Multiscale Change Detection in a Supraglacial Stream Using Surface Drifters

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ABSTRACT: High-resolution (1 – 10 m) observations of supraglacial streams are needed to improve process understanding and inform low-resolution (25 – 100 m) remote sensing observations and numerical models. To address this, we built small (0.25 m diameter) satellite positioning drifters. The devices recorded the surface flow velocity, linear acceleration and magnetic field intensity along a 250 m supraglacial channel during the summer ablation period from 30.06 to 04.07.2019 at Austre Brøggerbreen, Svalbard. Cross correlation analysis was performed on channel-fitted coordinates. Multiscale change detection was carried out by increasing the averaging window of the time series data and the stream-wise spacing of the drifter's planar coordinates. The locations of channel bends and step-risers were found to correspond to clearly defined changes in the streamwise cross correlations of the flow speed, magnetic field intensity magnitude and acceleration magnitude. The proposed drifter-based approach provides a simple method to collect and assess high-resolution satellite drifter data for multiscale planform change detection in supraglacial channels.

1 INTRODUCTION

1.1 *Background*

Supraglacial channels exhibit meandering planform dynamics driven by thermal erosion and subglacial topography. Thermal erosion rates are governed by flow speed, water temperature and channel aspect ratio. Supraglacial streams form an important part of the glacial hydrological system as they transport both meltwater and energy over the surface of glaciers and ice sheets (Pitcher and Smith 2019; Rippin et al. 2015; Smith et al. 2015). As such, they play an important role in the surface mass balance of glaciers and ice sheets, as recent research at the Greenland Ice Sheet has shown (Enderlin et al. 2014). Supraglacial channels can range from a few centimeters to tens of meters in depth and width (Germain and Moorman 2016), transporting meltwater either to the glacier margins or into moulins (vertical conduits transporting water to the subsurface) as well as into supraglacial lakes (Chu 2014). Recently, supraglacial discharges have been shown as a key physical driver of the observed changes in ice sheet dynamics via rapid drainage events into the subsurface (Chudley et al. 2019). Despite the recognition of their importance in glacial hydrology supraglacial systems remain understudied, and fundamental supraglacial fluvial science remains at a nascent stage of development (Gleason et al. 2016).

Supraglacial streams have several differences from their terrestrial counterparts: They are formed in ice rather than rock or gravel. Fundamentally, this is because they lack sediment (Knighton 1981), they have no vegetated banks, and adjust their channel form rapidly. This is because supraglacial streams are subject to thermal, rather than mechanical erosion as the main driving process, including significant diurnal discharge variations (Jarosch and Gudmundsson 2012).

Another noteworthy difference is that the energy dissipation in supraglacial streams is mainly controlled by surface melt, unlike rainfall accumulation in terrestrial rivers (Mantelli et al. 2015; Novakowski et al. 2004). Despite the myriad of differences, several similarities remain between terrestrial and supraglacial streams. Recent work on the southwest Greenland Ice Sheet has shown that the fluvial morphometry follows Horton’s law (decreasing river number, increasing mean river length, decreasing slope versus increasing stream order). It has also been observed that both terrestrial and supraglacial systems exhibit wider channels downstream, and that bifurcation ratios as well as braid index values remain comparable. Smaller supraglacial streams however, tend to have steeper water surface slopes than their terrestrial counterparts. This results in higher flow velocities and Froude numbers (Gleason et al. 2016).

The planform morphology of supraglacial streams is controlled by the relationship between channel incision and overall ice sheet ablation rates (Jarosch and Gudmundsson 2012; Karlstrom et al. 2013) and the channel planforms are observed to meander in response to channel curvature, thereby enhancing heat production and heat transfer to the surrounding ice at bend apexes (Karlstrom et al. 2013). Incision rates are dependent on the water flow velocity inside the channels (Isenko et al. 2005) and the greater the discharge or slope, the faster the incision and higher the sinuosity (Germain and Moorman 2019), as higher discharge is accommodated by increasing velocity (Gleason et al. 2016).

The most recent studies of supraglacial systems have focused on remote sensing over large scale (km) and on the Greenland Ice Sheet (Joughin et al. 2013; Legleiter et al. 2014). To-date, their remain few studies focusing on local, field-scale hydraulics (Germain and Moorman 2019; Gleason et al. 2016). Field data is however needed to calibrate and validate models and remote sensing data. Thus field research in the supraglacial environment is urgently needed to facilitate a broad scale understanding of ice sheet hydrology and runoff processes. These processes are important to reduce the uncertainty of sea level forecasts due to climate change.

