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Autonomous underwater vehicle (AUV) observations of recent tidewater glacier retreat, western Svalbard

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Abstract

Recent studies have highlighted the need to improve our understanding of the relationship between glacial-front bathymetry and oceanography in order to better predict the behaviour of tidewater glaciers. The glaciomarine fjords of western Svalbard are strongly influenced by temperate Atlantic Water advected from the West Spitsbergen Current. Marine terminating (tidewater) glaciers locally influence many Svalbard fjords through fluxes of sediments, nutrients and freshwater, however their response to ocean warming and the imprint left by their recent retreat on the seabed remains unresolved. Here we present glacial front data collected by an autonomous underwater vehicle (AUV) from four tidewater glaciers; Fjortende Julibreen (Krossfjorden), Conwaybreen, Kongsbreen and Kronebreen (Kongsfjorden). The seabed adjacent to the glacial terminus has been mapped providing high-resolution bathymetry (0.5m-1.0m grid cell size), side-scan and photographs with additional simultaneous oceanographic observations. The aim being to survey the glacial front submarine landforms, to identify the water mass structure and to observe any melt water plume activity. The bathymetry data displays a diverse assemblage of glacial landforms including numerous retreat moraines, glacial lineations, crevasse-squeeze ridges and sediment debris flows reflecting the dynamic depositional environment of the glacial front. The age of the features and the annual rate of retreat have been estimated using satellite remote sensing imagery to digitise the glacial front positions over time. The glacial landforms have been produced by the last few years of retreat as these glaciers gradually become land-terminating. The AUV also observed in-situ subglacial meltwater plumes at the two most active glaciers (Kongsbreen and Kronebreen) and an associated signature of warm Atlantic Water occurring at the glacier face. The presence of relatively warm, oceanic waters enhances subsurface melting, accelerating the ablation rate, while fresh (melt) water injection at depth influences local water mass structure and the wider fjord circulation. At the glacial fronts of Kongsbreen and Kronebreen sedimentation from subglacial meltwater plumes dominate the ice-proximal zone and settling from suspension is more prevalent away from the glacier. This study shows how sensitive dynamic glaciomarine systems are to change in the local marine environment and how the use of autonomous vehicles can greatly aid in the monitoring of glacial change by collecting simultaneous high-resolution in-situ datasets where vessel based observations are lacking.

Keywords: Autonomous underwater vehicle, tidewater glacier, meltwater plume, retreat moraines, Atlantic Water advection.

Introduction

The Arctic region has undergone significant environmental change over the past decade and will probably experience the most severe climatic changes on Earth with unprecedented warming leading to reduced sea ice cover and retreating glaciers (e.g. Boé *et al*., 2009). Studies from Arctic fjords have shown how marine-terminating (tidewater) glaciers are influenced by external factors such as atmospheric and oceanic warming in addition to glaciological factors and the topography and bathymetry of the surrounding areas (e.g. Stokes *et al.,* 2014; Jakobsson *et al*., 2018). Jakobsson et al. (2018) also highlighted the urgent need to understand seabed bathymetry and processes directly adjacent to the glacial front in order to improve modelling of glacier dynamics. Fluctuations of glacier dynamics may not only affect the physical environment, they may also affect the marine ecosystem including seabirds and marine mammals (e.g. Wlodarska-Kowalczuk *et al.,* 2005; Lydersen *et al.,* 2014). Hence, there is a pressing need to establish a baseline on which to build observations of further natural environmental fluctuations, such as monitoring changes in tidewater glaciers. In this study we focus on the tidewater glaciers of the Krossfjorden-Kongsfjorden region (Figure 1). The distribution and movement of some glacier fronts in the region have previously been mapped using surface vessels, yet the innermost part of these fjords and the glacier front environments have not been subject to detailed bathymetric and oceanographic surveys. Given the highly dynamic and potentially hazardous nature of the calving front of many glaciers, most direct observations have been made from surface vessels, which for obvious reasons of safety; maintain a safe recommended distance (typically >200m) (Kohler 2016). The use of an autonomous underwater vehicle (AUV) can both mitigate this risk and collect high quality data almost directly from the active glacial front (Dowdeswell *et al*., 2008b). Luckman *et al*., (2015) and recently Schild *et al*., (2018) demonstrate that the rate of glacial ablation is strongly controlled by ocean temperatures, via the process of submarine melting and collapse. The investigated tidewater glacier front environments of this study were chosen to demonstrate a continuum of glacier-ocean scenarios from fully marine to almost land-terminating to represent the present and future of Arctic fjordic glaciers (Figure 1). All four observed glaciers terminate in the marine environment and some are surge-type, experiencing long periods (decades) of inactivity followed by shorter periods of rapid flow (Mansell *et al*., 2012). The surge-type glacier, Fjortende Julibreen has a grounded shallow, (<50m) water glacier front. Conwaybreen has now almost retreated entirely onto land whereas Kongsbreen and Kronebreen are both dynamic, active tidewater glaciers (NSIDC, 2018; WGMS 1989; Figure 1). Very little previous work is available on the glacier front environments of Fjortende Julibreen and Conwaybreen (Mansell *et al*., 2012). In contrast an extensive literature documents on the behaviour and fjordic environments surrounding the glaciers in Kongsfjorden (Howe *et al.,* 2003; Svendsen *et al*., 2002; Machlachlan *et al*., 2010; Trusel *et al*., 2010; Kehrl *et al*., 2011; Forwick *et al*., 2015; Luckman *et al*., 2015; Streuff *et al.*, 2015; Burton *et al*., 2016b; Sundfjord *et al*., 2017; Schild *et al*., 2018). Previous studies using AUVs to investigate glacier front environments, including investigating sub-glacial meltwater, have been carried out in East Greenland (Dowdeswell *et al*., 2010) and Western Antarctica (Jenkins *et al*., 2010). Here we present in-situ AUV observations providing simultaneous bathymetric and oceanographic data from the inner, previously unsurveyed glacial front environment, including the very recent glacial terminus. The sea floor in these locations had been a sub-glacial environment as recently as five years ago (e.g. Schellenberger *et al*., 2015). The aim of this study is to determine the bathymetric setting of the ice proximal environment and where possible, the glacial grounded front, and to collect simultaneous oceanographic observations in order to better understand the processes driving retreat.

Regional and oceanographic setting

The Kongsfjorden-Krossfjorden system is situated on the western coast of Spitsbergen, Svalbard (Figure 1). The large icefields of Isachsenfonna and Holtedalfonna drain the adjacent landmass ($3074km^2$) feeding into the fjords through large glacier complexes (Svendsen *et al.*, 2002). Many of the major terminating glaciers in the region are tidewater glaciers (WGMS, 1989) including Kronebreen, Kongsbreen, and Conwaybreen. The southern arm of the system, Kongsfjorden, is ~20km long, and varies in width between 4 and 10km and trends east west. The bathymetry of the fjord is complex, with sills, basins and glacially streamlined exposed rock basement (Howe *et al.*, 2003; MacLachlan *et al.*, 2010). The investigated tidewater glaciers, Conwaybreen, Kongsbreen and Kronebreen are situated at the head of Kongsfjorden. The inner part of Kongsfjorden has previously been surveyed by Streuff *et al*., (2015) using a surface vessel thereby restricting any investigations of the glacier front environments. Of particular note are the bathymetric shallows of the Løvenøyane islands and the submarine bedrock sill extending both northward and southward from these islands (see Figure 1 of Streuff *et al*., 2015). This extended sill system presents a partial restriction to water exchange between the outer fjord, and inner fjord regions on which this study is focussed. To the north of Kongsfjorden, Krossfjorden is approximately 30km long and varies between 3 and 6km wide and trends north east to south west. Krossfjorden displays a much less variable seabed morphology than Kongsfjorden, with a large, predominantly flat basin reaching a maximum depth of 375m (Sexton *et al.*, 1992; Howe *et al.*, 2003). The bay northwest of Fjortende Julibreen on the eastern side of Krossfjorden had, up to this point, been unsurveyed.

