GRIS 15: Bioglaciology in South-West Greenland

Dr Joseph Cook, Dr Arwyn Edwards, Ms Ottavia Cavalli, Ms Sophie Cook, Dr Michael Sweet

July 2015

Trip Report

GRIS15: Bioglaciology in Southwest Greenland

Team:

The team comprised five young, early career researchers from UK Universities, led by Dr Joseph Cook (University of Derby). Four team members were present in the field, one (SC) remained in the UK and provided logistical support and expert advice in the field of environmental metabolomics.

Dr Joseph Cook (PI): a glaciologist at the University of Derby with specific expertise in ice-microbe interactions. Dr Cook has fieldwork experience in Greenland and Svalbard, as well as diverse achievements in rock climbing.

Dr Arwyn Edwards: a biologist at Aberystwyth University with specific expertise in applying molecular techniques in cold environments. Dr Edwards' field experience includes Svalbard, Greenland, Austrian Alps and South Georgia Island.

Dr Michael Sweet: A coral biologist at the University of Derby.

Ms Ottavia Cavalli: A microbiology PhD student at Aberystwyth University.

Ms Sophie Cook: A metabolomics PhD student at Aberystwyth University.

Location:

Field site on the Greenland Ice Sheet, approximately 3 km from the ice margin near Kangerlussuaq, Greenland (coordinates: 67°09.833' N, 050°00.889' W).

Aim:

The aim of the trip was to observe and measure ice-microbe interactions on the surface of the Greenland Ice Sheet.

Figure 1: The Greenland Ice Sheet (sourced from Wikimedia Commons)

Abstract:

A small team of four scientists established a field camp near the margin of the Greenland Ice Sheet in July 2015. They examined topographic controls upon ice surface morphology, in particular the shapes of microbial habitats known as 'cryoconite holes', finding that mesoscale topography influences both habitats shape and biogeochemistry on ice surfaces. Further experiments related to fungal ecology, microbial carbon and nutrient cycling, metabolomics and ice physics were also undertaken. The results are briefly discussed in this report, but will be analysed and discussed fully in peer-reviewed publications. The trip was successful in that all members of the team returned safely, and the science objectives were met. The trip unfortunately ended one-week early due to a vehicle collision on the road between Kangerlussuaq and Point 660.

Preparations:

There were several phases of preparation for this trip. The first was a pilot study carried out by Dr Cook and Dr Edwards in July-August 2014 at a nearby field site on the Greenland Ice Sheet. This involved noting the shapes and sizes of 'cryoconite holes' along three N-S oriented ten-metre transects. It was found that holes had dramatically different shapes, sizes and orientations on north-facing slopes compared to flat ice. Dr Cook's main project at the time focussed upon examining the impact of hole geometry upon microbiology and biogeochemistry in biologically-inoculated sediment on the holes floors, so it was immediately hypothesised that mesoscale ice topography may impart a control upon microbial processes on ice. This was recognised as an important research question because it links processes operating at the micro-, meso- and macro-scales on glaciers and ice sheets.

Intrigued by this hypothesis, Dr Cook set out to obtain sufficient funds to support a return visit to the Greenland Ice Sheet. An early donation from the British Society for Geomorphology encouraged Dr Cook to recruit a team of glaciologists and biologists (Dr Arwyn Edwards, Dr Michael Sweet and Ms Sophie Cook) and make further funding applications. The Mount Everest Foundation, Gino Watkins Memorial Fund, Andrew Croft Memorial Fund, Scottish Arctic Club, Gilchrist Educational Trust and Gradconsult made donations that covered our projected costs.

Once these funds were secured, several months were spent refining our experimental design, gathering equipment, arranging logistics and testing methods and techniques. Several exchange visits between the University of Derby and Aberystwyth University allowed the team to discuss plans at length and to get to know one another. Ms Ottavia Cavalli, a microbiology PhD student from Aberystwyth University joined the trip at the last minute and was a most welcome addition to the team. Unfortunately, Ms Sophie Cook had to withdraw from the trip the day very shortly departure and instead took on a support role in the UK.

Field site:

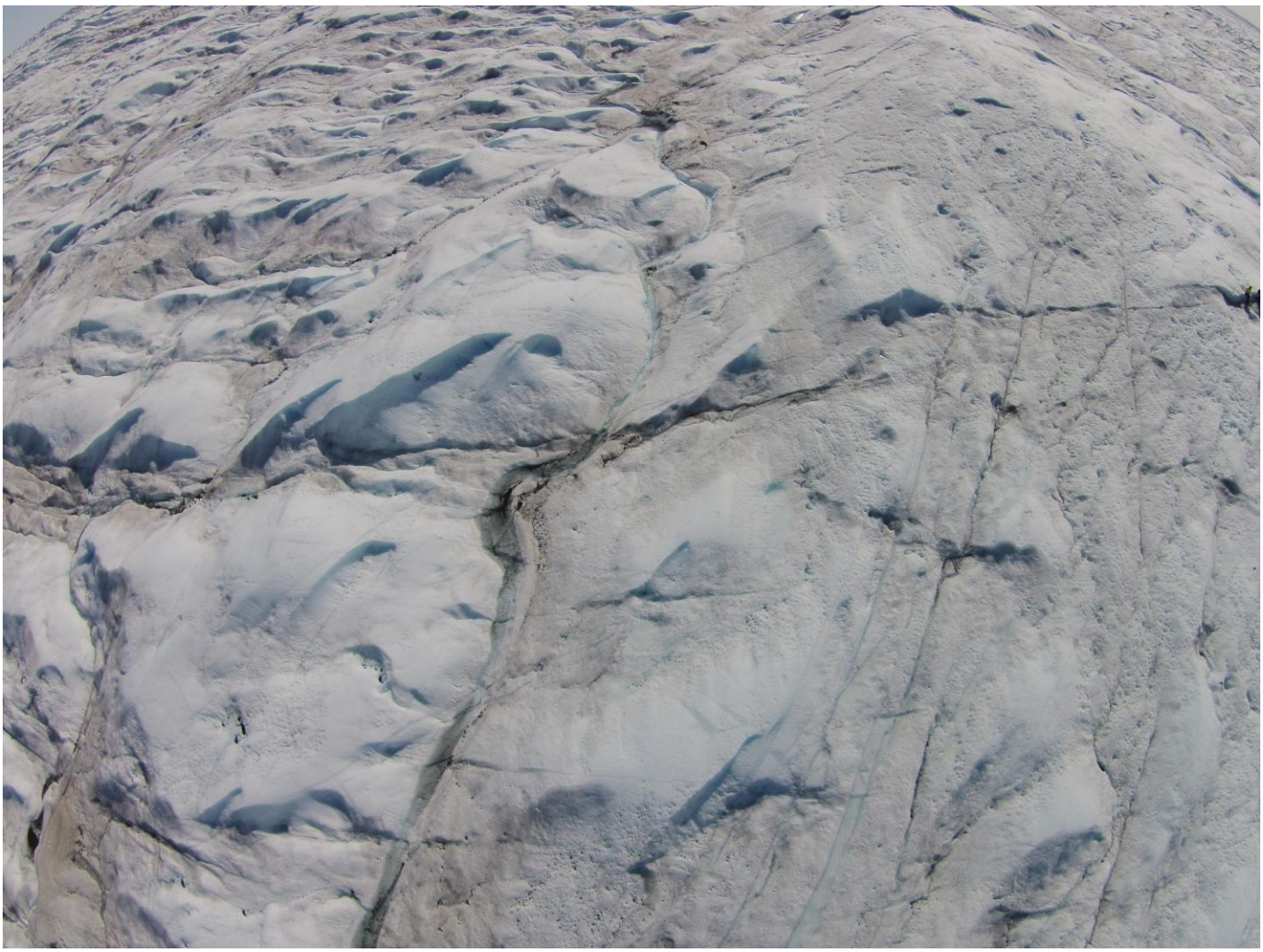
The primary field site was established approximately 3 km from the ice margin in the south-western part of the Greenland Ice Sheet. This site was chosen during an earlier reconnaissance visit for several reasons:

1. It is far enough inland for the ice to be relatively stable and slow-moving compared to ice nearer the margin and compared to many valley glaciers.
2. The ice is near-flat at the macroscale, meaning mesoscale topography can be more accurately examined.
3. There is no shading from surrounding mountains or landforms.
4. It is far enough inland to be free from detritus from tourist groups
5. There are abundant cryoconite holes
6. It is close to an established weather station
7. It is accessible on foot, meaning we avoided the financial and ecological costs associated with helicopter transport
8. It is usually an area of meteorological stability, offering high likelihood of clear-sky conditions and low risk of danger to researchers or equipment.

These factors combined to make the field site an ideal natural laboratory for examining the influence of mesoscale topography on glacier surface morphology and biogeochemistry. In 2014 Drs Cook and Edwards noted directions to the site as well as GPS coordinates, making it simple to return to the same location in 2015. However, once a certain distance into the ice sheet has been passed, the choice of field site is to some extent arbitrary as the above conditions are met by wide expanses of ice sheet. This is important for our study because it indicates that our field site is broadly representative of large swathes of ice sheet and that our study therefore has significance beyond our field locality.

The field site itself was a 500 x 500 m area of ice centred upon the coordinates 67°09.833’ N, 050°00.889’ W. At the field site were several distinct supraglacial environments, including north- and south-facing slopes, flat ice, supraglacial rills and streams, moulins, snowbanks, cryo-ponds, weathered ice and a very high frequency of cryoconite holes with diverse shapes and sizes.

Researchers at the field site, approximately 3 km from the ice margin on the south-western Greenland Ice Sheet (ph. J Cook).



An aerial view of the field site taken using a DJI Phantom Vision 2 + Drone. Dr Cook present in upper right part of image for scale.

Methods:

Several methods were used to observe and record cryoconite hole morphology and biogeochemistry at the field site.

1. **Quadrat Surveys:**
   0.5 x 0.5 m quadrats were randomly emplaced upon the ice surface. In each quadrat metadata pertaining to the ice surface topography was recorded. This included slope angle and aspect, measured using a compass-clinometer. A photograph of the quadrat was taken using a Pentax Optio handheld digital camera. The number of cryoconite holes within the quadrat was recorded. Callipers, tape measure and graduated probes were then used to record the dimensions of each cryoconite hole, including the hole depth at each wall and in the centre, the hole floor slope-angle, the aperture at the ice surface and the hole floor, the distribution of sediment within the hole, the orientation of the hole's x and y axes and the albedo in ten positions across the quadrat. This was repeated for twenty quadrats in each of four topographic settings (high plateaus, low plains, north-facing slopes, south-facing slopes).

