MOUNT EVEREST FOUNDATION

Patron: HRH The Duke of Edinburgh KG KT

BMC BRITISH MOUNTAINEERING COUNCIL

FINAL REPORT

from an MEF and/or BMC SUPPORTED EXPEDITION

1 - Name of Expedition: The first detailed and robust structural glaciological analysis of a highly dynamic calving glacier in south-east Iceland using ultra-high resolution UAV imagery.

2 - Expedition Leader/Organiser: Mr Nathaniel Ross Baurley
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3 - MEF reference: 21-07 BMC reference: N/A

4 - Country/Region: Iceland, Southeast region of Vatnajökull.

5 - Names of all expedition members, indicating leader, climbing members, and support:

1) Mr Nathaniel R. Baurley – Expedition Leader.

2) Mr Chris Tomsett – Expedition support/research assistant.

6 - Original objective(s) of expedition – mountaineering / scientific / medical, include location of objective (or study area) with indication of special points of interest (e.g. 'first ascent of NW Ridge') and heights of peaks:

The aim of this research was to undertake a complete structural glaciological analysis of Fjallsjökull, a large and dynamic calving glacier in southeast Iceland, to provide insights into its dynamic and hydrologic nature.

These surveys were completed as planned, but the focus of the research was shifted slightly due to time and logistical constraints while in the field. Primarily, we decided to focus more on the use of the laser-scanner and its ability to accurately delineate surface change and related morphology, rather than look at surface hydrology using the multispectral camera component of our integrated UAV sensor system. This was for three reasons. Firstly, the laser scanner allowed us to more accurately estimate the size and frequency of glacier calving events, which is of interest as glacier calving is known to cause incredibly rapid mass loss and retreat, yet the key processes forcing this behaviour remain poorly understood. Secondly, no study to date has ever used a UAV-mounted laser scanner to survey any glacier anywhere in the world, let alone a lake-terminating calving glacier, and so the findings of this research are extremely novel. Thirdly, in order to obtain the best coverage of the glacier using the laser scanner, we had to fly at quite a low elevation, which although good for the laser scanner, was less desirable for the multispectral imagery as it makes it far more difficult to then stitch this imagery together post-fieldwork, resulting in warped and inaccurate 3D models. Consequently, we decided to focus primarily on obtaining data using the UAV-mounted laser scanner.

It is also important to note that we were not able to fly daily surveys using the UAV-mounted laser scanner, and this was for two reasons: Firstly, we needed to carry all our kit from the carpark (see figure below) to the edge of the glacier, which wasn't too difficult when carrying a standard rucksack, but was far more challenging when carrying a large, bulky, 25 kg pelicase between the two of us across unstable and undulating terrain. We needed to transport the UAV this way as it was the only way we could move the UAV itself, as well as all the additional kit (e.g. the laser scanner) to the glacier safely and securely. Secondly, and linked to the first point, I was primarily in Iceland to collect data for my own PhD research, using a different model of UAV, and as a result data collection for this had to take priority. Therefore, we decided it was best to prioritise collecting data for my PhD every day using the 'other' UAV (where possible), and then on four of these days we also collected UAV-laser scan data, at different temporal intervals (e.g. sub-daily, daily, weekly).

