FINAL REPORT

Gathering ice thickness data on the western margin of the Greenland Ice Sheet (October 2018)

Figure 1. Leverett Glacier basking in evening sunlight. This view formed part of our spectacular daily commute onto the ice sheet. (Photo: Andrew Sole)

Introduction

Over the last decade or so, the Greenland Ice Sheet has lost on average approximately 300 billion tonnes of ice each year, which enters the surrounding oceans and contributes just under 1 mm/yr to global sea level rise. Currently about 60% of this loss is derived from surface ice melt and runoff, while the remaining 40% is lost via discharge of ice directly into the oceans (iceberg calving). The former process is controlled by the balance of accumulation and ablation processes (surface mass balance), while the latter is a response to changes in ice flow (or 'dynamics'). These two main routes for mass loss do not act in isolation; on the contrary, they are intrinsically linked. Increased ice flow into the ocean can draw-down ice from the interior of the ice sheet, reducing the elevation of the ice surface and thus exposing it to higher melt rates, while the transfer of surface-derived meltwater to the ice sheet bed can affect the rate of ice flow, and thus iceberg calving too.

Much research in west Greenland (around Russell and Leverett Glaciers – see Figures 1 & 2) over the last decade has attempted to quantify how melting of the ice sheet surface, which drains to the bed via crevasses and moulins, affects ice flow. This work showed that the flow of ice is most sensitive to rapid variations in the delivery rate of surface-derived meltwater to the ice bed, but that this sensitivity decreases over the course of a summer melt season as the subglacial hydraulic system evolves to accommodate greater volumes of water by forming efficient channels. Combining results from several years' of data from west Greenland has revealed that the ice sheet actually slows down slightly in the face of sustained increases in surface melt, because the efficient channelized drainage system expands year-on-year and drains areas of the bed where water pressures are high leading to an overall increase in friction between the ice and its bed.

However, despite this improved understanding of the physical processes occurring beneath the ice on seasonal and inter-annual timeframes, models of subglacial water flow have struggled to reproduce the observed flow pathways beneath this portion of the ice sheet. This is due to a paucity of ice thickness data with which to force the models (as shown in Figure 2) in the region close to Leverett Glacier. It is this gap in the data which we sought to fill during our October 2018 expedition to Greenland.