1.2 *Research objective*

Our work is motivated by the difficulty and cost associated with collecting ground truth data in glacial environments, with a focus on supraglacial streams. The long-term aim of our drifter development is to create new, open-source methods and hardware devices for scientific investigation of extreme environments. Such methods and devices could feasibly be implemented as autonomous sensor systems using air dropped drifters from light aircraft or autonomous aerial vehicles. Rugged drifters could be potentially deployed in glacial caves which are difficult or impossible to map because they are not able to receive signals from global positioning satellites.

In this work, we deployed the drifters by hand in a small glacial channel. After recovery, the drifter data were post-processed to explore potential relationships between the global navigation satellite system (GNSS) groundspeed, linear acceleration magnitude and magnetometer intensity magnitude. This was done over a range of spatial scales from 1 to 20 m in order to investigate new methods for planar and vertical change detection using surface drifters. The proposed method is based on simple statistical parameters which can be programmed for low-power microcontrollers used on the drifter platform.

2 METHODOLOGY

2.1 *Glacier study site*

The Svalbard archipelago is situated between 74° N to 80°N and 10°E to 35°E. The annual air temperature ranges from -5.9°C and the archipelago receives an annual mean precipitation of 196 mm. Due to these climatic conditions 59% of Svalbard remains glaciated. The field site was located on Austre-Brøggerbreen (78°54’N, 11°49’E), a small ~5 km long valley glacier located on a north facing slope of the Brøgger Pensinsula as indicated in Figure 1. This glacier was chosen due to its close proximity to the permanent research settlement Ny-Ålesund. The glacier elevation ranges from 80 to 600 mASL and is currently rapidly downwasting. Consequently, the glacier has developed a network of deeply incised supraglacial streams. The supraglacial stream chosen for investigation is located on the northeastern side of the glacier. This supraglacial stream was chosen as it has been observed to re-occur annually. In this study, we focused on the last 250 meters, after which the stream terminates via a 2 m drop into a larger northward flowing lateral supraglacial channel. At the start of the fieldwork on 30.06.2019, the channel remained largely snow covered and three step-raiser sequences were clearly visible. On the final day of fieldwork 04.07.2019, a total of six step-risers had developed.

The multimodal satellite drifters were deployed by hand dropping them into the supraglacial channel at the location shown with a green triangle in Figure 1. After passing downstream through the channel, each drifter was captured using a temporarily installed marine fishing net at the end of the channel, shown in Figure 1e. A three-person team was required to deploy, recover and maintain (e.g. batteries, satellite connection check, data quality) the drifters during field work.