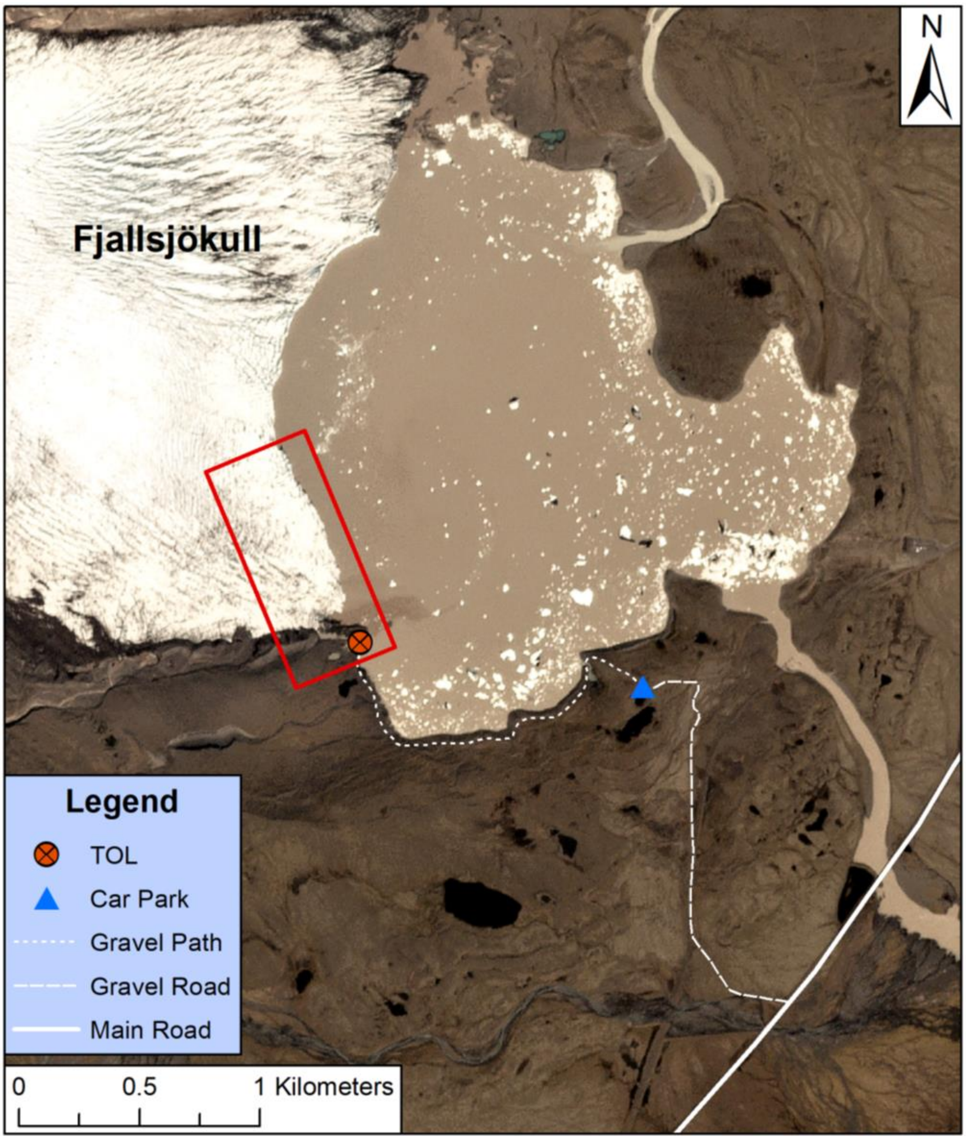

FIGURE 1 Study area map for the research undertaken between the 2nd-16th July 2021. Note the route used to access the glacier (white solid and dashed lines), the UAV take-off and landing site (TOL), and the area covered by the UAV surveys (solid red rectangle).

7 - Overall dates of expedition (e.g. 'March-June 2015'), showing time spent on approach, climbing, and return:

2nd – 16th July 2021

2nd – Arrived in Iceland late afternoon, drove straight to accommodation in SE Iceland (~4 and a half hours away).
3rd – Visited field site for orientation, which was a ~25-minute journey to a 'car park' followed by a 30-45-minute hike to the glacier. Set up ground control point network, marked locations with dGPS, and planned and designed the survey routes for both UAVs (in field for ~5 hours).

4th – Headed to field site to undertake surveys for my PhD. However, this was stopped prematurely due to adverse weather conditions (in the field for ~3 hours).
5th – Adverse weather conditions and so stayed in the accommodation.
6th – Headed to field site to undertake surveys using both UAVs. Weather stayed good so we managed to obtain a full set of UAV surveys using 'my' UAV, and flew two surveys using the integrated UAV system (in the field for ~6 hours).
7th – Headed to field site to undertake surveys for my PhD, with weather remaining good to allow full set of surveys to be obtained (in the field for ~4.5 hours).
8th – Headed to field site to undertake surveys using both UAVs. Weather stayed good so we managed to obtain a full set of UAV surveys using 'my' UAV, and flew two surveys using the integrated UAV system (in the field for ~6 hours).
9th – Headed to field site to undertake surveys using both UAVs. Weather stayed good so we managed to obtain a full set of UAV surveys using 'my' UAV, and flew two surveys using the integrated UAV system (in the field for ~6 hours).
10th-12th – Headed to field site to undertake surveys for my PhD, with weather remaining good to allow full set of surveys to be obtained (in the field for ~4.5 hours).
13th – Adverse weather conditions and so stayed in the accommodation.
14th – Adverse weather conditions and so stayed in the accommodation.
15th – Headed to field site to undertake surveys using both UAVs. Weather stayed good so we managed to obtain a full set of UAV surveys using 'my' UAV, while we flew one survey using the integrated UAV system (in the field for ~4 hours). We then returned to the accommodation, packed up all our kit and luggage and returned to Reykjavik ready for our early flight the next morning.
16th – Early flight out of Keflavik airport to LHR.

8 - Give the following details for each route climbed or attempted:
Name of mountain/crag, altitude, estimated route length, dates, grade, style (eg alpine, fixed rope), whether first ascent, successful or not, high point reached, reason for retreat (if applicable), weather conditions, and names of climbers:

N/A. No routes climbed.

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

We had our research permit from the Vatnajökull National Park authorities, and from the Icelandic Centre for Research on us at all times when in the field in case we were stopped by park rangers. However, this never occurred.

10 - Details of any injury or illness to expedition members/porters:

There were no injuries or illnesses suffered during the fieldwork.

11 - Details of waste disposal:

All food waste eaten and food packaging opened while out in the field was always placed back in our bags and then disposed of properly in the bins back in the accommodation. We were extremely careful with all other forms of rubbish (especially plastic) and made sure we did not leave any behind at the field site at the end of each day. All waste related to sanitation was disposed of correctly in the toilets in the accommodation.

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

Generally, the route from the carpark to the glacier front is relatively straightforward to follow. As was the case in 2019, there is a relatively well-trodden path, and with just backpacks on it only took us ~25 minutes to walk. The route begins by running along part of a large lateral moraine complex before dropping down right next to the lake shore. The route then follows the lake very closely (only about 1-2 m away), before the path then drops down again, this time onto a large, flat relict outwash plain, which by walking across will take you right up to the glacier. Walking further west from this location, directly along the lateral margin of the glacier, would bring you to a location from where you can walk onto the ice directly, although we saw no need to do this during this trip.

