researcher at University College London, in the Earth Sciences Department.

Murphy has worked in Arctic environments for four years and has spent a total of three months (including a total of three weeks with Stevenson) over the last two years doing reconnaissance of the different rivers and terrain within the Zackenberg River Catchment area and generating pilot data. She knows the terrain exceptionally well and can navigate the landscape in many different weather conditions. Murphy has had many safe encounters with polar bears and is well rehearsed in the protocol to handle the situation if one is spotted.

2017 & 2018:	Field leader - Zackenberg River Catchment, NE **Greenland** – reconnaissance and geochemical sampling (3 months over two years).
2015:	Yakutsk, **Siberia** – Sampling the Lena River during the spring flood (1 month).
2014:	Kalix and Råne Rivers, **Sweden** – Winter River and estuary sampling, by drilling under the ice.
2014:	**Iceland** – Sampling volcanic sediments from Eyjafjallajökull

4: Fieldwork and research:

The Arctic is changing. Over the past few decades, Arctic air temperatures have warmed twice as fast as the global average. As the Arctic warms, changes in air temperature are impacting the vast areas underlain by permafrost and glaciers. Climate-driven permafrost degradation and glacial retreat affects the mobilisation of greenhouse gases, solutes and sediments to rivers, oceans and the atmosphere. The delivery of these constituents via the physical and chemical breakdown of rocks on the Earth's surface, termed weathering, is a fundamental process controlling atmospheric carbon dioxide (CO_2) levels and in turn, climate. Rapid weathering of newly exposed, highly reactive sediments from glacial erosion and permafrost degradation promotes weathering reactions that can either remove, or release, atmospheric CO_2.

The weathering of silicate rocks removes CO_2 from the atmosphere by the generation of alkalinity (HCO_3^-). However, enhanced sulfide mineral oxidation in regions of high physical erosion (e.g., glaciers and permafrost) produces sulfuric acid that enhances carbonate dissolution and releases CO_2, potentially counteracting CO_2 consumption by silicate weathering. Rivers integrate continental weathering processes at the catchment scale, delivering freshwater, solutes, nutrients and suspended sediments to the oceans. The balance between the competing weathering processes in glacierised river catchments is not well known. Here we use a well constrained multi-proxy geochemical approach to understand the silicate, carbonate and sulfuric acid weathering fluxes in the ZRC. A multi-proxy approach is vital if we are to determine how much riverine dissolved sulfate comes from sulfides and hence sulfuric acid, how this varies relative to carbonic acid (HCO_3^-), and what rock and sediment types (i.e. carbonate or silicate) these acidity sources are weathering.