The two main water masses originating outside the study areas are the Atlantic Water (AW) element of the West Spitsbergen Current (WSC) and Arctic Water (ArW) of the coastal current (Table 1 summarises the water mass definitions). Both these currents flow northwards along the west Spitsbergen margin, steered by the shelf edge topography (Figure 1). The west-facing Spitsbergen fjords are adjacent to the WSC, therefore experience a strong influence of warm saline AW, much more so than any other Arctic fjord (Saloranta and Svendsen, 2001; Cottier *et al.,* 2007). Recent years have been characterised by an increase in the temperature and frequency of warm AW incursions into west Spitsbergen fjords, alongside an increase in the temperature of the WSC (Pavlov *et al*., 2013; Cottier *et al*., 2007; Nilsen *et al*., 2016). Due to the dynamic nature of cross-shelf transport, there is an annual cycle where water of Arctic origin dominates through winter and Atlantic water dominates through summer (Svendsen *et al*., 2002; Cottier *et al*., 2005). Tides are weak in Kongsfjorden, generally less than 1 cms^{-1}, as are the residual mean currents (Tverberg *et al.*, 2019). Observational (Inall *et al.,* 2015) and modelling studies (Nilsen *et al*., 2016; Sundfjord *et al*., 2017) show that the most energetic motions in Kongsfjoren are episodic in nature, manifested in wind-driven exchanges (Sundfjord *et al*., 2017) or two to four-day period oscillations driven by wind events outside the fjord (Inall *et al*., 2015). Though only by a few cms^{-1} (Tverberg *et al*., 2019) mean circulation of water masses within Kongsfjorden has a larger impact on the fjord circulation than the meltwater driven estuarine circulation. Even in winter, heat is transported as a heavily modified water mass into the inner part of the fjord. However, models do suggest that more heat is transported into the inner fjord during summer, resulting in a larger potential for glacier front melt (Sundfjord *et al*., 2017). A recent study of the Kronebreen-Kongsvegen glacier (Meslard *et al*., 2018) suggests that the high concentration of suspended sediment discharged in a surface water plume, is the result of a sub-glacial river. The presence of these focussed, concentrated discharges of sediment-rich meltwater can strongly influence the ecosystem of the fjord, with subsequent consequences for the benthos and biogeochemistry of the system.

Methods

The surveys were conducted between the 27th - 30th of July, 2016 (Fjortende Julibreen) and from 8th – 14th August, 2017 (Conwaybreen, Kongsbreen (north to distinguish this from the glacier's other southern branch) and Kronebreen) all from the Norwegian Polar Institute vessel MV Teisten. The AUV is a Teledyne Gavia Offshore Surveyor 'Freya'. The vehicle is equipped with a Kongsberg GeoAcoustics 500 kHz GeoSwath+ interferometric sonar, with a grasshopper benthic camera and strobe. The 500 kHz sonar was operated at altitudes of 2-10 m above the seafloor, with a 30m range, providing an approximate object resolution of 0.1m. The AUV has a maximum operational depth of 500m and uses a Kearfott T24 inertial navigation system (INS) providing a navigational accuracy of +/- 0.1% distance travelled (e.g. accuracy of 0.1m per 1km of survey). In addition to the bathymetry and side-scan sonar the AUV-mounted camera enabled photographs of the seabed to be obtained in order to determine the nature of the seabed sediments. At the glacier fronts of Conwaybreen, Kongsbreen and Kronebreen an Idronaut Ocean Seven 304 Conductivity Temperature and Depth (CTD) instrument mounted on the bow of the AUV was utilized to collect underway oceanographic data. Underwater survey progress was monitored using an Ultra-Short Base Line pinger to communicate whilst the vehicle was up to 2km away from the surface vessel. Endurance with a single lithium-ion battery module was 4 hours per survey.

In addition, vessel-based CTD water-column profiles were collected using a YSI CastAway mini-CTD (Table 2). Measurements of the speed of sound in water were calculated from both the AUV inboard velocity probe and the full water column measurements of the CTD.

Bathymetric and side-scan sonar data was tidally corrected using a synthetic 'zero-tide' application to reduce surveyed depths to a common datum as no real-time tidal observations were made during the duration of the surveys. The soundings were corrected using in-situ sound velocity measurements to correct for water column salinity and temperature artefacts such as refraction. The data were filtered and cleaned using the learning algorithm in GeoAcoustics GS4 software and imported into Caris HIPS and SIPS v.9 as a flagged .rdf file. The data were then further cleaned and a Combined Uncertainty Bathymetric Estimator (CUBE) surface producedwhich had a resolution of 0.5-2m (bathymetry) 0.1m (side-scan), dependent on data density and quality. These surfaces were exported as geo-corrected rasters into ArcMap v.10. The total combined survey area was 3.18km^2 and total survey (bathymetry, photographic and oceanography) duration was ~30hrs over 11 days.

Satellite imagery of the glacier front was obtained from the US Geological Survey Landsat dataset. Using these images the chronological position of the glacier fronts of the glaciers were digitized from 1976-2017 providing an up to forty-year record of glacier activity with which to inform interpretations of the bathymetric data. Ice fronts were manually digitized.

Seabed geomorphology was digitized using the editor tools in ArcMap 10.2. Seabed features were analysed using the bathymetric surface in ArcMap combined with the interactive CUBE surface in Caris to reduce any azimuth bias and to interrogate seabed features in higher-resolution.

CTD data were processed using Matlab software to generate temperature and salinity plots.

Results

Oceanography

The water mass fractions described in Svendsen *et al*., (2002) and adapted by Cottier *et al*., (2005) are used to investigate the origins of fjord water found within the proximal zone of each surveyed glacier (Table 1). The water masses found within the fjord during this investigation, and defined in Table 1, are: Atlantic Water (AW), originating from the WSC; Surface Water (SW), fjord water with a significant freshwater influence; Intermediate Water (IW) formed from the mixing of AW and SW; and Transformed Atlantic Water (TAW) formed from mixing AW with cold, deep, winter water (though no winter water was detected in these surveys).

The inner fjord region close to Kronebreen is described first, since that is where both a CTD profile transect and the AUV-based CTD data is available. To illustrate the layered nature of the along-fjord water mass structure, the profile transect and AUV CTD data were combined into a single section of temperature and salinity plotted against depth and range from glacier front (Figure 2). Range is defined as the perpendicular distance of each data point from a straight line drawn to best-represent the glacier frontal position at the time of the survey (Figure 3a). Since in reality the glacier front is not a straight line, there are some negative ranges when the AUV was flown particularly close to the glacier into regions of ice-front indentation.