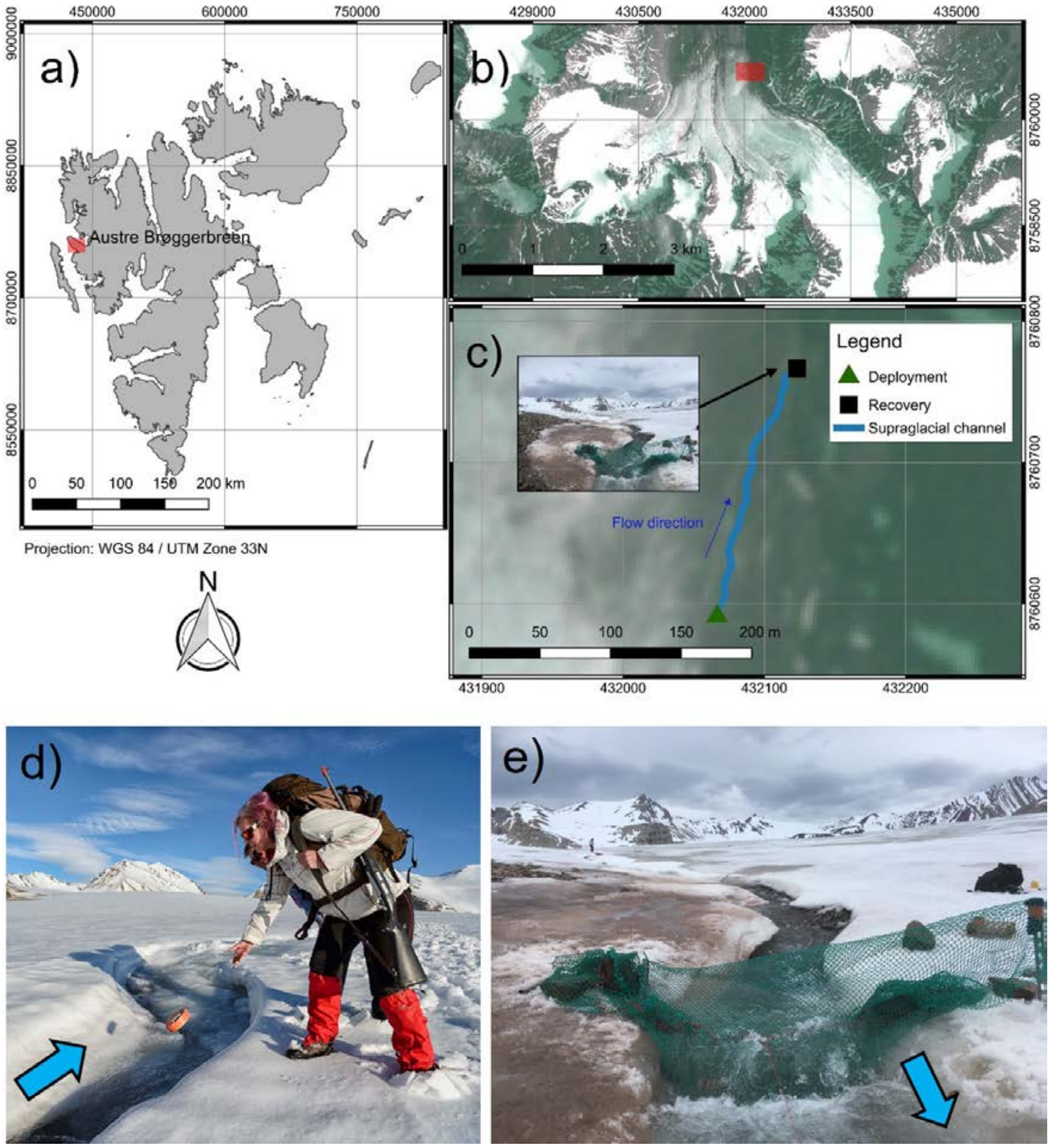

Figure 1. a) Map of Svalbard showing the location of the glacier, marked with a red dot. b) Satellite image of the glacier, the test region is highlighted as a red shaded rectangle. c) Close-up map of the ca. 250 m long supraglacial channel region. d) Deployment and e) recovery locations shown from terrestrial imagery taken during the field investigation period (30.06 – 04.07.2019).

2.2 *Multimodal satellite drifter*

The 0.35 kg multimodal drifter is positively buoyant and consists of a 25 cm diameter foam floater disk enclosing a waterproof box. Inside the box are two rechargeable lithium batteries (type 18650, 3.7 V, 3600 mAh) which supply power to a custom-built printed circuit board (PCB). Each PCB contained a Bosch BNO055 inertial measurement unit and NEO-M8T GNSS receiver. The GNSS receiver recorded the x, y, z locations (EPSG: 4326, static positioning of accuracy ±3 m in x and y, ±10 m in z) as well as the drifter groundspeed (accuracy ±0.35 m/s). The inertial measurement unit (IMU) measures the linear acceleration (m/s^2), magnetic field intensity (mT) and rate of rotation (°/s). Static positioning accuracy of the GNSS was estimated by comparing static drifter positions at the study site as they laid side-by-side over a 15 minute duration. Velocity measurement uncertainty was estimated by calculating the standard deviation of the groundspeed from three tracks of the final day (04.07.2019), which were aligned using the dynamic time warping algorithm (Keogh and Ratanamahatana 2005). These tracks were chosen because the channel was fully formed and the sensors were capable of passing downstream unencumbered. Data were logged to a 8GB microSD card at a sampling rate of 5 Hz. An overview of the drifter and its key components is provided in Figure 2. The recorded data consisted of a delimited text file including the GNSS coordinates (latitude, longitude, geodetic height) as well as the groundspeed (m/s). The inertial measurement unit recorded three linear acceleration components (ax, ay, az) as well as the three orthogonal magnetometer intensities (mx, my, mz).