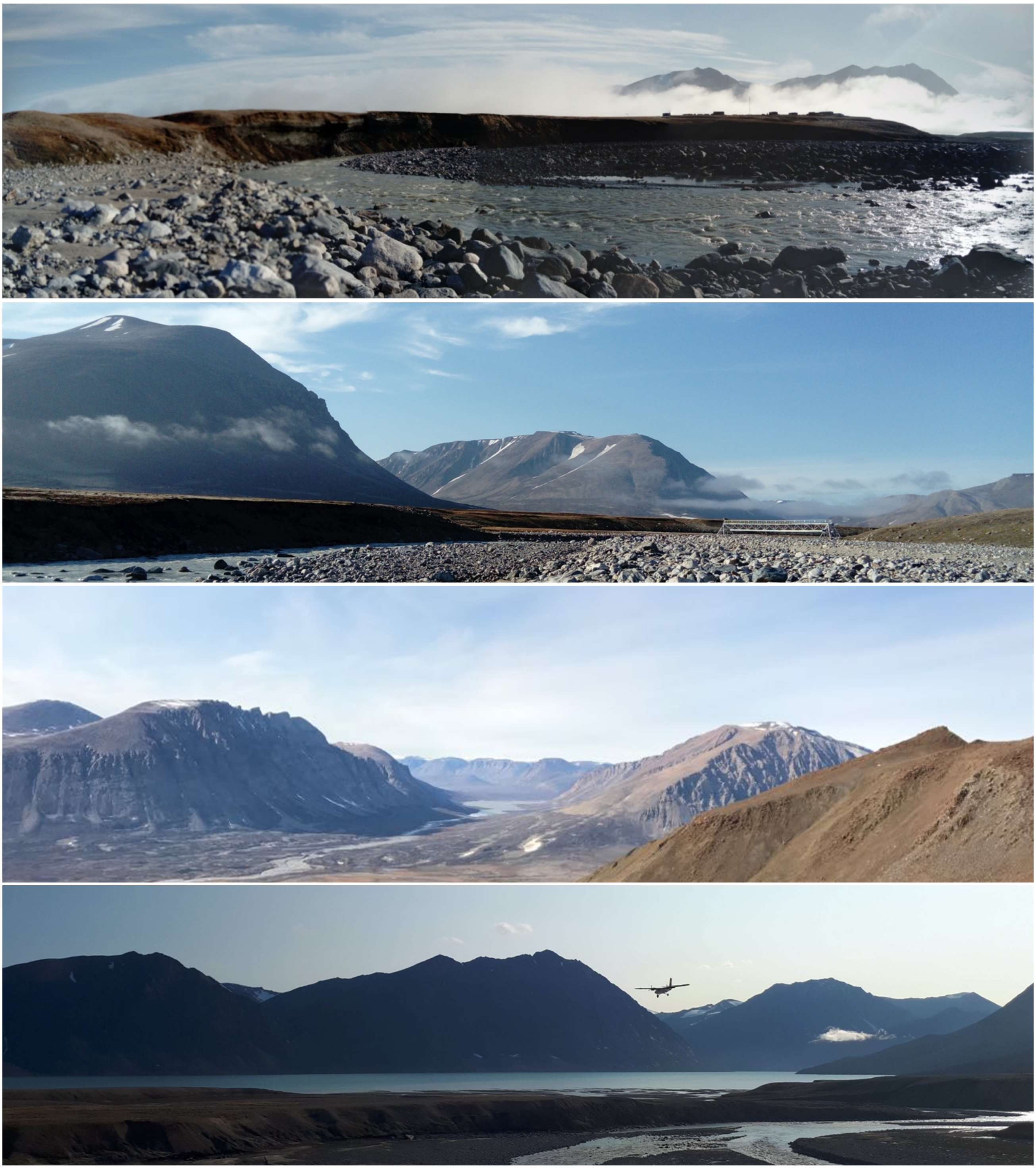


Figure 3: Zackenberg river catchment, the milky colour of the water is from suspended finely ground, highly reactive glacial rock flour. Top photo: Zackenberg River looking downstream with the field station in the background (two photos knitted midpoint). Upper middle photo: Looking upstream of the Zackenberg river showing the metal bridge where discharge measurements are made, the is also the point of the GLOF sampling campaign and the site of GEM[6] long term sampling and monitoring. Lower middle photo: View upstream of the Zackenberg river and valley from ~ 800m up on the Aucella mountain. The St. Sødal lake (Figure 2) can be seen in the middle of the Zackenberg valley. The GLOF thunders through and floods this Valley from the A.P. Olsen ice cap located behind the mountains (Figure 2). Lower (bottom) photo: Norland Air Twin Otter about to land at the Zackenberg air-strip, flying over the Zackenberg river delta and the Young Sound. Photo credits to both Stevenson and Murphy.