This viewing method collapses all the data onto a single x-z plane, which is appropriate (and standard) for the profile CTD data, but less so for the AUV-based CTD data, which span the along-glacier direction. Nevertheless, by combining these data sources close to Kronebreen the observations show that the lateral circulation follows a two-layer structure near the glacier face comprising warmer Atlantic-origin IW flowing towards the glacier, lying beneath outflowing cooler fresher SW. In the case of Kronebreen, this two-layer circulation structure sits on top of an isolated pool of TAW, a water mass not observed in the AUV CTD data collected in the vicinity of the other glaciers.

There are two processes by which the inflowing IW can be transformed into the cooler, fresher outflowing SW. 1) Buoyancy injections of turbulent, cold, fresh water at depth (sub-glacial discharge) lead to entrainment of ambient IW into a rising meltwater plume. 2) Direct contact between IW and the glacier face both cools the IW and adds fresh water through subsequent melting. The fraction of SW water created by these two processes may be called Glacially Modified Water (GWM). Surface run-off is less able to mix directly with IW, since run-off is generally isolated from IW by the GMW layer. These water masses and processes are illustrated in cartoon form (see Figure 10). Clearly for this two-layer circulation to occur, the grounding line of the glacier must be deep enough to expose the glacier front to IW. Furthermore, if the grounding line is equal to the maximum basin depth, for example at Kongsbreen, then any deep pool of remnant isolated TAW from the previous winter will be absent in later summer due to processes 1) and 2) above. Carrol (2017) models the effects of this fjord-glacier geometry on water mass renewal, concluding that a subsurface buoyancy injection (sub-glacial discharge) is independent of external shelf forcing and leads to deep basin renewal (i.e. eradication of TAW).

For Kongsbreen and Conwaybreen only AUV-based data are available (no profile data), so reconstruction of x z-plane sections of T and S in the vicinity of these glaciers were not attempted. However, the standard method of plotting CTD data in TS space, coloured by range is a more powerful, if less intuitive way to diagnose both layered circulation patterns, and to discriminate between melt and discharge transformation of IW.

By plotting the salinity against temperature, with contours of density, it is possible to analyse mixing lines and determine the origins of each water mass fraction (Figure 3). Applying this methodology to the AUV CTD data collected near the glacier fronts, two likely mixing lines can be drawn – a blue one for subglacial discharge, effectively ice cold freshwater (0°C, 0 g/kg), and red one for submarine meltwater (the so-called “Gade line”) (Gade, 1979), using a theoretical temperature taking into account the enthalpy of fusion of ice for a polythermal glacier (-83.9°C, and 0 g/kg) (Bartholomaus *et* *al.,* 2013). The cartoons illustrate the influence that grounding line depth and adjacent basin bathymetry can exert on the local hydrography (see Figure 10), though noting that only the Kronebreen model is substantiated with full depth CTD profile data. During the 2016 surveys of Fjortende Julibreen the AUV was not equipped with a CTD, therefore, the hydrography of that system is not discussed.

Kronebreen

Of the four glaciers surveyed, Kronebreen (Figure 3a and d) is the most exposed to Atlantic-origin water due to the cyclonic nature of the mean circulation in Kongsfjorden (Tverberg *et al*., 2019). Perhaps unsurprisingly, therefore, this was the only glacier where AW was observed within the proximal zone (Figure 3d). A core of warm IW and AW was observed penetrating towards the glacier front, with fresh, cool SW above and cool TAW below. The origins of the TAW are unknown, but as the highest density water observed it cannot be a local product of AW/Glacier interaction. Rather, it is likely the product of AW mixing with a pool of deep winter water at the onset of the seasonal AW intrusion earlier in the year. TAW remains present because the grounding line depth of the glacier is shallower than the full basin depth. Any water that is resident below the grounding line depth will not be subject to entrainment in a meltwater or a sub-glacial discharge plume, thus the TAW remains unmodified by the glacier and isolated. IW with a maximum temperature of 5.6°C and underlying AW at ~5°C was found within 100m of the ice face, accompanied by a strong submarine melt signature (Figure 3d)

At the closest approach of the AUV to the glacier front (20m) a parcel of water at 30-40 m with T=3°C, S=33 g/kg) is seen (Figure 3d, yellow star). The origin of this water mass could be attributed to a very large volume of glacial meltwater as it falls along the proposed Gade (red) mixing line. However, due to the position in space and proximity to the observed active meltwater plume, a fresh water mixing line (black dashed) can be used to trace this parcel (in TS-space) to the TS properties of water present at a depth of 60-70m. This is interpreted as indicating the existence of a submarine channel at 60-70m depth from which fresh water is discharging. Surrounding waters, including submarine melt, are entrained into the rising subglacial discharge, and the AUV encountered this rising plume at 30-40m depth. The presence of shelf water at the face of the glacier indicates a relatively unrestricted pathway from the shelf to the glacier and further suggests that the restrictive bathymetry at the Løvenøyane islands is insufficient to prevent inflowing AW. However, this restrictive bathymetry could theoretically be buffering the influx of warm ocean waters through increased mixing between the inflowing AW and the outflowing SW, essentially providing a short-circuit for AW heat to mix into SW without coming into direct contact with the glacier.

Kongsbreen (north)

Kongsbreen (north) (Figures 3b and e) differs from Kronebreen due to the deep (160m) basin found at the glacier face. The AUV CTD data reveal a homogenous fraction of IW at depth (highest density water mass) with no AW or cooler deep water (TAW) present, in contrast to Kronebreen. This provides further evidence to suggest that buoyancy injection at the base of the glacier are contributing towards overturning, driving fjord water renewal by entraining and exporting the ambient fjord waters (IW in the case of Kongsbreen) in a buoyant plume of subglacial discharge and submarine meltwater. Kongsbreen data also suggest that submarine melt plays the dominant role in water mass transformation, greater than subglacial discharge. This is evidenced in Figure 3e where the mixing signature follows the meltwater trend line (the Gade Line), and no direct evidence of sub-glacial discharge is seen in the AUV CTD data. However, the Kongsbreen data also presents evidence for a plume of submarine meltwater, reaching neutral buoyancy at depth (60m) and being exported from the glacier face (Figure 3e), suggesting that direct surface runoff has minimal direct interaction with IW. The AUV measurements reveal a complex and dynamic structure composed of interleaving layers of IW and glacially modified IW. A maximum temperature of 5.5°C was observed in the

Kongsbreen basin at a depth of 33m. The maximum temperature is lower than that of Kronebreen, probably indicating that the longer pathway over restrictive bathymetry, associated with northern limb of the Løvenøyane sill system, is playing a role in reducing IW heat transport to the glacier face (Figure 10a).

Conwaybreen

Conwaybreen (Figures 3c and f) is a glacier which has almost completely retreated from the fjord, though still has some subsurface presence to approximately 10 m water depth. Conwaybreen is down-stream of the cyclonic path of export waters from Kronebreen and Kongsbreen. Conwaybreen data show similar signatures to the surface waters of both Kongsbreen and Kronebreen, suggesting that the accessibility of shelf waters to the three Kongsfjorden glaciers follows a directional hierarchy of Kronebreen, Kongsbreen and finally Conwaybreen. There is reduced modification from submarine meltwater compared to the two previous glaciers, consistent with the reduced submarine portion of the glacier. Figure 3f shows that in TS space; the shape of Conwaybreen data in TS-space trends toward the fresh water mixing line than either Kronebreen or Kongsbreen, indicating the dominance of glacial run-off in modifying the water masses. Conwaybreen has a maximum temperature of 5°C at a depth of 41m. This is an example of a fjord in which runoff water does mix directly with IW (Figure 10c).