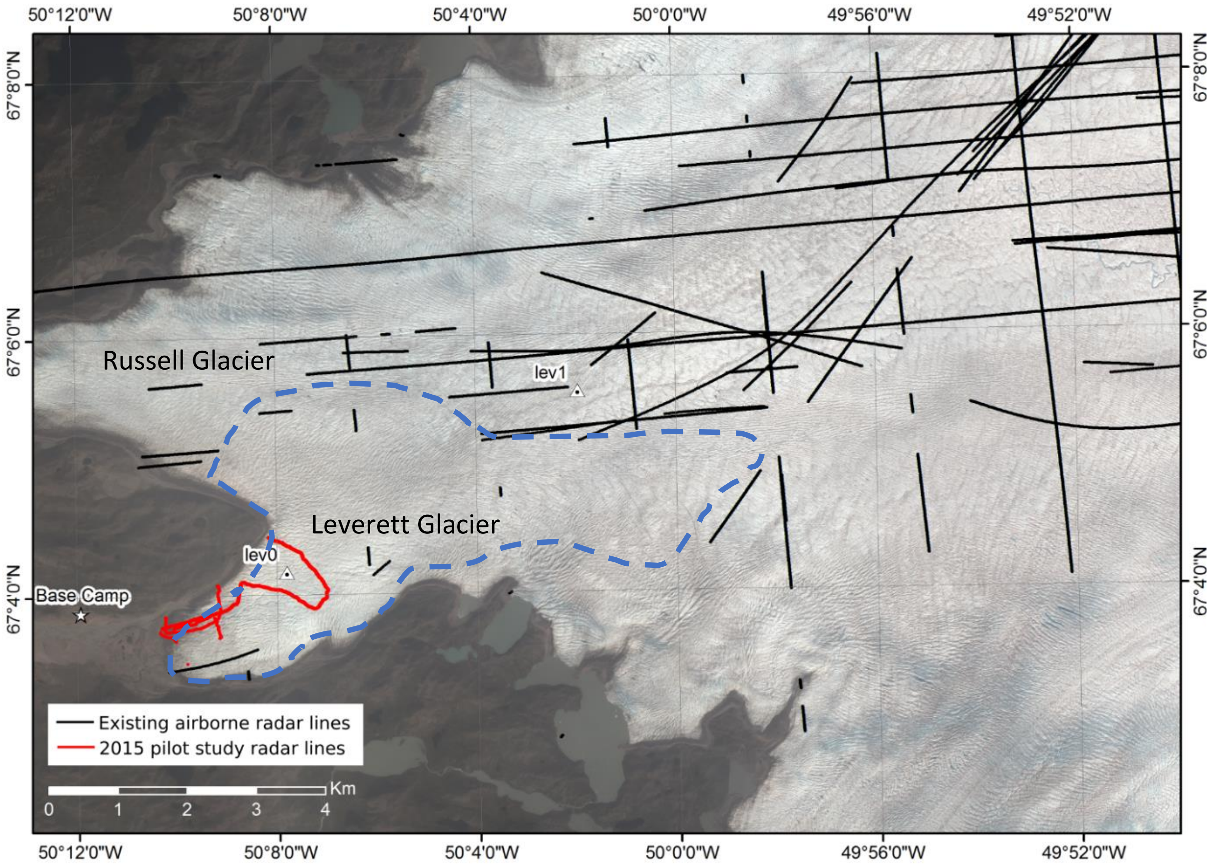

Figure 2. A SPOT (Satellite Pour l'Observation de la Terre) satellite image of our study area, acquired on 4th August 2013, showing our proposed off-ice base station (the base for previous field campaigns – although not used this time due to polar bear risk – see main text for more details), existing airborne radar flight lines, and the radar lines from our pilot study in April 2015. The approximate extent of the data-poor region we hoped to fill is shown as a dashed blue line. The locations of several instrument sites (Lev0 and Lev1 from previous field campaigns in the area) are also shown.

Ice-penetrating radar is used to image the internal structure, thickness and subglacial environments of glaciers and ice sheets. Lines of ice thickness data derived from ice-penetrating radar can be incorporated into mass conservation methods to produce gridded ice thickness and bed elevation data products (e.g. BedMachine). These work by filling in data gaps based on the physics of ice flow combined with upstream ice thickness and ice velocity measurements to produce continuous fields of ice thickness and bed topography for use in numerical models of ice sheet flow and behaviour. In addition to understanding future ice sheet evolution, direct ice thickness measurements are vital for determining current ice volume (e.g. to assess the total potential future sea level contribution). Airborne ice-penetrating radar data coverage is patchy in marginal areas where the ice sheet's surface is rough and heavily crevassed, as the disrupted surface confounds the retrieval of a strong signal from the ice-bed interface. We carried out a pilot study in 2015 that demonstrated the ability of a ground-based (human-hauled) ice-penetrating radar system to retrieve good quality ice thickness data in the very regions where the airborne systems fail.

The aim of our expedition was to build on our pilot study and fill in key gaps in existing airborne radar ice thickness data from the western margin of the Greenland Ice Sheet in order to produce more accurate datasets of bed elevation and ice thickness for use in numerical models of ice flow and water flow beneath the ice.

More specifically, we hoped:

1. To extend our pilot data from our 2015 field campaign on Leverett Glacier up to 15 km east, and several km north

2. To use the data gathered in objective 1 to test a method for estimating ice thickness from the roughness of the ice surface.

Travel & logistics

Flights & equipment: We flew from Manchester to Copenhagen, where we had an overnight stop, before flying on to Kangerlussuaq. This is the typical route for UK researchers to reach the west coast of Greenland. We carried all our scientific equipment as hold and extra luggage, with a total extra cost of approximately £400 each way. We deemed this a better option than freighting the equipment separately by air, as this, although cheaper, had led to delays on previous field expeditions which we could not afford given our tight schedule.

Expedition membership: Unfortunately Stephen Livingstone suffered a recurring knee injury in the week before the expedition departure date. Luckily we were able to recruit Ben Davison (a PhD student supervised by Andrew Sole) to replace Stephen. Ben was ideally suited to join the expedition having recently written a review paper on the links between ice melt and flow in west Greenland, being an experienced climber, and having visited west Greenland in the summer of 2018 as a graduate teaching assistant on a University of Sheffield masters field class run by Andrew Sole.