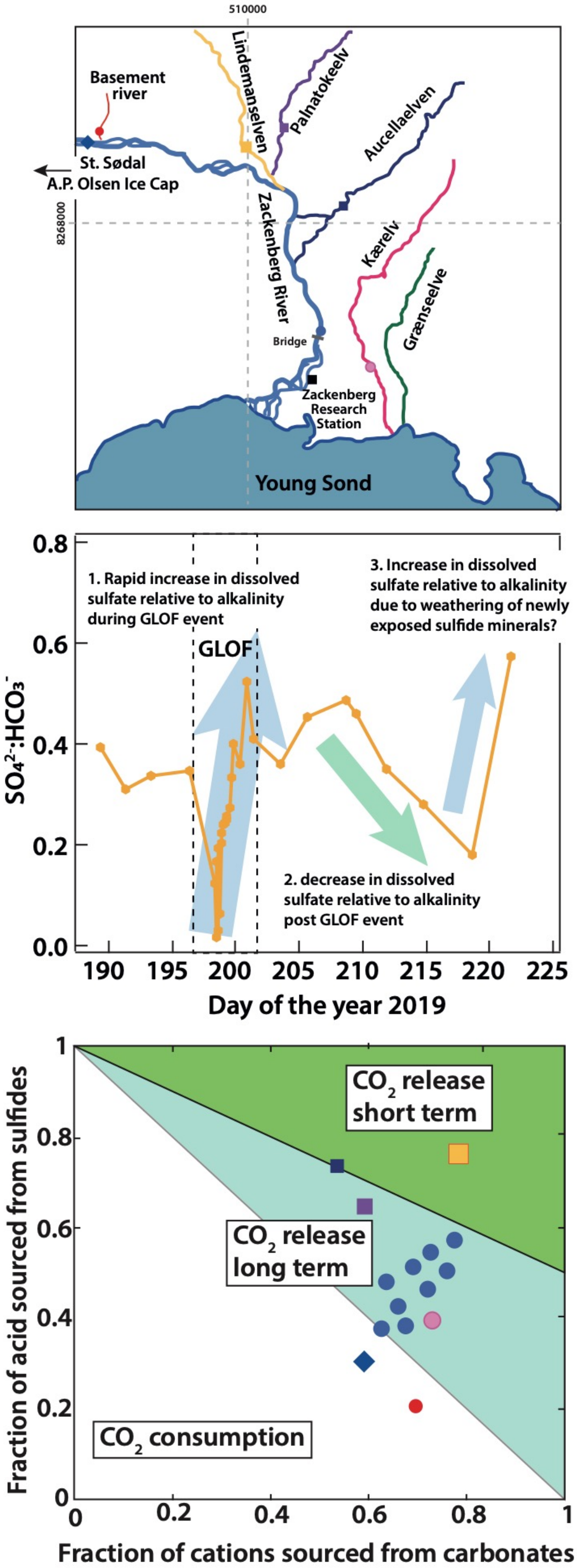
Figure 4: From Left to right, 1) Samples taken from throughout the GLOF event – over 20 samples were taken ever 2 hours during the event. 2) Murphy by Zackenberg river recording hydrochemical parameters of the water. 3) Stevenson recording the pH and conductivity of a small river, Kærelv (pink stream on Figure 6a). 4) Murphy in the laboratory carefully titrating 50 mLs of filtered water to determine the alkalinity (dissolved HCO_3^-) of the water. Photo credit Stevenson.

To achieve this, measurements of lithium[7] and strontium[8] isotopes, the isotopes of oxygen and sulfur in dissolved sulfate[5], and major elemental abundances[4] of river water and sediments, will be determined at our respective academic institutions using established techniques. These unique tracers independently fingerprint silicate, carbonate and sulfate weathering processes[4-5, 7-8], and when taken together they allow us to determine 1) if these high-Arctic rivers acts as a net source or a sink for inorganic carbon, and 2) if GLOF events enhance the exposure of sulfide minerals during or post GLOF events such that they transiently increase CO_2 evasion from the region, counteracting the drawdown of atmospheric CO_2 from silicate weathering.

Figure 5: Hand filtration equipment to separate the sediment and dissolved phases of river water. Photo credit Murphy.