Bathymetry

Fjortende Julibreen

The 1.03km^2 AUV survey of the glacially influenced bay in front of Fjortende Julibreen revealed a seabed composed of a diversity of glacial landforms and sedimentary depositional features (Figure 4). The glacier has presently retreated almost entirely on-shore and is now only partially marine terminating. The survey extended from water depths of <3m to 55m deep and came within 200m of the grounded glacial front. In general, the bay possesses a shallow, presumably depositional, platform in the north with water depths of <15m. AUV obtained seabed photographs reveal this region to be composed of mixed sediment dominated by sand and muds (see Figure 8e) with bathymetry data showing the presence of large (>1m) boulders (see Figure 4c). In the southern and central regions of the bay, water depths increase to over 50m and the seabed here is much smoother, being composed of fine-grained sediments. Notable in this area is a <400m wide, arcuate, linear basin that extends from adjacent to the glacier front and across the bay towards the west. The entire survey area is dominated by ~30 transverse ridges, which are more subtle or entirely absent from the floor of the deeper-water areas.

Conwaybreen

The Conwaybreen survey, similar to Fjortende Julibreen, reflects the current glacier position, with the glacier retreated partially onshore onto the land and is therefore no-longer wholly marine terminating. The seafloor displays a complex of glacial landforms. Most notable are the numerous (~13 large (>5m high and >100m long) and ~43 smaller (<5m high and <100m long)) transverse ridges orientated NW-SE, in contrast to the presently N-S orientation of the glacier front (Figure 5). The smaller transverse ridges are more well-defined and numerous to the north-east of the survey, closer to the grounded glacier. Bathymetry was collected from an area of 0.48km^2 and up to 26m from the grounded glacier front. Shallowest depths recorded were 5m in the east and the deepest surveyed point was 54m water depth in the south of the bay (Figure 5).

Kongsbreen (north)

Kongsbreen presents an active (i.e. calving), marine-terminating glacial front, when compared to Fjortende Julibreen and Conwaybreen. In contrast to the complex glacial landforms displayed by the bathymetric surveys of Fjortende Julibreen and Conwaybreen, the seabed adjacent to Kongsbreen is dominated by a smooth seabed composed of fine-grained sediments, as photographed by the AUV (Figure 8g). Bathymetry was collected from an area of 0.39km^2. The shallowest surveyed depth was 24m and the deepest 160m. The surveys were obtained to within 15m of the grounded glacial-front. The region of subglacial discharge, highlighted by Schild *et al.*, (2018) was surveyed by the AUV (Figure 6).

Kronebreen

Luckman *et al*., (2015) report that Kronebreen has the highest glacial flux rate in Svalbard. The present phase of retreat (~350m per year, Luckman *et al*., 2015) of the northern Kronebreen front presents an opportunity to observe the recent seabed exposed from beneath the ice. This annual retreat rate contrasts with the terminus speed of up to 3-4m per day during the summer (Luckman *et al.*, 2015). As a consequence of the well-documented dynamism of this glacier the glacial-front environment of Kronebreen received the most survey time with the AUV-mounted CTD in order to document and spatially map any sub-glacial meltwaters and advecting AW which could influence the behaviour of the glacier terminus. Seabed geomorphology adjacent to the glacier is complex and can broadly be divided into two regions. Northern Kronebreen is an area where an active sub-glacial meltwater plume is dominant. The meltwater plume was active during the 2017 surveys and has been reported by Meslard *et al*., (2018). The seabed in northern Kronebreen here is characterised by transverse ridges and irregular or hummocky terrain, in water depths of between 40 and 90m. In contrast, central Kronebreen is characterised by a flatter, smoother seabed in slightly shallower water depths of between 50 and 60m deep. Bathymetry was collected from an area of 1.31km^2 and up to 20m from the grounded glacier front (Figure 7).

Submarine Landforms

Streamlined ridges: ice flow direction

Elongate streamlined ridges, oriented parallel to the fjord axis and perpendicular to the glacial front, have been mapped principally adjacent to Fjortende Julibreen and Kongsbreen, usually in the central and deeper part of the bathymetry data, in water depths from 10 to 160m. The ridges are irregularly distributed, up to 750m long and 10-30m wide, with a tapering shape and a gently declining lee slope. Subtle streamlined ridges occur in front of Kronebreen associated with the deeper water region of northern Kronebreen. Most ridges occur on what appears to be soft sediment on the bathymetry data, although at times they are associated with rough, possibly rocky, knolls at their glacier-proximal end. Side-scan sonar examples of these streamlined features are shown from Kongsbreen and Kronebreen in Figure 8. Notably the best preserved streamlined features occur close (<30m) to the grounded ice margin (e.g. Figure 4 Fjortende Julibreen and 6 Kongsbreen). A region of well-developed streamlines in front of the ground ice front of Kronebreen coincides with a region of active ice calving, and is the area identified by Meslard *et al.,* (2018) as being the point of emergence of a turbid plume of subglacial meltwater providing high concentrations of suspended sediments (Figure 7 and 8).

Elongated streamlined ridges are interpreted to be subglacial lineations, produced by soft-sediment deformation at the glacier-bed interface (Stokes and Clark, 2002; King *et al.,* 2009; Maclean *et al.,* 2016; Dowdeswell et al., 2016b). During periods of tidewater glacier advance, the upper surface of the till is molded into a linear shape. Similar lineations are observed on the seabed in many other fjords in Svalbard (Ottensen and Dowdeswell, 2006; Maclachlan *et al.,* 2010; Flink *et al.*, 2015). Here lineations are restricted to the deeper parts of the survey suggesting that they can be either caused by the presence of a thicker deposit of deformable (presumably fine-grained) sediment or to an increased preservation potential.

Transverse ridges: moraines

Ridges that are transverse to the fjord axis and parallel or subparallel to the glacier margin are found in all the four study areas. In the bays of Fjortende Julibreen and Conwaybreen these features are the largest and most common landform and occupy a great portion of the sea floor (Figures 4, 5, 6 and 7). They extend from the northern to southern limit of the bathymetry datasets, probably continuing over into the unmapped areas. They are sinuous, arcuate features, with asymmetrical profiles - steeper ice-distal sides, that can be more rounded in some cases Figure 4 (profile a-b). The largest of these are 10m high and ~50m wide (e.g. Figure 4). The spacing between ridges is highly irregular, varying from 200m to less than 20m, in some examples ridges are superimposed on one another suggesting a complex depositional history reflecting a dynamic glacial front (Figure 4a). In between the larger transverse ridges, a series of smaller and shorter transverse ridges, still irregular but more consistently spaced between one another, occur. The best examples occur in front of Conwaybreen (Figure 5). These smaller transverse ridges are generally 1-3m high and 2-3m wide, with clearly sharp peaked, symmetrical crests. These features commonly display a highly pointed arcuate-style planar morphology with the ridge crest parallel to the glacial front (see Figure 4 and 5). In side-scan sonar data these features show as more subtle features of moderate backscatter (Figure 8). In front of Kronebreen and Kongsbreen both styles of transverse ridge are less common when compared to Conwaybreen and Fjortende Julibreen, those that occur possess a more generally subtle seabed relief. For Kongsbreen only a few large, discontinuous, fragmentary transverse ridges have been mapped in the southern part of the bathymetry data (Figure 6). In front of Kongsbreen, low (<10m high) and thin (~5-30m wide) transverse ridges have been mapped in the central part of the fjord, and no major transverse features are observed at the south of the survey area (Figure 7).