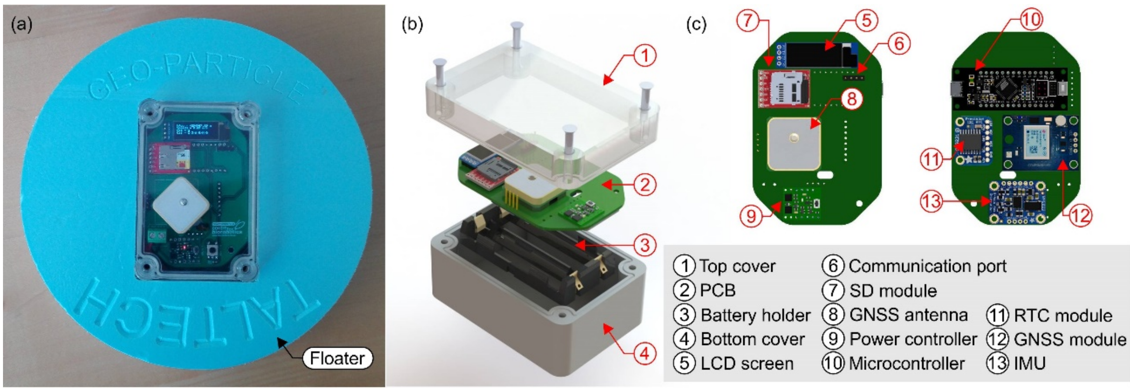

Figure 2. a) The electronics are sealed in a waterproof box placed at the center of a 25 cm diameter floater. b) Each box includes a clear plastic top cover, PCB, batteries and a plastic bottom cover. c) The PCB includes a LCD screen, IMU, SD storage as well as satellite tracking and radio communications modules.

2.3 *Data processing*

The drifter data were recovered by importing them from the microSD to a laptop computer, and post-processed in Matlab 2018b. Post-processing of the GNSS and inertial measurement unit data consisted of four steps: first, data were truncated by plotting each track and manually determining the indices of the corresponding start and end positions. Next, the truncated time series were converted into z-scores by subtracting each 5 Hz entry by the track time average and dividing it by the standard deviation. Afterwards, the covariance was calculated by multiplying the z-score of the groundspeed (GS) with the accelerometer magnitude (GSCA) and the groundspeed with the magnetic field intensity magnitude (GSCM). The approach was based on previous work using the z-score product to identify geomorphic covariance structures in rivers (Brown et al. 2016).

Multiscale change detection was performed using the GNSS track coordinates. First, the coordinates were transformed into a Cartesian grid (ETRS 89 UTM 33). Afterwards, the tracks were converted to a channel-fitted coordinate system (Legleiter and Kyriakidis 2006). Multiscale lateral and vertical deviations along the stream-wise axis were then calculated using the channel-fitted coordinate system by recursively aligning the planar track coordinates using evenly-spaced channel reference points taken at intervals of 1, 5, 10 and 20 m as shown in Figure 3. This method was chosen because it is numerically efficient and could be implemented on the microcontroller directly as it only requires the calculation of magnitudes, means and the standard deviations (z-score) and the product of the groundspeed and accelerometer / magnetometer magnitudes.