Polar bears: Polar bears have historically been extremely rare in and around Kangerlussuaq, with only one having been seen in the last decade. On arrival in Kangerlussuaq, however, Chris Sorensen (the manager of Kangerlussuaq International Science Support – where we would be staying) informed us that two bears had been seen over the summer, and one had unfortunately had to be shot in Kangerlussuaq itself the week prior to our arrival. Given that we had not come prepared with equipment to mitigate and protect against bad bear encounters, we decided that instead of camping beside the ice (as we had originally planned), we would stay in Kangerlussuaq and travel to and from the ice sheet each day in a vehicle and then on foot. This added ~12 km to our daily walking 'commute', and added extra cost (accommodation and transfer to the ice sheet), but enabled us to more effectively charge the radar batteries (which required a full day in above-zero conditions), and was we decided, necessary on safety grounds.

Equipment notes

Radar: We used an Icefield Instruments Inc. 5-20 MHz radar, dragged manually across the ice surface. This method, although time (and energy) consuming, can produce superior results to airborne surveys because the system uses a lower-frequency of radio-wave and the radar antennas are in direct contact with the ice sheet surface. These systems are able to resolve thinner ice near the margin, where airborne radars can struggle to image the ice sheet bed, and we were also able to avoid more heavily-crevassed regions, which interfere with good radar data retrieval.

We used two Aiguille Apline Snowsled polar pulks, separated by about 20 m to house the radar transmitter and receiver, with the radar antennas attached to climbing cord fore and aft of, and between each pulk. For safe glacier travel, we needed to move roped together, so the antennas and cord were also loosely attached to a 60 m climbing rope to which we were tied. Each pulk had a tether attached so that the second and third person could guide the radar system over uneven terrain (of which there was plenty), with the first person pulling the system. The climbing cord between the pulks was set to be slightly shorter than the antennas, isolating the relatively fragile antennas from any tension. The radar transmitter and receiver are each supplied in a sturdy plastic case, which we attached to the pulk with a small elasticated cargo net, and bungee cords. This, along with the climbing cord, ensured that the radar remained in the pulk, even if the pulk flipped over (Figure 3). This setup worked well and was robust to the rigours of tens of kilometres of travel over uneven glacier surface – and even survived a brief foray into a crevasse!

The radar was powered by three 7.2 amp-hour rechargeable lithium ion batteries. Lithium ion batteries retain their charge for longer in cold conditions, but must be recharged in conditions with a temperature greater than 0°C to avoid damage. Our batteries operated at 14.8 V, so could only be effectively charged by un-regulated solar panels. Because it was October daylight was limited, and since we were also not camping, a full battery recharge required a day in Kangerlussuaq. Each full charge would last for two days on the ice, with a lower voltage top-up overnight. We thus adopted a 'two days on, one day off' structure to the radar data gathering, which, in addition to enabling battery charging, also meant that we could analyse the data in real-time to better inform radar settings and acquisition routes for the following days.

Figure 3. Ice Radar system set up. The radar transmitter and receiver are each housed in a plastic pulk, separated by approximately 20 m. The radar antennas are attached to climbing cord which connects the pulks and radar transmitter and receiver, and also extends in front of and behind them. The whole system is loosely attached to a 60 m climbing rope to which expedition members are attached. (Photo: Andrew Sole)

Expedition diary

Our expedition took place between the 5 and 20th October 2018 inclusive. We chose this period to ensure that there would be very little liquid water present on or in the ice (as this reduces the radar's effectiveness), but also that we would have sufficient daylight to acquire a good amount of radar data, and to keep our base camp batteries topped up using solar panels. In the end, due to recent (historically unusual) polar bear activity around the town of Kangerlussuaq, we amended our plans slightly and did not camp (see 'Travel & logistics' above). Based on our 'two days on, one day off' routine (as discussed above), we were on the ice on October 8th - 11th, 13th - 14th, 16th - 17th, during which time we gathered some 40 km of good radar data. Temperatures at ~670 m elevation on the ice sheet varied between 1 and -25 °C during this period (see Figure 4) – our on-ice radar traces went from 270 m at the ice margin, up to 560 m.