According to their shape, position and dimensions, the large transverse ridges are interpreted as retreat moraines (Dowdeswell *et al*., 2008; Dowdeswell *et al*., 2016b; Burton *et al.*, 2018a). These could represent glacial still-stands or smaller re-advances during phases of grounded ice retreat. They result from frontal pushing and extrusion of soft deformable seabed during ice advance and subsequent settling during stagnation (Boulton *et al.,* 1986). The subtler, smaller transverse ridges are interpreted as De Geer moraines. These could be the result of seasonal glacial readvances across the bay (Linden and Möller, 2005; Dowdeswell *et al*., 2016b). Similar De Geer moraines have been noted elsewhere from the Kongsfjord-Krossfjord (Howe *et al*., 2003; Streuff *et al.,* 2015) and the Scotian shelf (Todd *et al*., 2007) and as relict features occurring inshore on the UK shelf (Van Landeghem *et al.,* 2009; Dove *et al.,* 2015; Bradwell and Stoker, 2018). The complex shape is here interpreted as being the product of a dynamic grounding line beneath the ice with possible modification by crevasse squeeze and meltwater discharge (Zilliacus, 1989). Flink *et al.*, (2015) note a similar seabed signature from Tempelfjorden. They interpret such features as crevasse-squeeze ridges and ascribe them to seasonal glacial winter surging and summer retreat.

Sediment lobes: debris flows

A series of six overlapping sediment lobes are observed in the southern part of the survey in front of Fjortende Julibreen (Figure 4c). These deposits extend northwest up to 300m from a rocky outcrop in the south into the linear basin. They are over 200m wide decreasing to ~50m width away from their source. These lobes are probably made up of debris flows deposited from the previous (1976; see Figures 4c and 9) glacial terminus (Flink *et al.,* 2015; Kristensen *et al.,* 2009; Ottesen *et al.,* 2008). The curvilinear and overlapping shapes, forming an inverted fan, suggest repeated sediment deposition from multiple downslope gravity flows.

A second extensive sediment lobe or plateau is observed in the central part of the Kronebreen survey area (Figure 7). The bathymetry shows a flat, regular seabed, interrupted by small transverse ridges. This is interpreted as an extensive region of sediment deposition dominated by downslope mass-wasting, principally debris flows, and forming a grounding line fan (Figure 7a). Bjarnadóttir *et al.*,

(2013) describe the complex of debris flows, smoother seabed and minor moraines as being indicative of a grounding line zone, the location of static or relatively slow moving submarine grounded ice.

Linear furrows and depressions: iceberg plough marks and pits

Numerous linear and narrow grooves are observed in the shallower (<20m) areas of the fjords. These features typically are <10m wide, 2-5m deep and in some cases, extend for over 0.8km (Figure 8a). They are only present in softer fine-grained sediment (determined from the AUV photographs) and are interpreted as iceberg plough marks (Dowdeswell and Hogan, 2016b). Occurring in conjunction with the linear iceberg plough marks are more irregular, sub-circular or elongate depressions. These are commonly 5-30m wide and up to 5m deep from the surrounding seafloor (Figure 8a). These landforms are interpreted as iceberg pits, produced by immobile, grounded icebergs rotating on the seafloor (Stewart *et al*., 2016; Dowdeswell and Forsberg, 1992; Streuff *et al.,* 2015). Visible in side-sonar, the linear plough marks are distinguished by having a low-amplitude signal, presenting a darker backscatter feature, presumably the result of sediments becoming mixed on the seafloor (Figure 8a).

Isolated boulders: glacial erratics

Common across the seafloor of the surveys are numerous isolated boulders, some are up to 5m high and 10m wide (Figure 4b). These are interpreted as erratics deposited on the seafloor either dropped subaerially from the calving margin, from melting icebergs or transported sub-glacially and left isolated after ice retreat. The largest mostly occur <0.3km from the ice-front. .

Satellite observations of glacial movement

The availability of the satellite imagery (USGS Landsat) enables the digitised position of the glacier front to be located relative to the AUV bathymetry (Figure 9). This produces an understanding of both the age of the seabed morphology, a linear distance of glacial retreat and hence an annual rate of glacial movement to be calculated.

Fjortende Julibreen

The AUV bathymetric survey covers a portion of seabed which was exposed by the glacier from ~1976 -2011, providing an estimate of the maximum age of the surveyed seabed of ~40 years old. In total the glacier front has retreated a distance of 1.3km east southeast from 1976-2016 (Figure 9), No useable Landsat images were available from 1976 to 1985. These observations indicate that the glacier experienced an average annual retreat glacial rate of 32m/yr. Since 2014 the glacial front has retreated a distance of ~0.6km, at a rate of 150m/yr. Between the years 2014 to 2015 the glacier experienced a phase of rapid retreat over a distance of ~763m, the furthest distance since 1976. However the glacier re-advanced ~240m between the years 2000-2002. This phase of active glacial surging was previously reported by Mansell *et al*., (2012), who describe the peak of advance as occurring in 2004. These authors report that this episode of surging ended after 2004, after which the rate of retreat increased as a function of increased calving rate. From 2002 to 2011, the glacier underwent a period of retreat, with only minor readvances (e.g. in 2006) including a phase of almost static activity from 2011-2014 (e.g. the year 2015-2016 shows a minor ~46m readvance) after which the glacier has been in retreat.

Conwaybreen

In contrast to the complex glacial dynamism and oldest exposed seabed displayed by the surging Fjortende Julibreen glacier, Conwaybreen presents a relatively simple recent history (Figure 9). The

AUV survey area covers a period of 17 years for the period 2000-2017 during which time the glacier front retreated a total distance of ~0.8km annual glacial rate (advance and retreat) of 47m/yr. The glacier readvanced ~170m during 2005-2006 followed by the furthest retreat of ~420m in 2006-2007. Since 2011 the southern region of the glacier has become pinned by a shallow (presently sub-aerial) rock outcrop and only now experiences retreat from its northern section, where the water is deeper (~40-50m). As a result the retreat of the glacier front has slowed and rotated in its direction. The glacial front has changed from retreating from west to east to its present confined north-west to south-east direction. During 2014-2015 the glacier front experienced a minor readvance of ~57m. Apart from this minor surge, and possibly as a result of being pinned by bedrock, the glacier has only retreated ~71m in the last year (2016-2017).

Kongsbreen

Of the four glaciers studied, the AUV bathymetry collected from Kongsbreen was the closest survey to the present-day grounded glacial front. However, it covers only the most recent period since 2013-2017 (Figure 9). Kongsbreen has been experiencing retreat since 2011, the glacial front retreating a maximum distance of ~907m between the years 2011-2013. During the period from 2013-2014 the glacial front readvanced a distance of ~84m followed by a retreat of a total of ~575m distance between the years 2014-2017. In summary, the glacial front of Kongsbreen has retreated southeast 1.5km since 2011 providing an annual glacial retreat rate of 250m/yr.