Incredibly, within 24 hours of arriving at the field station the GLOF event began. Every two hours during the ~30-hour event, we measured *in-situ* hydrochemical parameters such as temperature and pH using multiparameter probes, and alkalinity was determined by titration in the field at the Zackenberg bridge (Figures 3 & 4). For each river sample, we collected ~ 10L of river water, which was filtered to <0.22µm, and the suspended sediment archived (Figure 5). Approximately two litres of water per sample was shipped to the UK for elemental and isotopic measurements. The remaining filtered water was processed for sulfate analysis by pre-concentration onto an anion

[7] **Murphy** et al., 2019: Tracing silicate weathering processes in the permafrost-dominated Lena River watershed using lithium isotopes. Geochimica et Cosmochimica Acta 245, 154-171
[8] **Stevenson** et al., 2016: Insights into combined radiogenic and stable strontium isotopes as tracers for weathering processes in subglacial environments. Chemical Geology 429, 33–43.



exchange resin[9] in the field laboratory at the Zackenberg Research Station. In the laboratories at the University of Cambridge and University College London, the following analyses are be undertaken on the remaining 2L water: Riverine lithium isotopes (a proxy for silicate weathering processes) coupled with the major and trace element analysis will allow the determination of bedrock types such as silicates and carbonates to be traced, and allow us to determine reaction stoichiometries of carbon consuming and releasing reactions. Coupled oxygen and sulfur isotope ($\delta^{18}O$-$\delta^{34}S$) measurements on the preconcentrated sulfate on the anion resin will determined the origin of dissolved riverine sulfate from either sulfide or sulfate containing minerals, and strontium isotopes ($^{87}Sr/^{86}Sr$) to trace the lithological source of the water.

The samples arrived in the UK in September 2019. Elemental analyses and lithium isotopic measurements will be made at University College London by Murphy and coupled oxygen and sulfur isotope ($\delta^{18}O$-$\delta^{34}S$), as well as strontium isotopic measurements will be made at the University of Cambridge by Stevenson. To date we have generated over 500 data points of various elemental and molecular compositions from the rivers highlighted in the simplified catchment map in Figure 6a, as well as those from the GLOF.

Initial data from the GLOF (Figure 6b) shows that during the GLOF event, concentrations of sulfate in the water increase dramatically relative to alkalinity. This is what we had hypothesised, so it was fantastic to find this trend in our data. The question then becomes, where is this sulfate from? And, if it is from the oxidation of sulfide minerals, is the resulting sulfuric acid dissolving carbonate minerals, and thus releasing CO_2 to the atmosphere?

Pilot isotopic measurements ($\delta^{18}O$-$\delta^{34}S$) made by Stevenson from a previous field season to the ZRC

Figure 6: a) Simplified map of the ZRC showing different rivers and locations sampled, Lat. and Lon. as UTM zone 27X. b) major element ratios (sulfate, SO_4^{2-} to alkalinity HCO_3^-) measured before, during and after the GLOF event. c) Geochemical modelling of our sampled rivers revealing almost all rivers are a source of CO_2 to the atmosphere. Isotopic and elemental data go into these detailed calculations, e.g. methods in footnotes 4 & 9. Data point colours match rivers colours in panel a).

[9] Relph & **Stevenson** et al., *in prep*: Using oxygen and sulfur isotopes to partition sources or riverine sulfate and reassess the carbon budgets of large rivers. For submission to Earth and Planetary Science Letters