2. **NEP incubations**
   Microcosms were established on the ice surface to measure NEP. This was carried out twenty times in each topographic setting and each incubation lasted for 24 +/- 1 hours. NEP stands for Net Ecosystem Productivity and is a measure of the balance between primary production (PP) and respiration (R) occurring in all the organisms within a microbial community. Primary production is the conversion of atmospheric inorganic carbon (IC) into organic carbon (OC), primarily using energy from sunlight (photosynthesis). This is opposed by respiration, which is the process of metabolising OC back into IC for the purposes of energy harvesting. PP uses CO_2 and releases O_2, R uses O_2 and releases CO_2. Since NEP involves the usage and production of O_2, dissolved IC (DIC) and dissolved OC (DOC), NEP can be measured using changes in the concentrations of these nutrients after a period of activity. Most analyses have used closed-bottle incubations and measured changes in these nutrients over time periods of hours to days. Some incubations are undertaken under normal light conditions (to measure NEP) and some are undertaken wrapped in tin foil to eliminate irradiance (to measure R). These measurements are based upon several fundamental assumptions: firstly, that primary production ceases in the dark; second, that confining the community within a bottle does not significantly alter nutrient availability or hydrochemistry during the incubation; third that the temperature is not significantly lower in tin-foil wrapped incubations; fourth that the glass walls of the bottles do not attenuate harmful UV-B radiation such that photosynthesis is artificially enhanced; fifth that respiration rates are constant for both light and dark incubations; and finally that we can accurately correct for sulphide oxidation (in oxygen-based studies) and carbonate dissolution (in carbon-based studies). Whether these assumptions are justifiable is still somewhat uncertain. Changes in total dissolved inorganic carbon (TDIC) concentration has become the favoured technique for measuring NEP. This involves acidifying the incubated solution with HCl to force DIC to degas as CO_2 into a headspace full of "scrubbed" air. The CO_2 concentration of this air can then be measured using an infra-red gas analyser (IRGA). This is a slightly more convoluted procedure than using a DO_2 meter; however it has been proven to be robust, even in the field. There is less opportunity for degassing since the solution hardly ever becomes open to atmospheric exchanges. Telling et al (2010) identified TDIC as the optimum method for calculating NEP in cryoconite incubations for the reasons outlined above. Standard procedures for carrying out NEP measurements using TDIC

were developed by Hodson et al (2010) and Telling et al (2010; 2012). They suggested that, since sediment arrangement significantly impacts NEP (Cook et al, 2010; Telling et al, 2012), measurements should be normalised for sediment mass and incubations should last for entire days. Measuring NEP is important because it illustrates whether a habitat is a net source or sink of carbon. Cryoconite holes could be particularly active sites of microbial activity, and understanding their NEP tells us about their influence on carbon cycling.

3. **Transect Surveys:**
   Transects were used to record spatial changes in cryoconite hole morphology in areas of differing topography. Firstly, long 100 metre transects were established and marked using bright orange markers. These comprised circular discs of uniform diameter which were used not only as directional markers but also to standardise the scale of images taken of the ice surface, thereby allowing quantification of hole size and direct comparison between transect photographs. The transects were imaged at least daily, firstly using a drone flying at a constant altitude, which recorded high-definition footage looking directly downwards at the ice surface. The transect was then walked on foot and ground-truthed manually, with a second set of images taken using a hand-held digital camera. A second transect experiment was used to test the hypothesis that cryoconite hole morphology is influenced by proximity to hydrologic flowpaths such as rills, streams and moulins. Here, 10-15 metre transects were established on slopes leading towards rills and streams. The orientation of the long axis of cryoconite holes within 50cm either side of the transect were measured to determine whether proximity to the stream influenced their shape.

4. **Light and temperature**
   Light and temperature data were recorded at the field site using HOBO Pendant loggers. These were installed in a range of locations, including one suspended 1 m above the ice surface on an ablation pole, and four floating in cryoconite holes in four different topographic settings. Further meteorological data was obtained from a nearby weather station.

5. **Further analyses**
   In addition, experiments were undertaken to measure various properties of the local microbial communities, optical and physical properties of different ice types, and local hydrology and hydrochemistry.

Results

Preliminary results indicate that the morphology, evolutionary trajectory and biogeochemistry of cryoconite holes are influenced by ice-surface topography. Full analysis of the data is yet to be completed.

Trip Diary:

1st July:

Today was varied for team GRIS 15. Mike was attending a conference on water voles (!) while I was giving a talk on research-led teaching at the University of Derby's annual Learning and Teaching conference. Arwyn and Otti had the worst deal, taking a slow train from Aberystwyth to Derby on the hottest July day on record. The evening, however, was pleasant all around as we chewed over our research plans, redistributed our luggage and ate a final feast in my garden. A few minor dramas were

quickly resolved and a few final items added to the Mount Baggage, and we were all tucked in by 12:30!

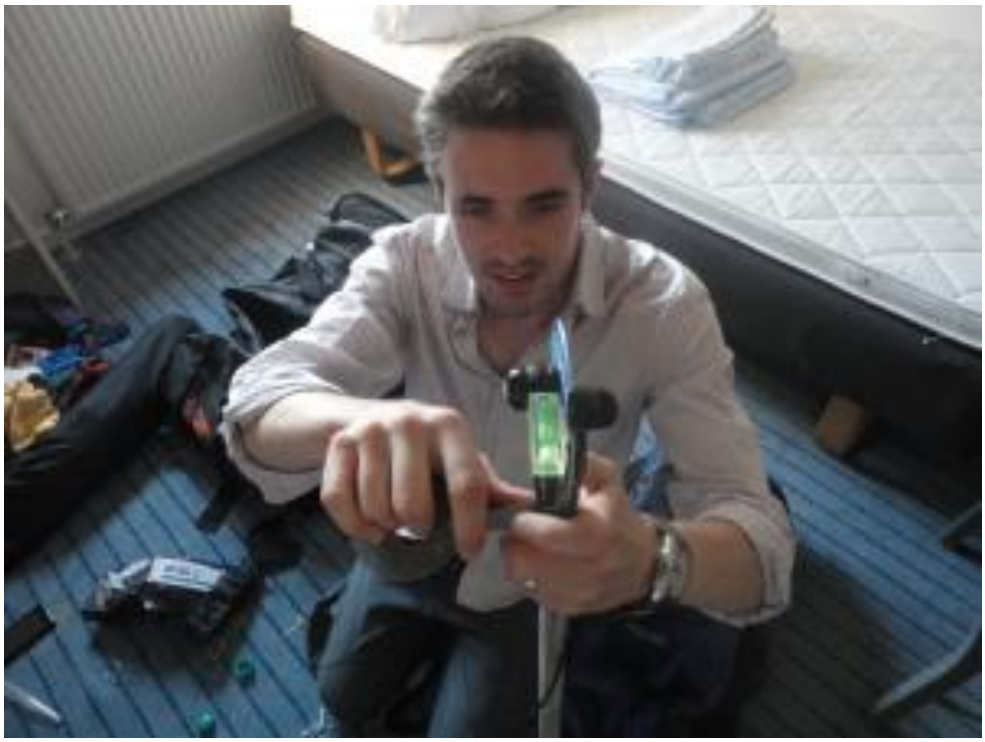
Getting this lot to Greenland was a bit of a nightmare!