Kronebreen

The bathymetry collected by the AUV from Kronebreen spans a 6 year period during which the seabed has been exposed by the retreat of the glacier since 2011 and until the survey in 2017. Kronebreen is the only glacier examined that exhibited only retreat with no phase of readvance in the studied period 2011-2017 (Figure 9). The maximum distance of retreat was during the most recent retreat between the years 2015-2017 when the glacier front retreated a distance of ~783m. In contrast, the previous year, 2014-2015 the glacier front retreated only ~64m. Based on these data, the glacial front of Kronebreen has experienced a total retreat of 1.8km over this period, the largest distance of consistent retreat of all the four glaciers examined in this study. This provides an annual rate of glacial retreat of 300m/yr.

Discussion

Submarine landform and glacier behaviour

The glacial front surveys have shown the capability of an AUV to reveal the presence of very well-preserved submarine landforms adjacent to an active tidewater glacier. In addition the ability to collect in-situ simultaneous oceanographic measurements from the seabed and water column provide insights into both the water mass origin and structure, and the behaviour of any subglacial meltwaters. This study also reveals that the seabed proximal to the grounded glacial front contains numerous diverse glacial landforms, which otherwise would be hazardous or difficult to survey using a surface vessel. The principal submarine landforms are; 1) large transverse ridges, which have been interpreted as moraines, indicating a period of time (‘stillstand’) of reduced glacial activity, producing focused proximal sedimentation in front of the glaciers. These features, a characteristic submarine landform in glaciomarine environments, suggest that in all the areas surveyed the ice was wholly grounded in order to produce the moraines. 2) Numerous smaller, transverse and arcuate ridges, interpreted as De Geer moraines, possibly modified by crevasse-squeeze ridges. These features provide an insight into the glacier front dynamism, the result of seasonal glacial movements and the subglacial deformation of sediment within the crevasses of the active calving margin (Ottesen and Dowdeswell, 2006; Streuff *et al.,* 2015; Flink *et al.,* 2017; Flink *et al*., 2015; Dowdeswell and Vásquez, 2013). 3) Glacial lineations, produced by subglacial erosion and deformation of the bed, are notably well preserved in the larger, more active glaciers of Kongsbreen and Kronebreen. This suggests that modification of the subglacial bed is much more pronounced in the larger and in this case mobile glaciers. Both these glaciers also display the strongest subglacial meltwater signature (with both glaciers having active meltwater plumes, visible at the surface), suggesting that glacial dynamism is driven both externally (e.g. by water mass temperature (Luckman *et al*., 2015 and Schild *et al.*, 2018) as well as internally, (e.g. such as by the behaviour of the glacier through processes such as surging). Such lineations form mainly during episodes of surging, (Streuff *et al.,* 2015; Ottensen *et al*., 2017;). 4) Whilst a minor feature of this study, the presence of mass flow deposits, especially the well preserved examples from Fjortende Julibreen, indicates unstable sediments becoming remobilized downslope, perhaps as a result of a high volume of sediment being supplied from the adjacent grounded ice. This scenario is a well-established feature of models of proximal glaciomarine deposition (e.g. Powell and Cooper, 2002; Ottensen *et al*., 2017). The overlapping debris flow lobes, especially those from Fjortende Julibreen (Figure 4c), are deposited in proximity to larger moraines suggesting rapid deposition associated with a grounded glacial front (these flows being adjacent to the 1976 glacial limit). . 5) An abundance of minor submarine features such as glacial erratics and iceberg plough marks. It is notable that most of these features are confined to the small glaciers, Conwaybreen and Fjortende Julibreen. Both Kongsbreen and Kronebreen although highly active, are modifying the proximal seabed by draping from sediment plume deposition (see Meslard *et al*., 2018) as well as the seabed being over-ridden and subsequently modified by surging. Iceberg plough marks, being the product of grounded bergs deforming the seabed they are in contact with, are more inclined to be preserved in shallower water (<50m), as is certainly the case with Svalbard tidewater glaciers which calve smaller icebergs in comparison with the substantial glacial front heights of Greenland or Antarctica (Dowdeswell and Bamber, (2007). The ability of Kronebreen to calve icebergs with a shallow pits depth was also previously noted by Dowdeswell and Forsberg, (1992).

The complexity and diversity of submarine landforms observed in the zone proximal to the grounded glacier front suggests that although the depositional models for glaciomarine deposition proposed by

Ottesen and Dowdeswell, 2006; Ottesen *et al*., 2008; and Flink *et al*. 2015 are highly applicable to the glaciers in this study, there are a number of subtle landforms (e.g. crevasse-squeeze ridges and streamlines) that, with distance from the glacier, become draped by sediment and preserved. However many of features are over ridden by glaciers or eroded by currents and are not preserved.

Bathymetric controls on oceanographic setting

Previous studies have considered the complex assemblage of submarine landforms in the context of Svalbard glacier dynamics, in particular the role of surging (Streuff *et al.,* 2015, Flink *et al.,* 2015, Ottensen and Dowdeswell, 2006; Ottensen *et al.,* 2017). Here we utilizein situ AUV oceanographic and bathymetric data in order to provide a comprehensive examination of glacial environment (bathymetry and water mass) and response. Three models are presented combining the oceanography with the bathymetric setting (Figure 10). These models, based on AUV observations, suggest that bathymetry provides a strong control on glacier behaviour, driving the water mass structure in the glacier front environment. The end-member models (1 and 3) represent a continuum from a deep grounding line scenario, with warm IW dominating throughout the water column and a high volume of submarine melting, to a near-surface grounded glacier with circulation driven by surface water and run-off. In all the models the controlling factor is the near-glacier (~0-10km) bathymetry of the fjord, which drives the local hydrography and hence circulation. Recent work has highlighted the significance of local hydrography on glacier calving and hence retreat. Luckman *et al*., (2015) present observations of ocean temperature (principally for Western Svalbard, advection of warm Atlantic Water into the fjord) as driving frontal ablation of glaciers. This process invokes melting of the ice (undercutting) leading to ice front collapse. Here the rate of frontal ablation exceeds the net advancing flow of ice and hence leads to glacial retreat. Recent studies, Schild *et al*., (2018), Holmes, (2018) reinforce this mechanism but in addition suggests both free convection (driven by surface water circulation) and meltwater (subglacial) as important contributions to calving rate. Both these studies focused on Kongsbreen and Kronebreen and whilst both provide valuable insights into the driving processes of the local hydrography neither study possessed observations of the local bathymetry. Two recent studies have suggested similar processes on glacier retreat. It has been suggested that the bathymetry beneath the Petermann Glacier in Greenland controls the calving line driving glacial collapse by local subglacial deep water (Jakobsson *et al*., 2018) and again from the Pine Island Glacier in Antarctica where the position of the calving line is the product of the local bathymetry (Arndt *et al.*, 2018). In this study we suggest that bathymetry is an important factor in helping drive the local hydrography, hence enhancing processes such as submarine melting, convection and mixing. Figure 10 illustrates cartoons of these processes and uses examples of glaciers examined in this study. The first model, based on observations from Kongsbreen illustrates a glacier grounded in the deepest part of a silled fjord. Based on our surveys, the AUV encountered water depths of 160m directly adjacent to the grounded Kongsbreen glacier. In this model AW is modified as it enters the fjord and mixes with outgoing SW, and IW is drawn into the basin by the convection of the meltwater plume. The signature of a fresh, buoyant plume was detected by the AUV at depth (60m) and again in the surface waters. In this model, submarine melting was the dominant modifier, while subglacial discharge was also detected. In the model the stratified waters suggest that perhaps multiple freshwater plumes from glacial melt reach neutral density at different depths. Model 2 (using the example of Kronebreen), has AW becoming modified as it enters the fjord and mixing with outgoing SW. The bathymetry adjacent to Kronebreen provides evidence that it is grounded before a deepening basin and has therefore retreated towards a shallower grounding line. Due to the open nature of Kronebreen to the fjord, some AW can, within a core of IW, reach the glacier front. AW at the glacier front can enhance melting, particularly through entrainment in the subglacial discharge plume, promoting SW flow away from the ice. A pool of dense TAW sits both beneath the core of IW and beneath the grounding line of Kronebreen where it remains isolated from the draw of subglacial buoyancy injections. Strong submarine melting associated with the warm water core is observed and surface water aligns itself with the presence of a subglacial discharge plume. This model, invoking the complex bathymetry of Kronebreen, is referred to as a 'mid-depth grounding line' model. The scenario encountered at Conwaybreen and Fjortende Julibreen is illustrated by model 3. Here in a 'shallow grounding line' model, AW becomes modified by SW as it enters the fjord. Only a small portion of the glacier sits within the fjord waters and there is no deep buoyancy injection (c/f Kongsbreen and Kronebeen). The shallow basin holds only predominantly SW, with IW at depth. The majority of the IW appears to be exported from the glacier as it moves to exit the fjord. AUV observations of Conwaybreen suggest further modification of IW with fresh run-off from subglacial discharge into the surface waters. Whilst the inferred hydrography and bathymetry of these models is supported by the near-glacier AUV data, in these scenarios, the position of the shallow sill is suggested to be the Løvenøyane islands or other inshore restrictions in the fjord (see Streuff *et al.,* 2015).