Friday, October 5th: We met at Manchester airport, and re-configured personal kit and field equipment. We had booked an extra bag each, so with the 2 x 23 kg allowance, we did not need excess baggage on this leg of the journey. We flew to Copenhagen with SAS at 12.35 which took ~1h 50.

Saturday, October 6th: Our flight to Kangerlussuaq left Copenhagen at 11.00, giving us plenty of time to rearrange our baggage as Air Greenland only allow 20 kg of hold luggage, and the only way to get more is to pay for excess baggage. We had ~60 kg of excess which cost ~£400. The flight took ~3hr 40, but due to the time difference we arrived at 11.40 local time. On arrival in Kangerlussuaq, Chris Sorensen of KISS collected us from the airport and delivered us at KISS. This is when we discovered that a polar bear had been shot in Kangerlussuaq the week before we arrived, so in the afternoon we met to consider our options. In the end all expedition members agreed that with long periods of darkness, and without the requisite bear deterrents and warning equipment, camping beside the ice sheet would be too risky. We therefore arranged with Chris to be dropped close to the ice sheet each morning and collected each evening (there is a rough track that gets within 6 km of our radar area). This added extra expense, and lengthened our daily walk somewhat, but allowed full battery charges and real-time data analysis as mentioned previously.

In the afternoon Andrew Sole and Neil Ross set up and tested the radar on a sandy river bed to the east of Kangerlussuaq. Ben Davison helped Clay Prater (a post-doc at Loghborough University who Andrew Sole had met on a previous trip to Greenland) retrieve some heavy and bulky equipment - used to measure dust transport – to prevent damage over winter.

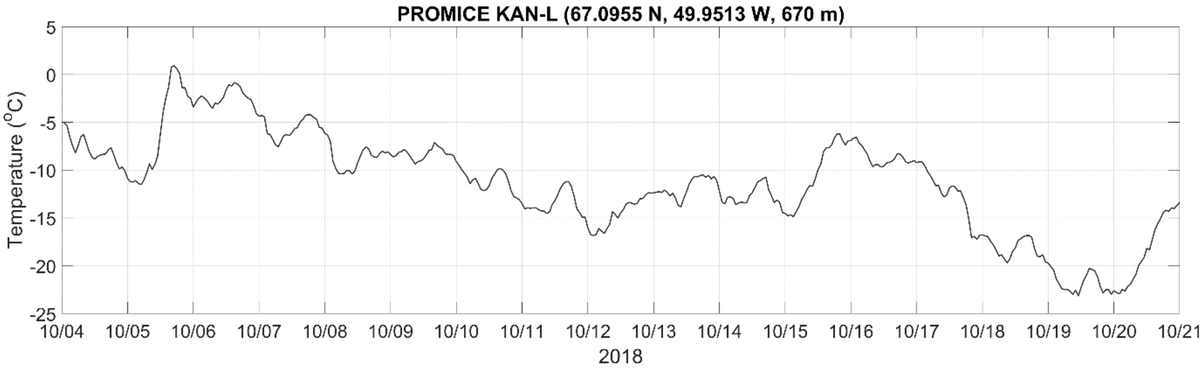

Figure 4. Atmospheric temperature data for a point on the ice sheet at 670 m elevation close to our expedition area. Our radar acquisitions covered an elevation range of 270 m (at the ice sheet margin) to 560 m (at our furthest point from the margin). Given typical lapse rates, we routinely encountered temperatures as low as at least -15°C while on the ice.

Sunday, October 7th: Andrew Sole and Neil Ross tweaked the radar set-up based on yesterday's test, while Ben Davison helped retrieve more of Clay Prater's equipment.

Monday, October 8th: This was our on-ice test day for the radar (see Figure 8). Clay Prater helped us to transfer the radar, glacier travel equipment and bulks to the ice sheet. We attached the radar to the pulks and set up the antennas and climbing cord in bitterly cold and windy conditions (gloves off for just a minute at a time for knot tying!) at the snout of Leverett Glacier. We completed a 2 km test foray onto Leverett Glacier, during which the radar set-up worked well and recorded some good quality data. On our return journey we took the chance to have a look at the subglacial water outflow portal at Leverett Glacier, which in summer discharges meltwater at a rate of >400 m^3s^{-1} from a 600 km^2 catchment.