2nd July 2015:
An early start today, but an excited GRIS 15 crew were awake and raring to go when the taxi pulled up outside my house at 6am. The obligatory airport tweets were sent out, then it was just a case of grabbing some food and awaiting gate opening at 10:45. We realised at 10:42 that the gate ***closed*** at 10:45, so boarding followed a sprint across the terminal. A smooth flight then a whirlwind tour of Copenhagen, including the famous Geological Survey of Denmark (GEUS) and then some dinner before some more strategizing for the second leg of the journey. Looking forward to being back in Kangerlussuaq tomorrow.

3rd July 2015:
As always, breakfast at the hotel in Copenhagen was spectacularly good – we shovelled some down and hot-footed it over to the airport, checked-in an eye-watering £462 worth of excess baggage and Mike and I flew to Kangerlussuaq. Arwyn and Otti stayed in Copenhagen today, and will follow on tomorrow. We went straight to KISS (Kangerlussuaq International Science Support) to check in and bumped straight into Alun Hubbard (Aberystwyth University) and Jason Box (Dark Snow Project) and their PhD student Johnny Ryan who had been gathering aerial imagery and data from UAVs. In the afternoon, I showed Mike the sights around Kangerlussuaq, including the Watson River which destroyed the bridge in Kangerlussuaq during a period of extremely high melt in summer 2012. We did a big food shop and met up with our Air Greenland contact providing a car and generator for the next month. Then the task was to assemble and construct some field kit. Unfortunately, our budget could not stretch to a top-of-the-range albedometer for measuring surface reflectance, so I enlisted Mike's help in building one.

The total cost of this instrument was around £200, almost all of which was accounted for by two Apogee SP-110 pyranometers. The albedometer does not give spectral reflectance values, but it can provide broad-band albedo (300-1100nm) cheaply and effectively, is very easy to use and took only an hour to construct. To use it the multimeter is set to read mV, and the upwards looking pyranometer is connected to the miltimeter using the fixed crocodile clips. The pole is then held out over the desired measurement area. Depending upon the size of the measurement area, the albedometer needs

to be held at a particular height. In this study we will be measuring areas with a diameter of 1 metre, for which a height of 0.13m is required. The plumb line is therefore set to 0.13 metres and the albedometer lowered until the plumb line touches the ice. The spirit level is then used to minimise error due to tilt. Once a reading has been taken, the downwards looking pyranometer can be attached to the crocodile clips and a measurement taken. The ratio between the upwards and downwards looking readings gives a measure of surface reflectance (albedo).



Building the albedometer at KISS (ph. M Sweet)

And testing it out the window! (ph. M Sweet)

I also whipped up some callipers and marker flags for identifying test holes at the field site while Mike cooked a tasty pasta dinner! Then, as I am prone to doing, I sat up late obsessing over the field plans.

4th July

Independence Day! Early breakfast and off to pick up the rest of the GRIS 15 team from the airport. Arwyn and Otti arrived in good spirits and we walked them back to KISS with their bags and caught up over lunch. We spent the afternoon hiking to Lake Ferguson and observing some of the beautiful flora and fauna (and getting swarmed by the fierce mosquitos which have plagued us since we arrived). The glacial geomorphology in this region is fascinating.

A late evening view of the dramatic glacial landscape of SW Greenland (ph M Sweet)

We picked up our vehicle and took it for a drive as far as the gate before Russell Glacier. Mike got his first glimpse of the ice and was suitably impressed! We are all now very excited to get onto the ice sheet and start working. I'm hopeful that by the end of tomorrow we will have gotten onto the ice sheet, established a camp and selected a suitable field site ready to start taking measurements in earnest the following day.

5th July.

I awoke very early today, the twenty-four hour sunlight always plays havoc with my sleep for a while. I took the last opportunity to use a shower and packed up the field kit ready to depart from KISS and start the field season proper. The others awoke a little later and we had a group breakfast before loading up the wagon and heading off in the direction of the ice… We spent the morning setting up a camp near the margin of the ice sheet. The temperature difference between here and Kangerlussuaq was very noticeable – we went from sweltering in shorts and t-shirts to wrapping up in base layers and down jackets. The wind was strong and constant, which was partly welcome as during the brief lulls the mosquitos swarmed in thick clouds. Once tents were up and pegged down firmly, we made our way onto the ice in search of a field site. We went in light, leaving science kit at the camp, as this was mainly reconnaissance for tomorrow. We accessed the ice sheet at 'Point 660' and walked approximately 4 km to a flat plateau beyond the crevasse field which I had identified last year as a potential site. Here, the ice is much lower gradient and less influenced by the intense cracking and deformation of the ice closer to land, and includes a wide variety of ice types, from patches of dirty snow, flat-ice plains, steep north and south facing slopes and several supraglacial streams. The

cryoconite holes here ranged from tens of millimetres to metres in diameter and were present in all kinds of shapes and sizes, with the classic cylindrical 'pipes' and 'buckets' the most prevalent, but irregular holes and complexes aplenty. In other words, it's a near-ideal field site for glacier ecology. This site will be our home for the next twelve days. We marked the site on our GPS and hiked back to dry land, excited to start our experiments. Everyone was a bit whacked afterwards, and we noted that after repeating the hike every day for two weeks, we will be either very fit or very tired! We cooked up our freeze dried food, ate it on a picturesque rock ledge near a fierce glacier-fed river, and got an early night, except for Arwyn and I who sat up enjoying a whisky (which required sacrificing two 50 mL falcon tubes as shot glasses) and chatting cryo-bio until late!