showed that the source of sulfate is 85 to 100% from pyrite oxidation, a result which formed the basis of this field expedition. Stevenson and Murphy have both been invited to present the isotopic data at national and international conferences[10,11,12], which were very well received. This isotopic data is essential to partition both sulfur sources and acidity sources in the river (y-axis, Figure 6c), so that a calculation can be made using geochemical modelling techniques[4,9] to quantify the amount of CO_2 sequestered or released based on the rock types being weathered (x-axis, Figure 6c). Stevenson and Murphy have made these calculations based on their combined elemental and isotopic data for the individual rivers which show conclusively that, from spot sampling at least, the ZRC acts as a source of CO_2 to the atmosphere, counteracting the long-term geological drawdown of CO_2 through silicate weathering[13]. This was an astounding result. The long-term drawdown of CO_2 through silicate weathering is what controls Earth's climate and long-term levels of CO_2. However these rivers seem to be acting as a source, potentially acting as a positive climate feedback: as the climate is warming due to anthropogenic CO_2 sources causing a greenhouse effect, this will continue to warm the Arctic resulting in increases in melt and sediment generation through permafrost thaw and glacial retreat. Weathering of these sediments releases CO_2 to the atmosphere, with the potential to exacerbate the greenhouse effect in a positive feedback loop.

Since the GLOF samples arrived in the UK, Murphy has measured major and trace element abundances in the samples (e.g. such as on Figure 6b) but we still have to make isotopic measurements (of lithium, strontium, and oxygen and sulfur in sulfate) which we hope to achieve in the next 6 months. Once we have the isotopic measurements, we can propagate the fields on Figure 6c to determine the impact of the GLOF event on the release of CO_2 to the atmosphere. Given the results in Figure 6b (and increase in sulfate relative to alkalinity during the GLOF event), we would expect the data to show an increase on the y-axis in Figure 6c during a GLOF event, such that the river would fluctuate between and long- and short- term source of CO_2 to the atmosphere when sulfate concentrations are at a peak.

5: Notes on access, porters, or other issues of interest to future visitors:

Administration, coordination and logistics from the Zackenberg research station were timely and professional, making them a delight to work with. Science permits, park fees and cargo handling were seamlessly organised through logistics. Export permits for river sand were obtained from the Naalakkersuisut, Govornment of Greenland (Aatsitassanut Pisortaqarfik, Råstofstyrelsen Mineral Licence and Safety Authority). The latter must be applied for three months in advance.

The Zackenberg research station is part of the Greenland Ecosystem Monitoring program (https://g-e-m.dk) which is an integrated monitoring and long-term research programme on ecosystems and climate change effects and feedbacks in the Arctic. The data collected by the participating institutions is updated yearly as open data for everyone to access. All the GEM staff at the

[10] **Murphy**, M.J., **Stevenson**, E.I. et al. Impact of permafrost thaw on chemical weathering in the high Arctic Zackenberg River, NE Greenland. Geochemistry Group Research in Progress meeting, Portsmouth, UK
[11] **Murphy**, M.J., **Stevenson**, E.I., et al. High Arctic rivers: a transient source or sink for atmospheric CO2? Goldschmidt Conference, Barcelona, Spain.
[12] **Stevenson**, E., **Murphy**, M. J., et al. The impact of glacial lake outburst flood events on mineral weathering in a high arctic watershed. Invited AGU Fall Meeting 2019. San Francisco, USA.
[13] **Stevenson**, E.I & **Murphy,** M.J et al., *in prep.* Mineral weathering in the Arctic as a positive climate feedback. For submission to Science

Zackenberg research station (e.g. Geobasis and Biobasis) went above and beyond expectations and provided the extra laboratory support and equipment we needed (which we could not bring due to weight restrictions), and even helped with sampling when necessary.

Previous weapon training and polar bear awareness courses prior to heading to the high arctic are always highly recommended. Nonetheless, the Zackenberg Logistics team provide an excellent polar bear and weapon for protection course, specifically for the firearms used at the station. All visitors (be they new or returning to the station) must take the course before they are allowed out of the research station. Everybody must carry a minimum of a rifle and flare gun (with extra ammo), and radio whenever stepping out of the bounds of the research station which are clearly marked.