Figure 5. The subglacial water flow exit portal at Leverett Glacier (with Neil Ross for scale). (Photo: Andrew Sole)

Tuesday, October 9th: After yesterday's successful on-ice test we were keen to take the radar further from the ice margin, beyond the extent of our 2015 pilot data. We headed north-east up Leverett Glacier across some relatively steep and high relief terrain. The radar continued to function well, but it was exhausting work! Where their orientation coincided with our planned route, we used the frozen beds of supraglacial streams and lakes as our route across the ice. The going was much tougher (for us and the radar) when travelling against the 'grain' (mainly frozen streams) of the ice surface as we had

Figure 6. Example ice surface topography on Leverett Glacier. One of the radar pulks is visible to the right of the photo. (Photo: Andrew Sole)

to continuously climb and descend steep icy hills of ~6 m in height. Towards the end of the day we noticed that the batteries were running down fairly quickly, despite our set-up including a 5 W solar panel to continuously charge them. At one point we strayed into the crevassed region between Leverett and Russell Glaciers and had to turn back. Later analysis showed that we had crossed into a 'rough' part of the glacier based on our pre-expedition satellite-derived map. We managed 6 km of good radar data.

Wednesday, October 10th: During the walk in to the ice sheet we attached a 15 W solar panel in an attempt to charge the batteries, but this did not seem to have much effect (likely due to the very cold temperatures). We therefore left the batteries attached to the solar panel at the ice sheet margin for an hour or so. This charged them partially and we managed a further ~3 km of on-ice data.

Thursday, October 11th: We decided to use the remaining charge to gather a little more radar data (~ 1 km), and then to use our walk back to the pick-up point as a recce for our move to Russell Glacier the following week. We found a good access point on Russell Glacier, and also thought that we could move the radar between the glaciers on the ice, but very close to the margin where the surface was smoother. We also decided that tomorrow we would have to stay in Kangerlussuaq to fully charge the batteries.

Figure 7. The crevassed region between Russell Glacier (left) and Leverett Glacier (right). The route we chose to transfer between the two at the ice margin is visible as the dusty flat ice area. (Photo: Andrew Sole)

Friday, October 12th: This was our first rest and battery recharge day. We had a look at the data we had collected so far and planned where to take the radar tomorrow to best fill the gaps in the airborne radar dataset.

Saturday, October 13th: Batteries fully charged, and legs fully rested, we were excited to get a full day of data collection. We set off through light snow east across Leverett Glacier before turning north-east away from the ice sheet margin for a further 2 km. This would be our furthest point from the Leverett Glacier margin. In total we covered ~7.5 km on the ice.

Sunday, October 14th: The batteries had retained their charge well, so we headed off for another day on the ice. This was our final day on Leverett Glacier as we planned to transfer to Russell after our battery charging day tomorrow. We followed a similar route to yesterday, but filled in a gap in our data over the centre of Leverett Glacier. We also retraced a section of yesterday's route where one of the radar batteries had reached the cut-off voltage. We managed a further 7 km of data.

Monday, October 15th: Second battery charge and rest day.

Tuesday, October 16th: Today we transferred the radar set-up from Leverett to Russell Glacier by tracing a relatively smooth route around the ice margin. We then headed off to the north-east across Russell Glacier. Despite having seemed relatively 'smooth' from our recce last week, the surface was in fact quite crevassed and snow covered. This made for some tortuous route finding as we had to ensure that the pulks did not flip over or fall into a crevasse. However, we nevertheless covered a further 7 km.