However, in comparison to 2019, we had to carry at least one, and sometimes two, large, heavy and unwieldy pelicases between us along this route as it was the only way to safely and efficiently transport all our research equipment. As such, we decided to take a slightly longer route to the glacier in order to avoid any sections of the path that were particularly unstable or uneven. For example, the section of the path that ran close to the lake edge was characterised by lots of loose rocky material and was therefore unstable and difficult to traverse when carrying the equipment, so we instead went up and over the moraine mounds next to the lake, and then cut down to the floodplain in order to avoid this section. It may also be of interest to future parties to know that the glacier is retreating relatively quickly. At least ~100 m of retreat occurred near the southern lateral margin between 2019 and 2021, with significantly greater retreat occurring towards the middle of the glacier. As such, in future it will become increasingly difficult to access the ice safely as the glacier continues to recede and thins at its margins.

It is also worth noting that this glacier is actively calving, and such events can occur at any time, although they tend to occur most frequently in the summer months, particularly in July. When these blocks of ice calve off, they cause tsunami-like waves to propagate outwards from where the ice calved into the water, with the size of the waves depending on the size of the ice lost. We observed a significant number of these calving events during fieldwork in July 2021, with many of these events being particularly large in size (>1000 m^2). Indeed, although the majority of these events often occurred over 1 km away from our position, the waves that reached the shoreline near us were still a good size, and could quite easily knock someone more unaware off their feet into the freezing lake water. Furthermore, several large events also occurred less than 1 km from our location, with the waves that resulted from these events being sufficient to significantly inundate the shoreline in a very short period of time. Therefore, it is advisable that if someone hears a calving event occurring (signalled by a very loud cracking sound as the ice fractures) that they immediately head for higher ground or away from the lake edge until the waves have dissipated.

13 - Summary of exhibition accounts, including income and expenditure:

<u>Income</u>:

Grants awarded: 1) MEF: £1350.

2) Royal Geographical Society: £1000.

Personal Contributions: 1) Own savings: £322.93.

2) From my PhD personal research budget: ~£1862.07 (used pre-fieldwork to pay for flights and excess baggage, and post-fieldwork to cover the travel costs to/from LHR, and to claim back on the PCR, fuel and subsistence costs).

<u>Total Income</u>: £4535.00.

<u>Expenditure</u>:

2x PCR tests pre-travel to Iceland: £298.00.

2x PCR tests pre-travel before returning to UK: £88.52.

2x PCR tests within two days of returning to UK: £139.98.

Return flights (including 4x pieces of extra hold luggage): £484.24 (+£300.90): £785.14.

Travel to/from Heathrow airport (fuel costs): £42.50.

4x4 Hire car for 14 days (includes full insurance and extra driver): £1303.24.

Fuel costs: ~£249.07.

Accommodation for 14 nights: £1409.66.

Subsistence: ~£258.86.

<u>Total Expenditure</u>: ~£4535.00.

14 - Photographs of glaciers for comparison with past/present images:

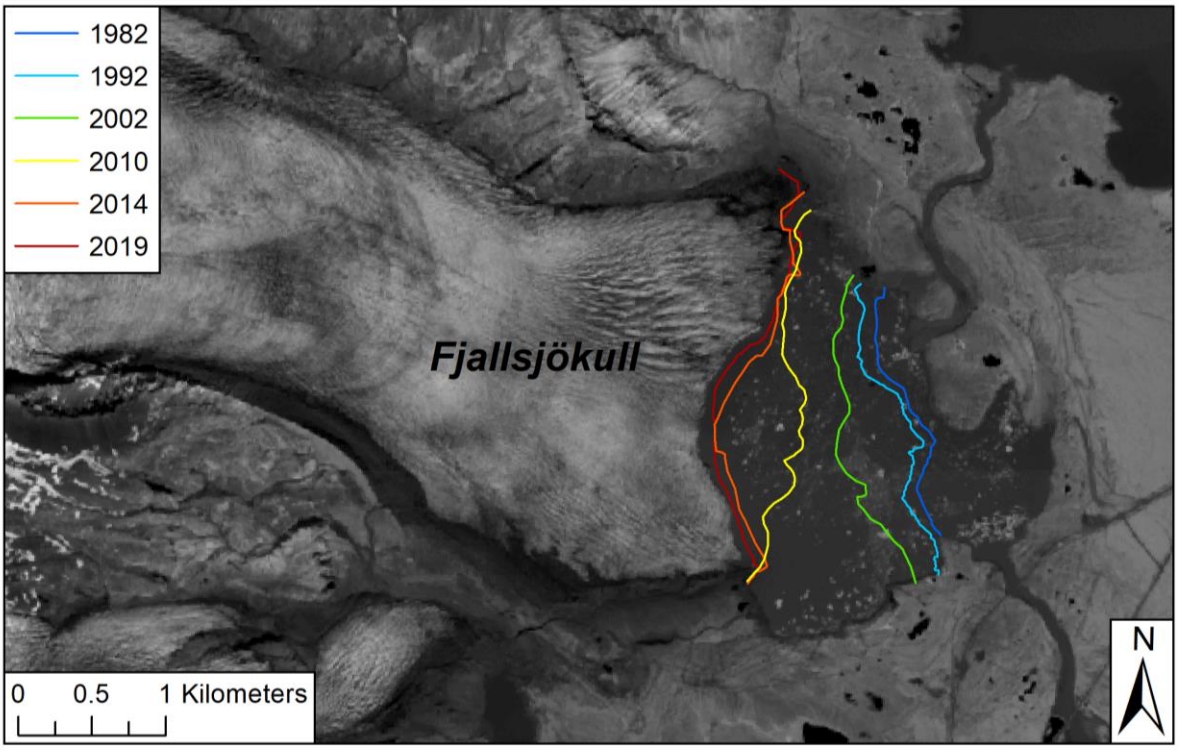

FIGURE 2 Change in the terminus position of Fjallsjökull since 1982. Note the clear pattern of retreat occurring over recent years, particularly since ~2002. Also note how as the glacier has retreated the area of the lake has also increased. Background image is from 7th July 2021.