Flights from Iceland to Zackenberg are organised by Norlandair, (www.norlandair.is) based in Akureyri Iceland, via Nerlerit Inaat (CNP) near Ittoqqortoormiit. We found that CNP is an ideal location to fly to many other remote regions of Greenland. Should future MEF expeditions explore more of Greenland, especially the East coast, we would highly recommend this company. However, if you do go to CNP (or any other small Greenlandic airports on the East coast) be sure to pack food and water in case the weather closes in!

6: Suggestions for new routes or new subjects for study in the area:

We were unable to access the region outside of the dashed area in Figure 7 due to injury (see section below), however after talking to the logistics managers at the research station they then suggested some modifications to our original route in that instead of hiking through the Zackenberg valley and past St. Sodal lake, a small RIB from the Zackenberg research station could be sailed to the boat landing site on Figure 7. This would enable us, or future expeditions, to take more samples and also allow access to the small trapping hut which would increase polar bear safety overnight. This would allow access new sites as well as the previously ear-marked ones. New sampling sites would also include the glacial rivers from the glaciers of the A. P. Olsen ice cap south of the LAPO lake.

Additionally, thanks to fieldwork this summer, we have a fantastic set of GLOF samples with which we can also encourage collaborative work with other geochemists, biologists and atmospheric scientists so that the sample set can be used to their maximum extent and we can learn the most about how such a pristine and vulnerable region is responding to climate change.

7: Injury and illness

Unfortunately, a fluke accident early in field season meant Stevenson popped/dislocated two ribs, through no fault of the station or location. The injury was swiftly and successfully dealt with (given the limitations of rib injuries) and the field plan was modified such that Stevenson was able to see out the rest of the field season with Murphy. However, the limitations of the rib injuries meant that we were unable to make it to the toe of the A. P. Olsen glacier as anticipated as Stevenson was at too higher risk of further injury, especially on a 3-day trip on highly uneven ground from the research base station. Nevertheless, we still captured the GLOF event, which was the primary objective of the expedition, as well as many other water and sediment samples from within the pink dashed region of Figure 7, (e.g. Figure 6a)