Date	Day	Programme
05-Oct-18	Friday	Fly UK to Copenhagen
06-Oct-18	Saturday	Fly Copenhagen to Kangerlussuaq. Set up & test radar, help Clay Prater (post-doc at Loughborough University) retrieve equipment used to monitor aeolian processes and fertilisation of subaerial lakes around Kangerlussuaq to avoid damage over winter
07-Oct-18	Sunday	Prepare radar for use on ice (attach to pulks, attach tethers), help Clay Prater retrieve more equipment
08-Oct-18	Monday	On-ice radar (test): ~2 km good data acquired + Clay helped carry in radar and pulks and had a go on the ice
09-Oct-18	Tuesday	On-ice radar: ~6 km good data acquired
10-Oct-18	Wednesday	On-ice radar: ~3 km good data acquired
11-Oct-18	Thursday	On-ice radar: ~1 km (battery cut-off voltage reached)
12-Oct-18	Friday	Rest day & battery charging
13-Oct-18	Saturday	On-ice radar: ~7.5 km good data acquired
14-Oct-18	Sunday	On-ice radar: ~7 km good data acquired
15-Oct-18	Monday	Rest day & battery charging
16-Oct-18	Tuesday	On-ice radar: ~7.5 km good data acquired
17-Oct-18	Wednesday	On-ice radar: ~6 km good data acquired
18-Oct-18	Thursday	Collect equipment from a previous cache for safe storage in Kangerlussuaq over winter. Pack up equipment for travel.
19-Oct-18	Friday	Fly Kangerlussuaq to Copenhagen
20-Oct-18	Saturday	Fly Copenhagen to UK

Table 1. Summary of expedition activities (see main text for more details).

Wednesday, October 17th: We returned to Russell Glacier for what would be our final day collecting radar data. We followed a route sub-parallel to yesterdays but closer to Leverett Glacier, hugging the intervening heavily crevassed area. By doing this we hoped to be able to discern the subglacial topography in the area which determines whether water flows out beneath Russell or Leverett Glacier. We covered a total of 6 km on the ice.

Thursday, October 18th: We had to retrieve some equipment from a previous trip by Andrew Sole and Ben Davison for safekeeping in Kangerlussuaq over winter. We also drove to the end of the dirt track, where it is possible to easily access the ice sheet to do some filming for Bloomberg (see future work section below). We then packed up the radar and other equipment in preparation for the return journey tomorrow.

Friday, October 19th: We flew from Kangerlussuaq at 11.40, arriving in Copenhagen at 20.00 local time. Similar to the outbound trip, we had ~60 kg of excess baggage which cost ~£400.

Saturday, October 20th: We caught our flight to Manchester at 08.30, arriving at 09.20 local time.

Radar data

In total we gathered ~40 km of good on-ice radar data (Figure 8). We were able to pick out the ice bed clearly along most of the radar lines (see for example Figure 9). We measured ice up to 540 m thick, and also found evidence for layers of sediment several tens of metres thick beneath parts of Russell