The camp on the first day of field measurements

Arwyn and Otti enjoying the view from 'the kitchen'.

July 6th:

Breakfast was early porridge, again at the riverside. This is a really beautiful spot to eat – we can see the river rising and falling in synchronicity with cycles of melt on the ice sheet (plus a lag) and we can also see a glacier fed lake graudally filling past the moraines. The spot is generally sheltered from the wind, but catches most of the day's sunshine, so is a comfortable oasis away from the wind, dust,

mosquitoes and cold up by our tents. I wonder whether this spot might get submerged as the river swells later in the season though. After shovelling some breakfast, we hot-footed it to the field site and put in a big day's sampling. The walk-in was quite slow because we were hauling all the science equipment, including the drone, ice corers, drills and biogeochemistry apparatus. My own work was hampered slightly by the strong katabatic winds belting my equipment as I worked, often sending it sliding down towards a nearby supraglacial stream, or making it difficult to work with. We attempted a drone flight, which was also a bit hairy, with the quad-copter strafing uncontrollably in the strong gusts and using a lot of energy trying to right itself against the wind. Nevertheless, good data was obtained and field equipment was stashed away in an ice hollow – this will make the walk in much easier tomorrow. An accidental diversion on retreat landed us in the crevasse field, which had to be negotiated carefully and slowed down our return – we eventually ate at 22.15.

Mike Sweet, Arwyn Edwards and Ottavia Cavalli walking in to the field site

July 7th:

More of the same at the field site today, except that we have hit our stride. Our route from camp to field site is now pretty well known and we cut it down to one hour and got lots of measurements and samples during the day. However, it was really, really cold and extremely windy at the site today, making working very uncomfortable and difficult. The infra-red gas analyser I use to make carbon flux measurements could not maintain sufficient internal temperature and could therefore not be used in situ, and so I had to revert to decanting the incubated samples into falcon tubes, taking them off the ice entirely and running a make-shift NEP lab in the back of the truck. Not perfect, but needs must, and most importantly the data look good. More tasty dehy's for tea and a nip of whisky before bed!

On the way to constructing NEP-wagon…!

One of the team (Mike? Arwyn?) working under spectacular skies at the field site.

Walking in to the field site (me, Arwyn, Otti). Ph. Mike Sweet

July 8th:

Mike and I went to the field site alone today, as Arwyn and Otti stayed in camp and filtered seemingly endless water samples. At the site, the conditions were much calmer, much more pleasant than on previous days. I took advantage of the favourable conditions and managed to make extra measurements today. The wind was still occasionally gusty, but we managed to make three drone flights. One was slightly hair-raising and it was only luck that kept the quadcopter from bouncing inelegantly into a supraglacial stream on more than one occasion. Nevertheless, we got some nice footage of the ice surface, imaged our field site and made repeat high resolution imagery of our experimental transect.

Video showing a drone flyover of our field site

Disaster struck on the way back down from the field site though, as Mike's crampon snapped, leaving him pin-less. Thankfully that occurred past the crevasse field and on relatively flat, solid ice so there was no major drama. On return to camp we arranged that three of us would go to the field site tomorrow, then all back to Kangerlussuaq the day after to find Mike some new crampons and restock food, gas and generator fuel. Back at camp, I made my measurements in the NEP-truck, ate dinner and Arwyn and I stayed up chatting science again, and then it was off to bed ready for a big day tomorrow.

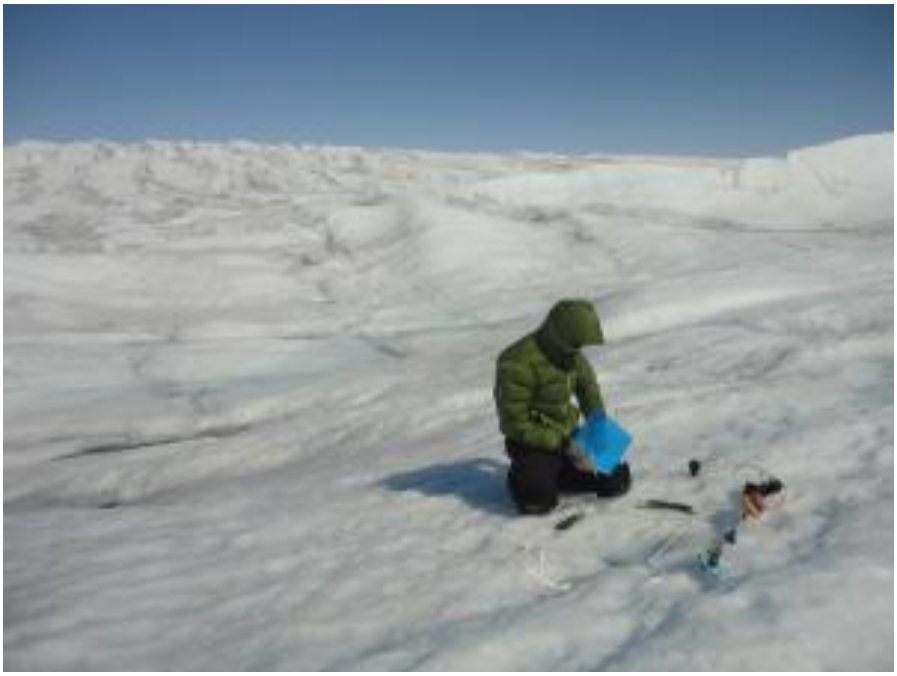
July 9th:

We decided to split the team today, given that we were a pair of crampons short and navigating the crevasses pin-less seemed unwise. Of the four of us, Otti was most willing to stay at camp since she had filtering and sample prep to do that did not require visiting the field site. So Mike, Arwyn and I went up to the field site as a three, while Otti stayed behind. We made quick time getting to the site, and the conditions were perfect. The wind had finally died down, meaning we could work without constantly pinning or weighing equipment down and continually fighting to hold down sheets of paper etc. This increased our productivity hugely – I managed to record more than three times the amount of measurements today than the other days. It really was the perfect glacier field work day –

bright and calm and a temperature that was comfortable to work in in just base layers, salopettes and down jackets. We capitalised on the conditions and returned with lots of data.

Working under a beautiful solar corona

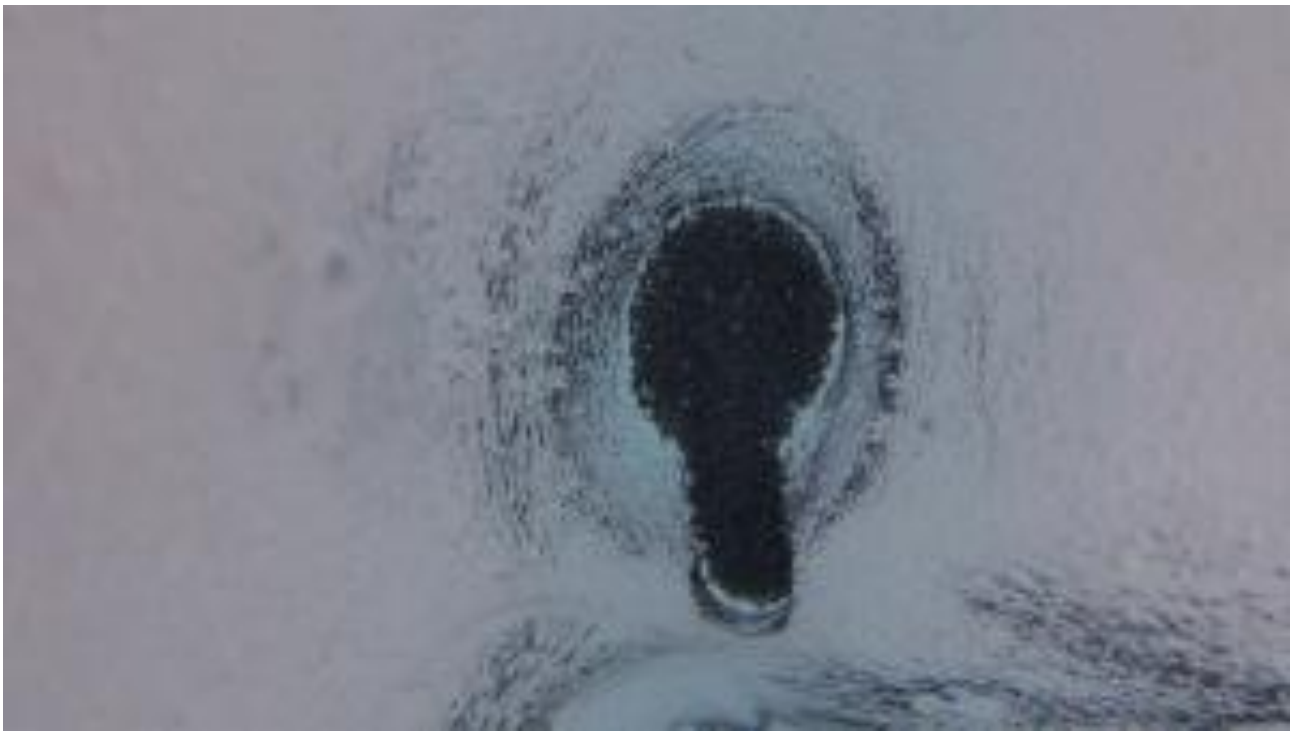
The walk-off was pleasant and we stopped on the way back to appreciate the surroundings. This spot is truly other-worldly – the scale of the ice sheet is quite unlike any other glacial environment and the sense of remoteness at the field site is unique. We discussed the aura of the place – the spooky noises of the winds over the rough ice and through channels and ravines, the sound of cracking ice, of moulins and streams, and the odd, beguiling light. Back at camp I spent a couple of hours taking measurements in the 'NEP-wagon' and revising the plans for the rest of the trip. The priority is to get replacement crampons for Mike so that the whole team is field-ready again, so we will have to sacrifice an ice day tomorrow to go back into town. This is a significant journey, so we will combine it with refuelling the truck, restocking food and maybe sneaking in a shower before a big ten day stretch of focussed work on the ice. We convened in the bigger of our tents for whiskey and debriefing before bed.



July 10th:
We began at the usual 06:00 am, but instead of heading to the ice we headed the opposite direction and drove all the way back to Kangerlussuaq. Half the team restocked food while Arwyn and I went to Air Greenland to refuel the truck. Everything went smoothly except for the crampons! However, thank goodness, this was remedied late in the day by the kindly staff at 'World of Greenland' who offered up a spare pair. There was also a bit of mucking around trying to find gas for the stove, which packed up this morning, and it ended up costing us an eye-watering £175 to buy enough gas to last the rest of the trip. That was a major blow, but at the end of the day a necessary cost to put us back in business and facilitate time on the ice. Today was an unplanned inconvenience forced by the breakage of both stove and crampons, but unavoidable and probably largely for the best as it put the whole team back in action and we are sufficiently fuelled and fed for the next ten days of uninterrupted field work.