Finally, the modern tidewater glaciers of Svalbard, experience phases of retreat and readvance with subsequent inter-annual seasonal (winter-summer) movement. In addition some Svalbard tidewater glaciers can experience phases of active surging whereby the glacier front can advance several kilometres, the glacier becomes heavily crevassed and the rate of iceberg calving subsequently increases. Of the glaciers observed in this study, only Fjortende Julibreen has displayed this behaviour in the past. Fjortende Julibreen displays the longest and most complex history with phases of glacial retreat and readvance, possibly as a result of the longer time-period examined. Conwaybreen has recently become topographically pinned and displays a record of only very recent retreat with only minor readvances. Both Kongsbreen and Kronebreen both show the greatest distance retreated for their respective glacier front positions.

Conclusions

Autonomous underwater vehicle (AUV) surveys of recently exposed sea floor directly in front of retreating tidewater glaciers in Kongsfjord-Krossfjord, western Svalbard have revealed submarine landforms from which glacial processes have been inferred. In addition underway oceanographic measurements were collected that has allowed both bathymetric and hydrographic data to be collected simultaneously and continuously . The AUV detected active meltwater plumes at two glaciers; Kronebreen and Kongsbreen indicating that these glaciers, both presently displaying active retreats, are influenced by local hydrographic conditions. The presence of warm Intermediate Water of Atlantic origin was detected at both these glacier fronts, perhaps suggesting a mechanism for melting of the glacier face and hence driving active calving. Conwaybreen is grounded in shallow water and therefore dominated by glacial run-off, which drives a more estuarine circulation. The seafloor surveys displayed submarine landform assemblages that indicate the glacial retreat activity. The seafloor in front of the two most active glaciers, Kongsbreen and Kronebreen display abundant subglacial lineations, with few moraine ridges identified, reflecting the mobility of the glacial front. Sediment deposition is interpreted as being directly from settling by active meltwater plumes in addition to direct modification of the bed via subglacial erosion and mass-wasting. In contrast Fjortende Julibreen and Conwaybreen display a seafloor dominated by numerous De Geer moraines and crevasse-squeeze ridges the result of recently wholly grounded ice, now retreated. Utilising Landsat imagery estimates of glacial retreat were obtained and indicates that Fjortende Julibreen has a retreat rate of 32m/yr (with periods of surging); Conwaybreen has a glacial rate of 47m/yr, Kongsbreen 250m/yr and Kronebreen 300m/yr. Three models of proximal glacial environments based on the AUV observations are proposed, producing a continuum from deep grounding line, with subglacial melting as a result of direct Atlantic Water influence to a near-complete subaerial grounding line scenario dominated by run-off and subglacial meltwater.

These observations demonstrate the inter-relationships between bathymetry and hydrography in the glacial front environment. Bathymetric setting can influence local hydrographic conditions and hence lead to glacial front melt. Sills within the fjord can promote mixing which although they can protect the glacier front from direct contact with warming waters, enhances local circulation. Circulation in front of shallow grounded glaciers can be driven by surface meltwater run-off and hence the glacial front is not so vulnerable to oceanic waters. This study highlights the utility of AUVs in the potentially hazardous proximal glacial front zone of marine terminating glaciers. Further work using small, readily deployable AUV's in the glacier front environment is proposed to continue to monitor tidewater glaciers in the Polar Regions.

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Figures

Figure 1: Location of the Krossfjorden-Kongsfjorden system, Western Svalbard. The AUV surveys are located at the glacier fronts of Fjortende Julibreen (Krossfjord) (Figure 4) and Conwaybreen (Figure 5), Kongsbreen (Figure 6) and Kronebreen (Kongsfjord) (Figure 7) (insets). Also indicated is the approximate position of the West Spitsbergen Current (WSC) which strongly influences the marine environment of the fjords through the advection of warm Atlantic Water. Landsat image of Kongsfjord and Krossfjord from 2017.

Figure 2: The Kongsfjord water mass structure, combining profile and AUV CTD data from Kronebreen into a single along-fjord section of temperature and salinity plotted against depth and range from glacier front. Range is defined as the perpendicular distance of each data point from a straight line drawn to best-represent the glacier frontal position at the time of the survey.

Figure 3: AUV tracks on Landsat images and Temperature-Salinity (TS) plots from all the AUV collected CTD measurements obtained in 2017: Kronebreen a) and d), Kongsbreen b) and e), and Conwaybreen c) and f). Ranging line approximations are coloured green. Contours of density are depicted with thin black lines and water mass fractions are labelled: Atlantic Water (AW), Surface Water (SW), Intermediate Water (IW), and Transformed Atlantic Water (TAW). Blue lines (and an alternate black dashed line) represent the mixing line for subglacial discharge and run-off (ending in 0°C, 0 g/kg), and red lines represent the mixing line (the 'Gade' line) for submarine meltwater production (ending in -83.9°C, 0 g/kg). A yellow star identifies a parcel of heavily modified water in d), and it's location in a).