Fjallsjökull, like many outlet glaciers in Iceland, has undergone significant change over recent decades (i.e. frontal retreat and mass loss). Figure 2 above illustrates the frontal retreat of the glacier since 1982, with each coloured line representing the glacier frontal position at a previous time. To show this slightly differently, Figure 3 below shows an image of the lower portion of Fjallsjökull from six different dates since 1982. Like Figure 2, it clearly shows that rapid retreat began after 2001, and again clearly shows the corresponding increase in lake area as the glacier has retreated. Since the mid-1970s the glacier has retreated by ~1.21 km, resulting in an increase in lake area of ~2.72 km^2 and a 40% increase in the portion of the terminus that is in contact with the lake. As of 2018 the lake covered a total area of ~3.7 km^2 (at a growth rate of ~0.1 km^2 a^{-1}), and observations suggest that practically all of the glacier terminus is now in contact with the lake.

This is important as it indicates that the process of calving (where icebergs calve from the glacier front) is likely to be the primary driver behind the recent retreat of Fjallsjökull, with these processes themselves likely forced by the growth of the lake and the deep bedrock topography under the glacier. Such processes can cause a glacier to become decoupled from climate (at least partially), leading to far greater mass loss and retreat than would otherwise be observed if the behaviour of these glaciers was being forced solely by climate (i.e. if they did not terminate in a lake). Indeed, recent analysis has shown that since 1990 nearly three times as much retreat has occurred at the lake-terminating margin of Fjallsjökull than at the land-terminating margin (1554 m compared to 576 m), equating to a retreat rate of -52 m a^{-1} and -19 m a^{-1} respectively, despite both regions undergoing the same climatic forcing (+0.4°C) during this time.

This clearly indicates that the retreat of the lake-terminating margin during this time has likely been primarily forced by glacier specific factors (i.e. the growth of the lake, influence of bedrock topography and calving processes), rather than by solely rising air temperatures in the region. Furthermore, due to the majority of the terminus now being in contact with the lake, it is likely that this rapid retreat will continue until the glacier retreats out of the lake and can begin to stabilise. It is, therefore, important to continue our research into this glacier to help better predict its future response.