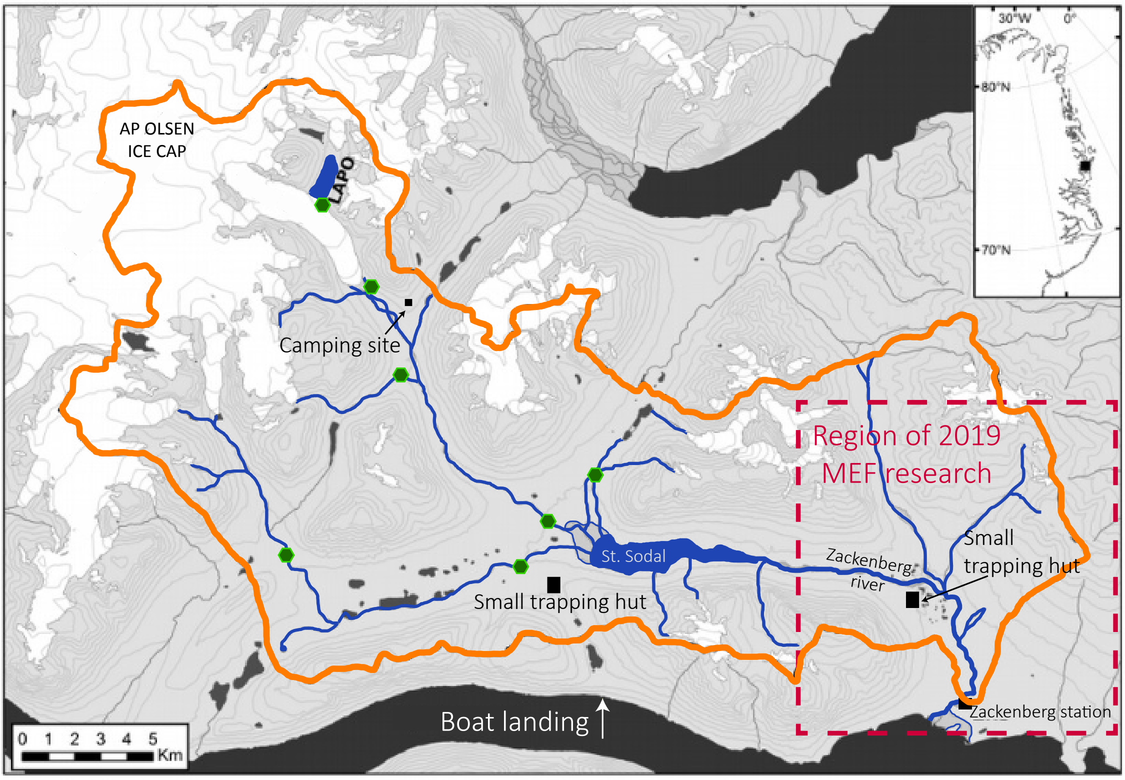


Figure 7: Orange outline is the ZRC hydrological catchment, red dashed region is the area of 2019 MEF research, locations for outdoor camping and trapping huts for overnight accommodation or a field base are shown, as well as good spots for future sampling (green octagons). Proposed boat landing site from Zackenberg research station is shown at the bottom of the figure for easy access to the west of the catchment area.

8: Waste disposal

All types of our waste were brought back to the research station for treatment after long days in the field. At the station, waste is separated into organic waste, combustible items and non-combustible items. Paper and cardboard were burned in the small incinerator. All other types of waste are flown out from Zackenberg for treatment or deposition. Use of the station toilets always had a clear priority over open-air defecation in the field. Toilet waste is then fragmented and dumped into the river downstream of the station. But where not possible, we covered our faeces with a stone big enough not to be removed by a fox.

9: Expedition Income and Expenditure

Income/grant	**GBP**
Mount Everest Foundation to Stevenson	3,250
Gilchrist Fieldwork award to Murphy	9,800
Donation from Dr Philip A E Pogge Von Strandmann	1,000
British Soil Science Society Field Equipment Grant to Stevenson	974.89
Total	***15,024.89***

Expenditure	**DKK**	**GBP**
Return flights for ES and MM from UK to Zackenberg via Iceland	61,200	6,987.64
Accommodation, safety equipment and subsistence (meals) over four weeks	52,800	5,950.76
Cargo, shipping, permits and handling fees	19,682	2218.24
Total	***133,682***	***15,066.48***

The anticipated cost of the field expedition was £15,303.83 (quoted in the original MEF proposal) therefore we have successfully completed the fieldwork underbudget.

10: Any other relevant comments (permits, liaison officer, etc):

During the expedition, the Zackenberg River Catchment experienced the second hottest summer on record. The air temperature reached 19.5 degrees at its maximum, when temperatures during this time of year are more typically 9 to 10 degrees. This resulted in some dramatic changes to the landscape with permafrost slumping in the highly incised rivers at higher altitude delivering additional sediment to the rivers, and massive thermokast development causing the riverbanks to become highly unstable. This lies in stark contrast to the previous year where the winter snowpack never fully diminished, leading to the failure of reproduction for many bird species: https://www.scientificamerican.com/article/late-snowpack-signals-a-lost-summer-for-greenlands-shorebirds/

11: Acknowledgements

None of this fieldwork would be possible without the generosity of the funding bodies; the Mount Everest Foundation, the Gilchrist Award, and the British Society of Soil Science, as well as generous donations for fieldwork and geochemical analyses from Dr P.A.E. Pogge Von Strandmann, (UCL) and Dr E.T. Tipper and Dr. A. Turchyn (UCam), and the modelling framework of Dr K. E. Relph (UCam). Big thank you also to the Zackenberg secretariat, the logisticians at Zackenberg, the GEM Basis teams and Norland Air.