Figure 4: Fjortende Julibreen AUV-derived bathymetry showing the 1.03km^2 survey area and Landsat image. Vertical exaggeration is x2 to enhance the seabed morphology. Sun illumination of the bathymetry is from the north-west. Inset boxes are the location of insets 4abc and the location of side scan image in figure 8a. The white circle denotes the location of seabed photograph shown in Figure 8e. Below is the interpreted geomorphology map highlighting the principle submarine landforms and cross-section a-b. a) Inset of the superimposed transverse moraine ridges and location of cross-section a-b. b) Inset of the boulders between the moraine ridges and c) Inset of overlapping sediment debris flows (lobes).

Figure 5: Conwaybreen AUV-derived bathymetry showing the 0.48km^2 survey and Landsat image. Vertical exaggeration is x2 to enhance the seabed morphology. The zone of grounding on exposed, subaerial bedrock is also illustrated. Sun illumination of the bathymetry is from the south-west. Insert boxes are the location of 5ab and the side scan image shown in Figure 8b. Below is the interpreted geomorphology map highlighting the principle submarine landforms and cross-section c-d over the

transverse ridges and e-f across the minor transverse ridges. a) Transverse ridges and cross section c-d. b) Minor transverse ridges and cross section e-f.

Figure 6: Kongsbreen (north) AUV-derived bathymetry showing the 0.36km^2 survey and Landsat image. Vertical exaggeration is x2 to enhance the seabed morphology. Sun illumination of the bathymetry is from the south-west. The arrow indicates the location of the subglacial meltwater discharge (after Schild et al., 2018). The insert boxes are the location of the inset 6a and the side scan image shown in Figure 8c. Below is the interpreted geomorphology map highlighting the principle submarine landforms and cross-section g-h over the glacial lineations. a) Glacial lineations and the location of cross section g-h.

Figure 7: Kronebreen AUV-derived 1.31 km^2 survey with Landsat imagery showing the two contrasting seabed regions, northern Kronebreen characterised by moraines and glacial lineations and central Kronebreen which is dominated by mass-flows, predominately debris flow lobes, contributing to the ground line fan. The approximate point of the meltwater discharge noted in 2017 (after Meslard *et al*., 2018) and the zones of active glacial calving are illustrated. Vertical exaggeration is x2 to enhance the seabed morphology. Sun illumination of the bathymetry is from the south-west. Note the numerous linear data artefacts resulting from acoustic scattering of the sonar signal as the AUV travelled through the sediment-rich meltwater plume. Insert boxes are the location of insets 7ab and the side scan image shown in Figure 8d. Below is the interpreted geomorphology map highlighting the principle submarine landforms. a) Shows the detail of the relatively smooth depositional seafloor of central Kronebreen. b) From northern Kronebreen showing the meltwater discharge point with numerous transverse ridges, lineations and data artefacts.

Figure 8: Examples of side scan sonar imagery of the seabed at the glacier front. Location of the insets is shown on Figures 4-7. a) Ice-berg plough marks in ~20m water depth from Fjortende Julibreen. b) Crevasse-squeeze wedge and moraine with recent debris-rich glacial diamict in the shallow water (~20-50m) adjacent to the grounded glacier, Conwaybreen. c) Glacial lineations and push moraine ridges, in ~140m water depth, Kongsbreen. d) Numerous glacial lineations and moraines, in front of the grounding line of Kronebreen in ~80m water depth. The scale bar in all images is 100m. e) An example of an AUV seabed photograph from Fjortende Julibreen showing seabed composed of gravelly mud in ~45m water depth. The photograph location is shown as a white circle on Figure 4. f) AUV seabed photograph from Conwaybreen showing fine-grained bioturbated muds in ~50m water depth. The photograph location is shown as a white circle on figure 5. g) AUV seabed photograph adjacent to the glacial front of Kongsbreen showing common starfish (*Asterias rubens*) on a fine-grained muddy seabed in ~100m water depth. The photograph location is shown as a white circle on Figure 6.

Figure 9: Landsat images 2016-2017 with bathymetry and digitised glacial front positions. Landsat courtesy of U.S. Geological Survey (https://landsat.usgs.gov/). a) Fjortende Julibreen 1976-2016. A selection of the digitised glacial front positions are shown (1976, 1985, 1986, 1989, 1994, 1999, 2011, 2014 & 2016). b) Digitised glacial front positions for Conwaybreen (2000, 2002, 2005-2007, 2011, 2013-2017). c) Digitised glacial front positions for Kongsbreen (2011, 2013-2017) and d) Digitised glacial front positions for Kronebreen (2011, 2013-2017).

Figure 10: Model cartoons illustrating the influence of glacial grounding line depth and ice-proximal bathymetry has on driving fjordic circulation, based on the AUV observations from the western Svalbard tidewater glaciers. Water depth is shown on the left hand side of each model, and is based on data from Forwick et al., (2015).

Table 1: Definitions for water masses found in Kongsfjorden and on the adjacent shelf. These domains are represented in the T-S diagram of Figure 3

Water Mass		**Characteristic**		
		T (°C)	Salinity (S)	Density (σ_θ)
External				
Atlantic water	AW	> 3.0	> 34.65	< 27.92
Arctic water	ArW	–1.5 to 1.0	34.30 to 34.80	
Internal				
Winter-cooled water	WCW	< –0.5	34.40 to 35.00	
Local water	LW	–0.5 to 1.0	34.30 to 34.85	
Surface water	SW	> 1.0	< 34.00	
Mixed				
Transformed Atlantic water	TAW	1.0 to 3.0	> 34.65	< 27.92
Intermediate water	IW	> 1.0	34.00 to 34.65	

Table 2: Hand held CTD profile locations for each survey.

Area	**Latitude**	**Longitude**	**Cast Depth**
Fjortende Julibreen	79.119	11.898	16m
	79.118	11.903	12m
	79.117	11.906	12m
	79.119	11.906	13m
	79.118	11.906	11m
	79.114	11.890	19m
	79.115	11.882	16m
	79.114	11.905	26m
	79.113	11.894	28m
	79.115	11.889	20m
	79.118	11.907	9m
	79.115	11.939	26m
	79.115	11.939	38m
	79.113	11.936	53m
	79.111	11.934	45m
	79.109	11.932	46m
Conwaybreen	78.992	12.498	25m
	78.992	12.498	27m
	78.991	12504	26m
	78.988	12.514	30m
Kongsbreen	78.883	12.562	51m
	78.882	12.580	76m
	78.882	12.567	81m
	78.883	12.559	75m
	78.884	12.553	76m
	78.884	12.555	74m
	78.884	12.552	76m
	78.884	12.547	81m
	78.885	12.541	83m

	78.885	12.567	27m
	78.870	12.574	73m
	78.870	12.568	27m
	78.988	12.526	37m
	78.966	12.579	132m
	78.970	12.600	86m
	78.959	12.594	87m
	78.964	12.605	134m
Kronebreen (north) CTD transect	78.883	12.562	51m
	78.882	12.580	76m
	78.882	12.567	81m
	78.883	12.559	75m
	78.884	12.553	76m
	78.884	12.555	74m
	78.884	12.552	76m
	78.884	12.547	81m
	78.885	12.541	83m
	78.885	12.567	27m
	78.870	12.574	73m
	78.870	12.568	27m
	78.886	12.571	56m
	78.888	12.573	40m
	78.885	12.570	70m
	78.885	12.582	24m
	78.884	12.581	70m
	78.884	12.576	58m
	78.886	12.579	53m