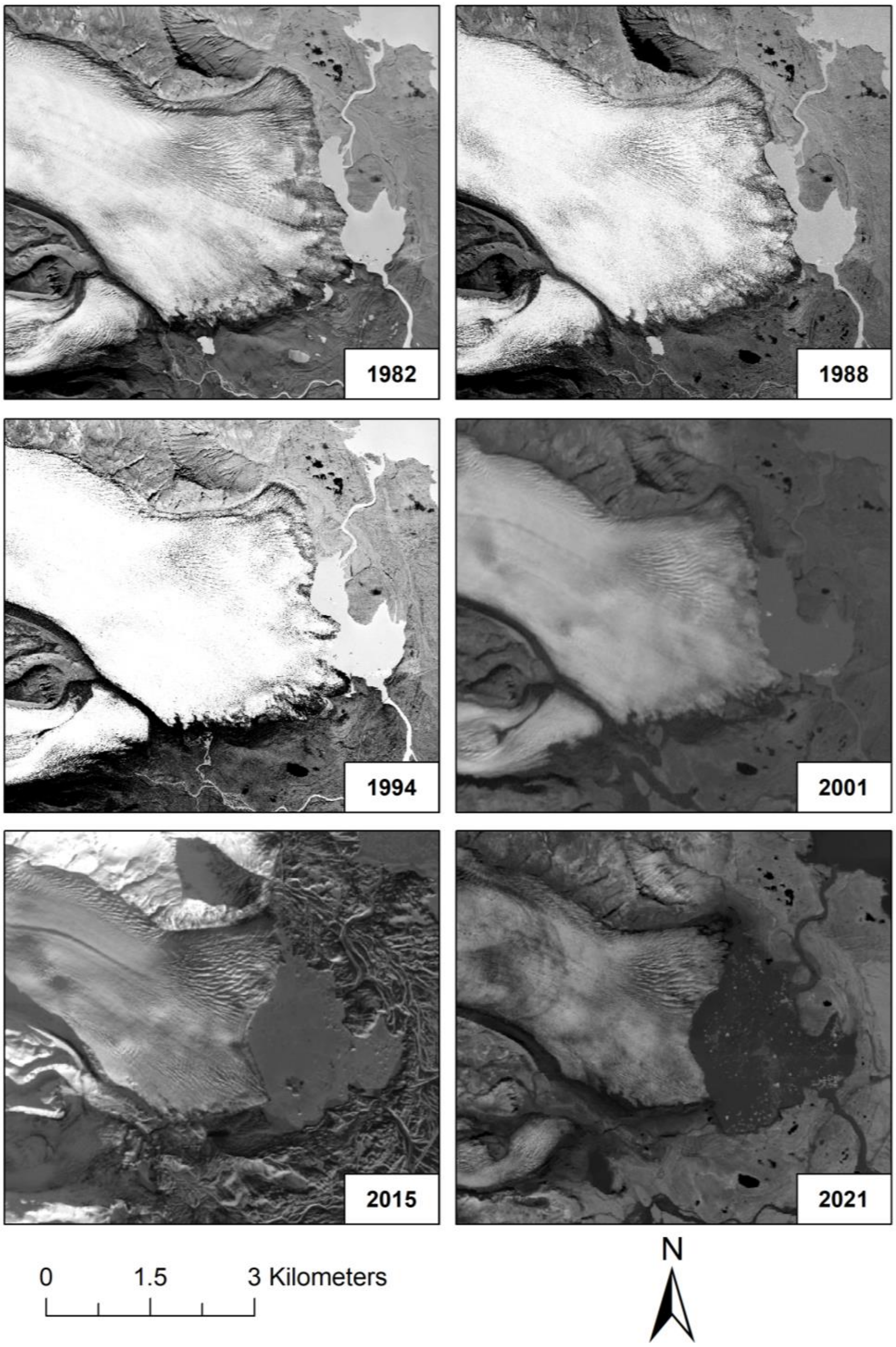

FIGURE 3 The retreat and mass loss of Fjallsjökull for selected dates since 1982. Extensive retreat (laterally as well as frontal) can be seen to have occurred over this period. It is also clear that the area of the adjacent proglacial lake has also increased considerably over this period. The images from 1982, 1988 and 1994 are black and white aerial photos, while the images from 2001, 2015 and 2021 are satellite images shown in greyscale**.**

15 - Observations/accuracy of Google Earth imagery:

Google Earth is an extremely useful tool in scientific research. It is free, simple to use and allows you to undertake some basic analyses. The resolution of the imagery is particularly good for planning trips and exhibitions as well as analysing landscape change and evolution using the historical images tool. Such imagery can then be exported resulting in high quality maps of landforms, features and landscapes.

However, for more in-depth analyses, such as those undertaken in this study, it is beneficial to use commercially-available satellite imagery, such as those acquired by the Sentinel satellites. These images are acquired every 12 days over the entirety of the Earths' surface at a resolution of 10 m. Such imagery cannot be obtained from Google Earth. Data acquired this way can also be imported into GIS software, such as ArcGIS, which allows the user to undertake a wide variety of additional processing and analyses on their data.

Therefore, Google Earth certainly has its merits in exhibition and route planning, however, if thorough analyses are required, as is often the case in scientific research, then it is more beneficial to utilise different imagery and GIS software to undertake this analysis.

16 - Suggestions for new routes or new subjects for study in the area:

As discussed previously, the process of calving, resulting from the increase in lake area and underlying bedrock topography, combined with rising air temperatures, is causing increasingly rapid glacier retreat at Fjallsjökull. This is also true for the neighbouring glacier to Fjallsjökull, Breiðamerkurjökull, which has seen over 3.5 km of retreat since 1982, with the majority of this occurring since the early 2000s, and which coincided with the increase of its proglacial lake and retreat into its deep (300 m) bedrock trough. However, this response may not be solely limited to these two glaciers, as there is a strong possibility that the other southern outlets of Vatnajökull will undergo a similar pattern of retreat and mass loss in future. Indeed, many of these glaciers are also underlain by deep bedrock troughs, and have also been retreating rapidly since the end of the Little Ice Age, meaning they have also seen the development and growth of large proglacial lakes at their termini during this time. Yet while at present these lakes are currently situated in the outermost part of these bedrock troughs, this means they are likely to further grow in size as these glaciers continue to retreat rapidly in response to warming air temperatures. This will cause these glaciers to recede down their reverse-sloping beds into deeper water, causing calving processes to become the primary driver of change and likely initiating a dynamic response similar to what has already been observed at Fjallsjökull and Breiðamerkurjökull.

However, there is much we still do not understand about glacier calving, particularly how the process varies between glaciers and regions. There is, therefore, a need to further our understanding of these processes and how this will impact upon the future response of calving glaciers. Iceland is the perfect place to do this as access to its calving glaciers is relatively straightforward, meaning a large amount of quality research can be undertaken on these 'natural laboratories', the data of which can then be applied to other calving glaciers worldwide, such as those from the two ice sheets. Such research would involve UAV surveys, satellite imagery, laser scanning and monitoring/recording equipment set up on the ice surface to obtain a full picture of the calving activity and dynamic response occurring at these glaciers.

A key limitation of this fieldwork was that I was again not able to fully survey the entire calving front of Fjallsjökull due to the fact the UAV had to operate at a relatively low flying height in order to obtain the most detailed scan data. Flying at a low height, and at relatively slow speeds, means less area can be covered than if you were to fly at a higher elevation and at faster speeds. However, technological improvements in UAV longevity are constantly being made, which means that in future we should be able to obtain coverage over the whole calving front in just one flight. Indeed, we have recently acquired a UAV system with laser scanner attachment that has a much longer flying time than the one we utilised in July 2021, so we hope in future we will be able to undertake some further research with this model. Furthermore, because we prioritised the laser scan data, it means we were not able to obtain any multispectral imagery. Future work should also focus on collecting this data as it would complement the laser scan data nicely, and provide in-depth information on the surface hydrology of the glacier, and how this evolves through time.