July 11th:
Another day at the field site in clear but windy conditions. The cryoconite holes we are here to study have really changed since we arrived, with different groups showing distinctly different evolutionary trajectories, biogoechemistry and morphology. The diversity of cryoconite entities on the ice surface is remarkable, in their size, shape, cryoconite content, frequency and distribution. Our job here is to test whether these properties follow predictable patterns. It is becoming clear that cryoconite is not just cryoconite – actually the variables controlling the properties of cryoconite granules and cryoconite holes are numerous and interconnected across the micro, meso and macro scales. Hopefully our data will go some way towards shedding some light on these processes.

The irregularly shaped ‘cryopools’ are in stark contrast to the traditional model of cylindrical, pipe-like holes.



Some cryoconites appear to be complexes formed by merging of mobile holes.

Others seem to have melted out completely and left 'smudges' on the ice surface

Being Saturday, Arwyn and I insisted upon adhering to an Arctic science tradition – one which originated on the ships of the great polar explorers and was introduced to us by Nick Cox at the NERC base in Ny Alesund… The tradition is formal dinner after a day in the field. So we donned shirts and ties and ate our freeze dried food rations under the British Ensign flag and made a bit of a do. Obviously it was silly given the squalid camp conditions and meagre edibles, but we had three courses – tea, freeze dried curry and a dessert of rye bread and Nutella. Mike was a good sport and humoured us through it and we took a couple of pictures to send to Nick to show him the tradition lives on! We even had a night cap of a shot of whisky and a square of chocolate and toasted the polar greats. Cheers!

A classy formal dinner!

July 12th

Today we awoke to calm, clear conditions and therefore prioritised drone flying. We hiked in to the field site and used the drone to obtain aerial imagery for creating field maps, completed our transect study, flew some gridded flights to obtain surface images for analysis, and then spent half an hour using it to obtain footage for outreach work. This included attempting a so called 'sky selfie' where

handheld camera footage is spliced into a gradually rising drone video, spliced into a reversed google earth zoom, creating the illusion of zooming into a cryoconite hole from space… we'll see if it works when we get home. We also flew several flights over the field site and surrounding area for aesthetic and contextual footage. Afterwards, we nailed the day's measurements and treated ourselves to watching a movie on Otti's Ipod before bed.

Otti on ice

All in all a fun day; except for one major factor. THE MOSQUITOES. The drop in the wind has allowed them to take over. It is mosquito hell. We are having to stay completely covered at all times, and even then they bite through socks and thin trousers. In theory they should die off in ten days or so, but they are making life here rather unpleasant at the moment!

July 13th

Despite the mosquitoes, Greenland is a beautiful place. The rocks glisten with flecks of pyrite, the lake waters are beautifully clear, the rivers are turbid with glacial flour and as the season progresses the green land is becoming freckled with blooms of cotton flowers. We have seen Arctic foxes and reindeer. The ice is spectacular, changing colour throughout each day as the melt rate waxes and wanes. Melt pools grow and shrink, cryoconite holes deepen and shallow, supraglacial streams swell and shrink and migrate across the ice surface. The colours are whites and blues to greys and greens. It is a magical, beautiful place and we are very lucky to be working here. Today's field work went well. We are ahead of schedule on our science goals and the data is looking good. No sign of the weather changing at the moment either, so we are putting our heads together to come up with more ideas to extend the science programme and make the very most of our time here. When we arrived back at camp to find fellow glacier researchers Marek Stibal, Karen Cameron, Jakub Zarsky and Tyler Kohler (collectively @CryoEco) at camp. It was good to catch up and find out a little about their field season over at Leverett Glacier.

A Greenland lake in summer bloom (ph. M Sweet)

Cotton grass near the ice margin (ph. M Sweet)

Midnight sun over a glacier-fed river

July 14th

Today was another productive day in relatively good weather. Another solid day's worth of data was recorded by all members of the team. Everything ran pretty much according to plan. I had a look over the data so far and am hopeful of some good results, but it will require some deep analysis once back in the UK. I have been sleeping badly since we got here, largely due to the midnight sun and tonight was especially bad. I walked down to the river and read my book in the early hours and it felt like midday.

Cavalli, Edwards and Cook en route to the site (ph. M Sweet)

Observing a cryopond at the site

July 15th

My initial science objectives were met today! The weather has been extremely kind to us thus far and our productivity has been higher than expected. I plan to continue to make further measurements and expand the dataset, whilst also establishing some associated extension experiments. Today was hard going though. The katabatic winds were right back up to full strength and it was bitterly cold at the site, especially once my hands had been in a few cryoconite holes! We are all starting to feel tired after a long stretch of continuous field work, but the end of the first observation period is in sight and everyone's primary science objectives should be in the bag in the next couple of days.

Otti at work (ph. A Edwards)

July 16th

Another hard day weather-wise. It is really the wind that makes things difficult and slows us down. It's also hard work to stabilise the drone in the wind, and I doubt we will have much useful imagery from these very windy days. Thankfully, there have been enough calm days to ensure sufficient data capture, and more importantly, we haven't lost or broken the drone! Again, I decanted samples into

falcon tubes to process back at camp, and the mosquitoes made it very unpleasant. Still, it got done and as a team our minimum science aims have now been met. This is quite a weight off our minds, since data collected from here on in is largely bonus and if the weather or logistics turned against us from tomorrow onwards, we can still be assured of returning home with some science achievements and data to work up in the autumn.