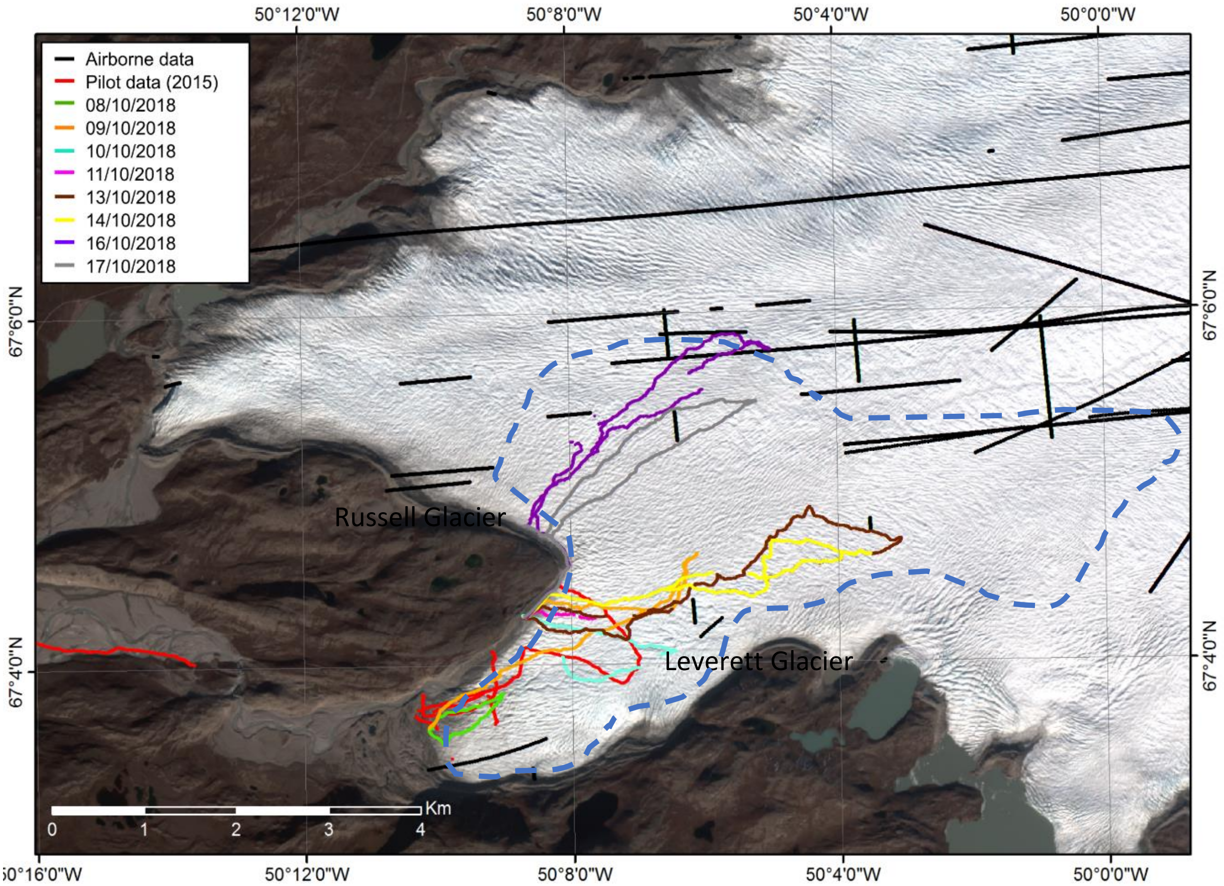

Figure 8. Sentinel-2a satellite image overlain with the traces of our radar data, coloured by date. The approximate extent of the data-poor region we hoped to fill is shown as a dashed blue line. The black lines represent existing airborne radar data, and the red lines represent our pilot data gathered in 2015. Our 2018 lines fill some important gaps around the divergence of Russell and Leverett Glaciers, and should help to elucidate subglacial water flow in this region once they are added to the BedMachine ice thickness dataset.

Glacier. Our radar lines fill in some useful gaps in the existing airborne ice thickness data across both Russell and Leverett Glaciers. As suggested by our pre-expedition satellite analysis, the area between the two glaciers was too heavily crevassed to enable safe crossing with our radar system. Instead we moved from Leverett to Russell Glacier along the ice margin. We were not able to extend our coverage quite as far from the margin as we had hoped due to the extra walk in to the ice necessitated by staying each night in Kangerlussuaq (due to polar bear risk).

We will calibrate our radar data with the existing airborne data where the coverage intersects (e.g. several points on Russell Glacier). Based on our pilot data from 2015, we expect that these new data will significantly improve the accuracy of the BedMachine ice thickness product in this region.