Finally, once I complete my PhD I will be starting a Post-Doc position at the University of Southampton, where I will be further developing the key themes of my PhD with Iceland once again the field location. As part of this Post-Doc, I am hoping to undertake some surveys of Fjallsjökull using a UAV-mounted ground penetrating radar (GPR). This is an incredibly novel piece of kit, and will provide insights into the hydrology and structure of the basal system under the glacier. Such data is really important as it can provide key insight into the movement and dynamics of glaciers, yet it is incredibly difficult to obtain as the bases of glaciers are usually inaccessible, particularly if the glacier terminates in a large lake. Often these systems are modelled or are studied with probes or boreholes, but this would be the first research of its kind to ever directly image the basal hydrological system of a calving glacier using a UAV-mounted GPR. Apart from being a highly novel piece of a kit, and the research itself being the first of its kind, it is hoped that the data obtained from these surveys will provide new insights into the structure and evolution of these basal systems, which in turn may help us to better predict the future response of glaciers to climate change.

17 - UAV-based laser scanning for the monitoring of glacial processes and interactions:

UAV-based laser scanning (UAV-LS), through the use of an active sensor, emits a pulse of light, with the detection of the reflected pulse resulting in a point cloud with a consistent quality regardless of flight characteristics, wind conditions or illumination conditions at the time of survey. This ability of UAV-LS to obtain continuous and consistent point coverage of a scene, regardless of environmental conditions, is one of its primary advantages relative to those surveys undertaken using traditional UAV imagery. As such, it can result in incredibly dense and highly accurate point clouds being obtained, which can then be used for geomorphic analysis. Yet the method has yet to be deployed in a glacial setting, despite the clear advantages that the method offers glaciologists, and as such that was our aim – to test the suitability of the method for use in glacial research. We also further tested its relative merits by comparing it to the most similar surveying method currently available, UAV-SfM. Some of the results obtained so far are given below for the interest of MEF, its trustees and members, whilst the full article and its findings will be published in a leading scientific journal in the coming months.