Otti and Arwyn doing lunch

Mile and I: drone selfie

July 17th

We finally took a bit of a rest day today, and gained a new recruit to our camp. Leo Nathan is an MSc student at Aberystwyth University who is working under the supervision of Prof. Alun Hubbard. Leo is flying fixed-wing UAVs over long transects to generate Digital Elevation Model data of several of the rapidly melting glaciers in this region. We visited his original camp, up near Point 660, where he has been building and launching the drones. It was all very impressive stuff, and Leo was very knowledgeable and happy to talk about the project, and made a welcome addition to the team.

Field site panorama (M Sweet)

The team by one of many dramatic and picturesque cryoponds (M Sweet)

July 18th

Today was a final day of measurements at the original field site and was relatively routine. Leo cooked dinner tonight and it was a damn fine spaghetti bolognese (although our resident Italian may disagree)!

July 19th

Today we pulled our equipment out ready to change field site. This meant dismantling the loggers we had set up, collecting in pieces of equipment and markers, and generally leaving the place as pristine as we found it. This took the morning and we were off the ice just after 1pm. We had some lunch and then went to another nearby glacier to scope out possible access points for obtaining some basal ice samples. On the way we encountered a family of six musk oxen, including two very small calves. Mike and I took a walk over to another nearby glacier and watched the calving ice for a while before dinner. The sun is starting to get lower in the sky at night now, and this evening was especially beautiful down at the river. I sat there and read until it was late and eventually too cold to be out of a tent.

One of the bigger musk ox (M Sweet)

Musk ox family (M Sweet)

July 20th

Today was Otti's final day in Greenland with us. To make it a good one, we took a trip to Russell Glacier, where we watched the glacier calve. This site has changed dramatically since my last visit in 2014, having undergone some major calving and slumping. If there is some out there, I'd love to see some time lapse imagery of this piece of ice. We had some lunch and did some reconnaissance for a future research idea before walking out. Back at camp, we had a good sort out of our field kit, rearranged the tents and packed up gear that Otti would take back to the UK. We also organised the equipment that the remaining team members would need for the rest of the trip and nailed down some further research plans for the final leg of the trip. I stupidly fell asleep out in the open and woke up having been feasted upon by mosquitoes – my face looks like a sheet of bubble wrap!

The calving face of Rusell Glacier

The ice cave and calving face of Russell Glacier

July 21st

Today was not a good day. We awoke as usual and ate breakfast, then piled into the truck to drive Otti to town in time for her flight. About 12 km from Kangerlussuaq we were involved in a collision with another vehicle and had to evacuate to KISS. Thankfully nobody was hurt, but there was damage to both vehicles. A police report was filed and the rest of the day was spent trying to contact relevant insurance agencies and our university contacts.

July 22nd:

Today we necessarily stayed in KISS to try to sort out the vehicle issues. While we wait, the last of pour funds are evaporating in accommodation costs, plus food etc and we are without a vehicle to get to a field site to extend our science! We also have the additional problem that our camp is still established at the ice margin… Late in the evening two cancellations were made for tomorrow's flight out of Kangerlussuaq, so Arwyn and I snapped them up. With Otti already home safe and sound, and Mike's flights only two days away anyway, this was seen as the most prudent damage limitation option. An extremely kind offer of a lift out to decamp by a University of Essex research group meant we could quickly get our kit packed up in time to bail tomorrow.

July 23rd:
It is with heavy heart that we leave Greenland today. However, we managed to achieve our primary science aims before the collision, and everyone is leaving injury free. So overall, although we are a few days early retreating from Greenland, we have the data we need to produce our manuscripts as planned and have loads of images and footage for outreach and analysis. We have met some great folks and seen an incredible part of the planet, and should produce some science publications as a result. However, two secondary objectives that were scheduled for the last few days were not met: depth sampling in a crevasse and bulk sampling of cryoconite. Things could have been a whole lot worse and we are now looking forward to getting stuck into analysing and writing up our findings!

Finances

We here provide an outline of our expenditure and grant income to aid the budgeting of future projects. We were extremely frugal in our approach to the expedition in that we established a field camp to avoid unnecessary accommodation costs, reduce transport costs and maximise time at the field site. We ate mostly freeze-dried food pouches from 'Adventure Food' (which we decided were both the most enjoyable, nutritious and cost-effective of several brands tested) for our evening meals, porridge with chocolate spread or jam for breakfast and tinned fish with bread purchased from Kangerlussuaq for lunch. We also had chocolate bars, biscuits and tinned fruit. Insurance was

provided by our respective universities. Equipment costs were mainly covered by personal expenditure, while some science equipment was bought using grant money. Our grant money was mostly spent on travel, food, vehicle hire, Iridium phone hire and brief periods of accommodation in Kangerlussuaq during transit to and from the field site. We provide two tables below, one summarising our expenditure and a second showing our grant income.

Expenditure:

Expenditure Type	**Cost (£GBP)**	
Food	914.21	
Flights	3661.22	
Vehicle Hire	1618	
UK Transport	251.90	
CPN Transport	29.75	
CPN Accommodation	552.06	
Science Equipment	442.84	
Baggage Charges	946.25	
Science station fee	550.40	**Total**
Iridium Phone rental	263	**9229.63**

Grant Income:

Source	**Amount (£GBP)**	
British Society for Geomorphology	3400	
Mount Everest Foundation	2000	
Gino Watkins Memorial Fund	1200	
Gilchrist Educational Trust	1000	
Andrew Croft Memorial Fund	900	
Scottish Arctic Club	200	**Total:**
Gradconsult	200	**8900**

The final shortfall was covered by contributions from our universities and personal expenditure.

Final Thoughts

Our data still requires further analyses. Further materials e.g. videos and scientific publications are forthcoming.