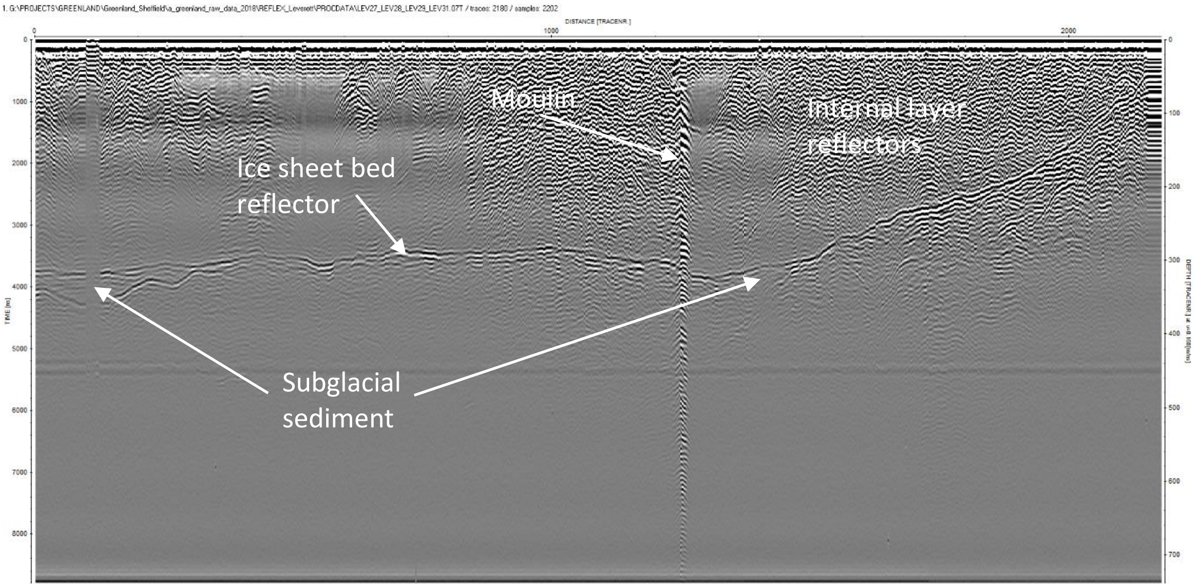

Figure 9. Example radargram from Russell Glacier showing the ice sheet bed. The ice surface is at the top of the image, and the ice bed is the prominent continuous pair of relatively light and dark lines (reflector) just under half way down the image. The ice is thickset to the left of the image, and the bed slopes up towards the ice surface to the right. Reflectors within the ice represent internal layers, or the presence of crevasses and/or moulins which partially reflect the radio waves.

Future work

Radar data analysis: Firstly we will need to 'pick' the bed reflector within each radargram - usually done manually within specialist software. This will produce a dataset of geographical position and ice thickness. We can also calculate the ice bed elevation by subtracting the ice thickness from existing ice surface elevation data. These data will be added to the BedMachine ice thickness mass conservation data product to enable their inclusion into numerical models. We will use the improved BedMachine product to recalculate the subglacial routing of meltwater within the Russell and Leverett Glacier catchments to ascertain whether our additional radar lines increase the fit between the theoretical subglacial water routing and observations of meltwater outflow.

In addition we will quantify the depth of subglacial sediment by 'picking' the base of sediment packages beneath the ice bed (e.g. Figure 9). Very little is known about the amount of subglacial sediment beneath the margin of the ice sheet, yet its presence can affect the relationship between subglacial water pressure and ice dynamics, with potential implications for future sea level rise.

Roughness-ice thickness relationship: Glaciological theory suggests that the roughness and topography of the ice surface over length scales from several meters to tens of kilometres is affected by the topography of the underlying bedrock and sediment. Shallower ice is more likely to be broken up with crevasses as it is forced over bed undulations, while thicker ice is able to accommodate variations in bed topography by deforming internally. We will use our radar ice thickness data (combined with existing similar measurements) to quantify the relationship between ice thickness and surface roughness and test the feasibility of utilizing the ice surface roughness measurements to determine ice thickness in other data-poor regions of the ice sheet.

Bloomberg film on climate change science: Prior to our expedition, Neil Ross was contacted by some journalists from Bloomberg who were interested in a story of scientists conducting field research related to climate change. With this in mind, we recorded some of our on-ice radar data gathering, and also conducted some filmed interviews where Neil provided context for our expedition. We made these videos, along with hundreds of photos available to Bloomberg on our return from Greenland, and they have decided to make a short piece about our trip. They will be visiting Neil in Newcastle in January to undertake some extra filming.

Mt Everest Foundation contribution expenditure

The Mt Everest Foundation's contribution was spent on the expedition permit (£457), travel and accommodation (£2131.31) and equipment (£295.39) as specified in the table below. Remaining costs were covered by a grant from the White Rose University Consortium, and contributions from the University of Sheffield and Newcastle University.

Date	Company	What for	Amount (£)
20/09/2018	Windward Marine Limited	VHF radio (required safety equipment for permit)	215.90
25/09/2018	SAGA Hotel	Copenhagen Hotel outbound (2 pers)	139.99
18/09/2018	Air Greenland	Flights (3 pers)	1,761.44
26/09/2018	Park Inn	Copenhagen Hotel return (2 pers)	229.88
01/10/2018	Go Outdoors	Fleece	79.49
02/10/2018	Greenland Government	Exped permit	457.00
		TOTAL	**2,883.70**

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