(i) Changes in Surface Elevation

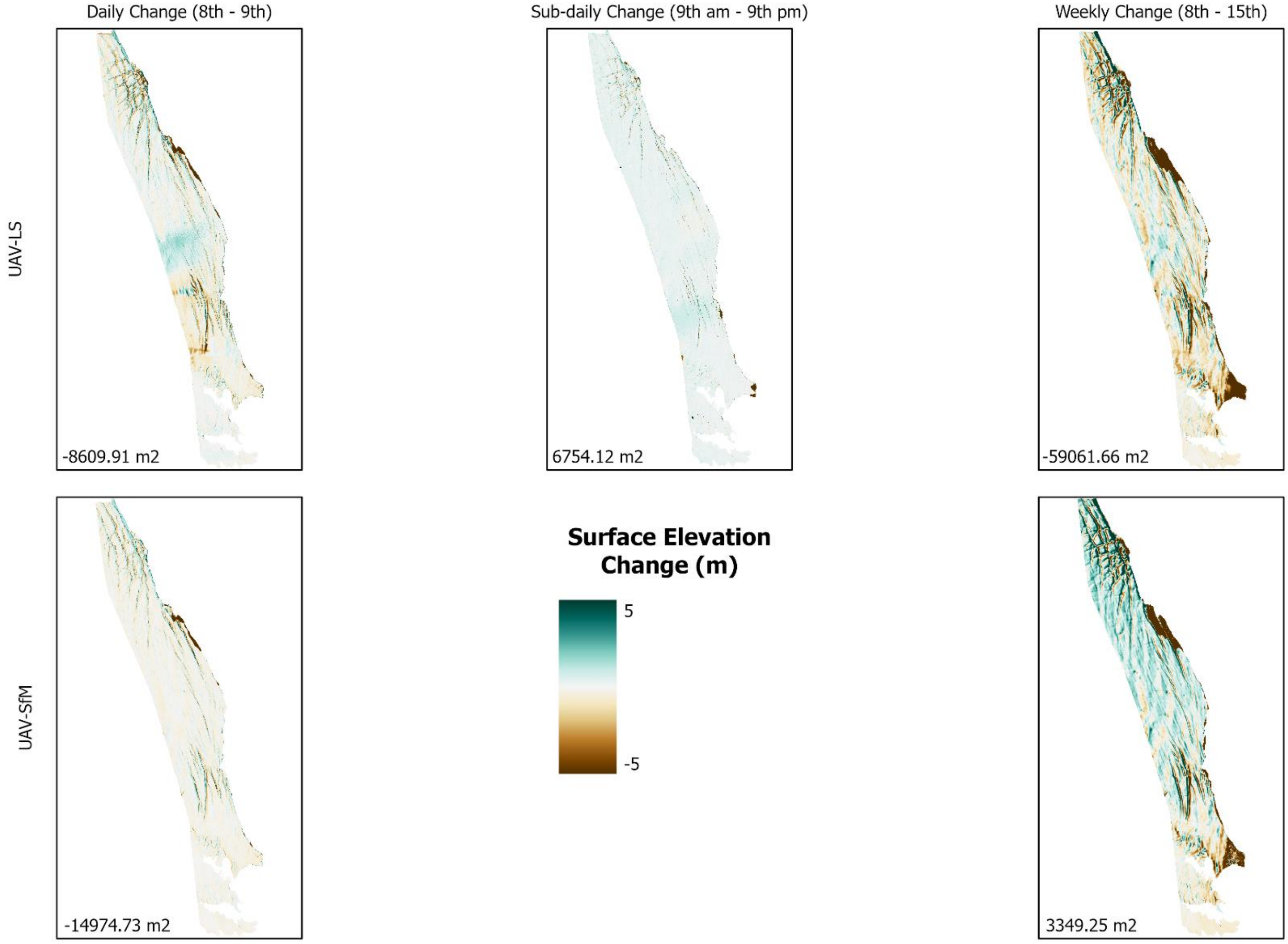

FIGURE 4 Results of the surface elevation change analysis, carried out using DEM differencing for different time periods for both the UAV-LS and UAV-SfM-derived DEMs. Total volume change for each time period is also shown. It is also worth noting the deep brown areas along the calving front likely represent large calving events (i.e. mass loss).

Spatially variable changes in surface elevation can be seen to have occurred over each time period of interest in both the UAV-LS and UAV-SfM differenced DEMs (Figure 4), although the pattern and magnitude of surface change varies between the results of both methods. Overall, the changes observed using the UAV-LS DEMs are more consistent, whilst those observed using the UAV-SfM DEMs are considerably more variable, with large extremes between the two time periods investigated. For reference, the darker blue/green colours representing mass gain (surface thickening) while the dark brown areas represent mass loss (surface thinning). The total surface change for each period, expressed as volume (in m^2) is shown in the bottom left of each pane

(ii) Changes in Calving Front Geometry

The change in calving front position for each time period of interest is shown in Figure 5, compromising sub-daily, daily, and weekly changes. Due to the imagery angles from the UAV-SfM survey not adequately capturing the front of the glacier, this analysis was only performed on the UAV-LS data. For reference, the brown, grey and blue regions represent calving events, areas of no change or regions of terminus advance, respectively. As can be seen from the three outputs, calving occurs across all time periods, even in those surveys taken across the same day (top figure). In the weekly comparison (bottom figure), these changes are much more variable, with large regions of terminus retreat (up to 10 m), as well as terminus advance (up to 5 m) observed, suggesting a highly changeable environment.

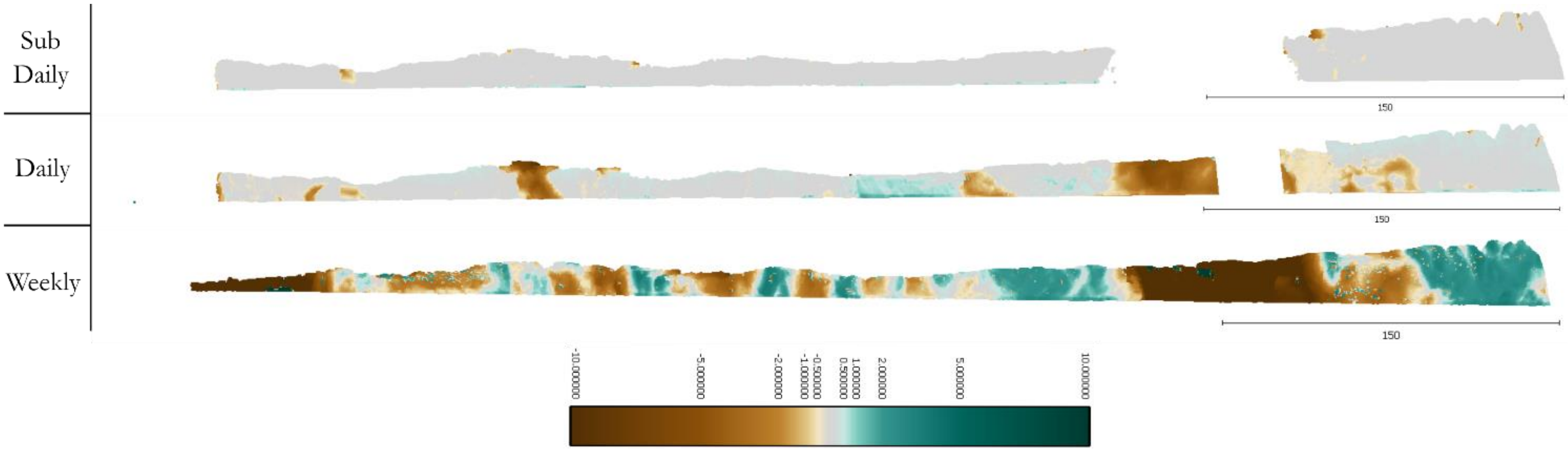

FIGURE 5 Changes in calving front position for different time periods, calculated using UAV-LS data. Gaps in the data series are where there were insufficient data points in order to accurately interpolate the calving front.

(iii) Surface Crevasse Morphology

The cross sections extracted from both the UAV-LS and UAV-SfM point clouds can be seen in Figure 6, with the three transects used shown relative to their location on the glacier surface. The most striking difference between the two methods is the ability to detect the calving front itself, with variable point densities between the two methods in different scenarios. In all three of the transects, the calving front from the UAV-SfM is incomplete, whereas for the UAV-LS a complete front is reconstructed. Furthermore, UAV-LS is, in general, much better at reconstructing the geometry and depth of the deepest crevasses (e.g., Transect 1), as well as those smaller crevasses (all transects), highlighting a further key advantage of the method.

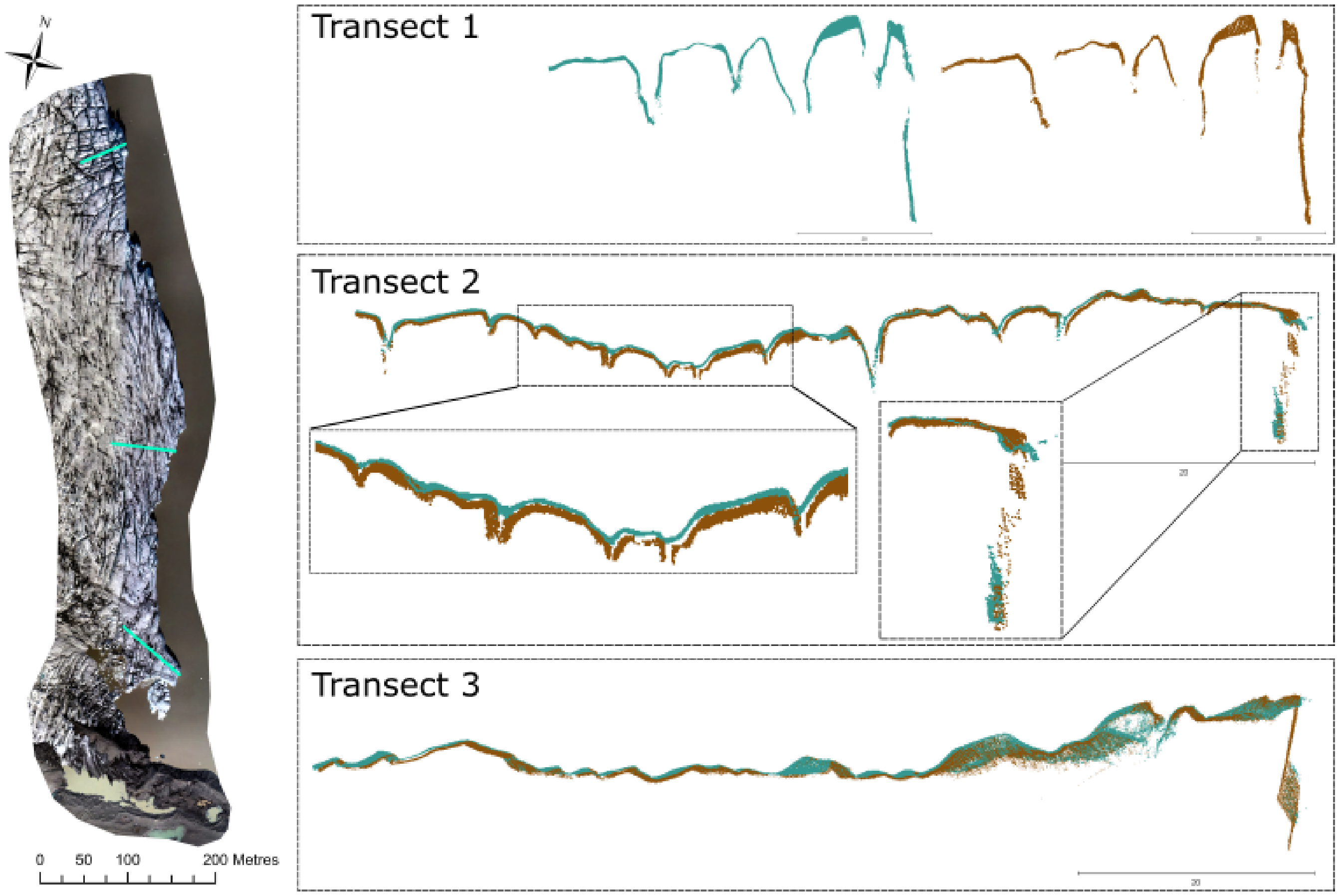

FIGURE 6 Transects across the glacier extracted from UAV-LS (Brown) and UAV-SfM (Blue) point clouds for the 9th July. Each transect compromises a different region of the glacier characterised by different crevasse morphologies. The location of each cross section on the glacier surface can be seen in the left panel.

The main aim of this study was to assess the suitability of UAV-LS for glacial research by investigating several different glacial processes across a variety of temporal resolutions by undertaking repeat surveys over a ~0.1 km^2 region of Fjallsjökull, an actively calving glacier in southeast Iceland. In doing so, we have become the first study to demonstrate the successful deployment of a UAV-LS system in a glacial environment to date, as well as the first to investigate the suite of different processes occurring in the near-terminus region of a calving glacier through the production of several different glacial products to a high degree of spatial accuracy.

Indeed, based on our data, some of which is illustrated above, it is clear that UAV-LS shows real promise for use in glacial research, and that the method has several important advantages when compared to UAV-SfM. Indeed, whilst UAV-SfM is hindered by several factors, because UAV-LS is an active sensor it can result in a consistent point cloud of a scene regardless of flight characteristics, wind conditions or illumination conditions at the time of survey. Although the method does have limitations, issues such as areal coverage and cost are continually being addressed through the production of new, cost-friendly systems which can survey much larger areas, whilst those related to GPS and direct georeferencing issues, as well as adverse weather conditions, are also limiting factors when utilising UAV-SfM. As a result, the method is clearly suitable for deployment in glaciated regions, primarily due to its advantages relative to UAV-SfM, and thus shows huge promise if utilised in future studies, particularly for investigating glacier mass balance, changing ice dynamics and calving glacier behaviour.