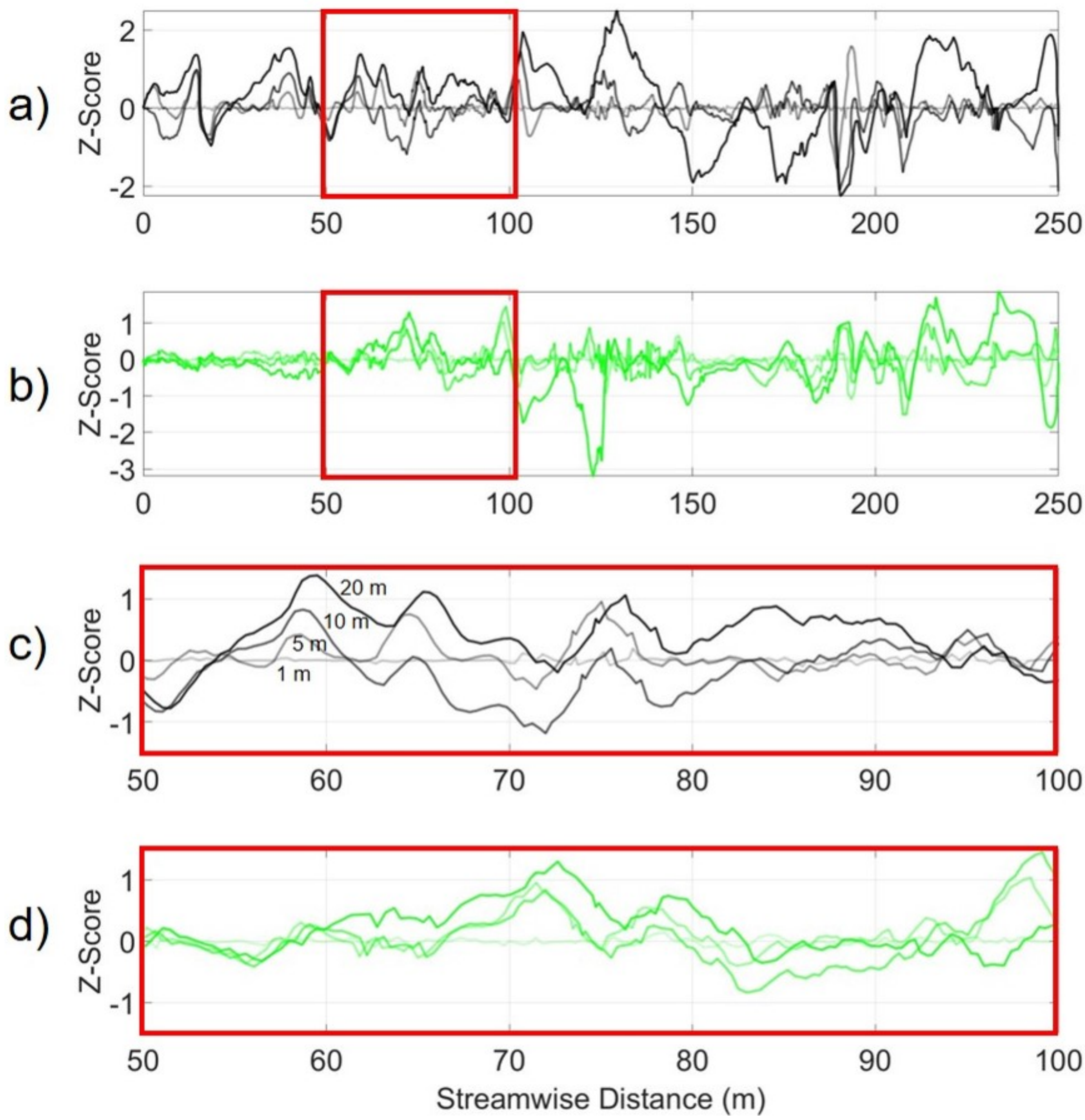

Figure 3. a) Multiscale lateral deviations (z-scores) based on 1, 5, 10 and 20 m track alignment to a channel-fitted coordinate system. b) Multiscale vertical deviations (z-scores) using the same procedure as the lateral deviations. c) Rescaled region between 50 and 100 m along the streamwise axis showing the progressive changes in 1, 5, 10 and 20 m lateral deviations. d) Vertical deviations of the rescaled region.

3 RESULTS AND DISCUSSION

3.1 *Groundspeed and acceleration covariance*

The multiscale approach allows for the determination of changes in both the planar and vertical channel, corresponding to bends and step-risers, respectively. The stream-wise locations of bends and step-risers were determined by locating persistent high and low points along the stream-wise profile after averaging the multiscale deviations in the lateral and vertical directions.

The results of the GSCA calculated for an example track from the first field day (30.06.2019) are shown in Figure 4. Bends are detected as persistent lateral deviations across multiple scales and are shaded in gray. It can be seen that the GSCA peaks (e.g. at 60 and 125 m) tend to occur out of phase with the occurrence of a bend. This likely corresponds to the local increase in the velocity due to radial acceleration as the drifter travels through the bend, where the theoretical maximum velocity occurs downstream of the maximal lateral deviation, and is highly dependent on the bend geometry (Kitanidis and Kennedy 1984). The first two bends (20 and 40 m along the streamwise axis) did not co-occur with peaks in the GSCA, and it was observed that both bends had low gradients of both groundspeed and acceleration magnitude.

Similar to bends, step-risers in the supraglacial channel can be determined based on persistent multiscale vertical deviations along the streamwise axis of the channel-fitted coordinate system. Considering the investigated track in Figure 4, it can be seen that the GSCA failed to detect the smaller initial step-risers at 75 and 100 m. Co-occurrences of GSCA fluctuations and step-risers were however found further down the channel at 150 m as well as the final sequence of three step-risers (centered around 200 m), which ranged from 175 to 250 m along the streamwise axis. A large, non-persistent vertical deviation from the 20 m spacing data set was observed from 116 to 127 m. This region was found to correspond to a large diameter bend which transitioned into a higher velocity chute, and corresponded to a local increase in the GSCA in the same region. In general, it was observed that the strongest co-occurrence of GSCA peaks and fluctuations were related to regions with both bends as well as step-risers. This is consistent with rapidly-varying open channel flow, where it is well-established that changes in the current speed and acceleration magnitude are strongly coupled with the variations in bed height (e.g. vertical deviations) and cross-sectional form (e.g. lateral deviations) common to supraglacial streams.

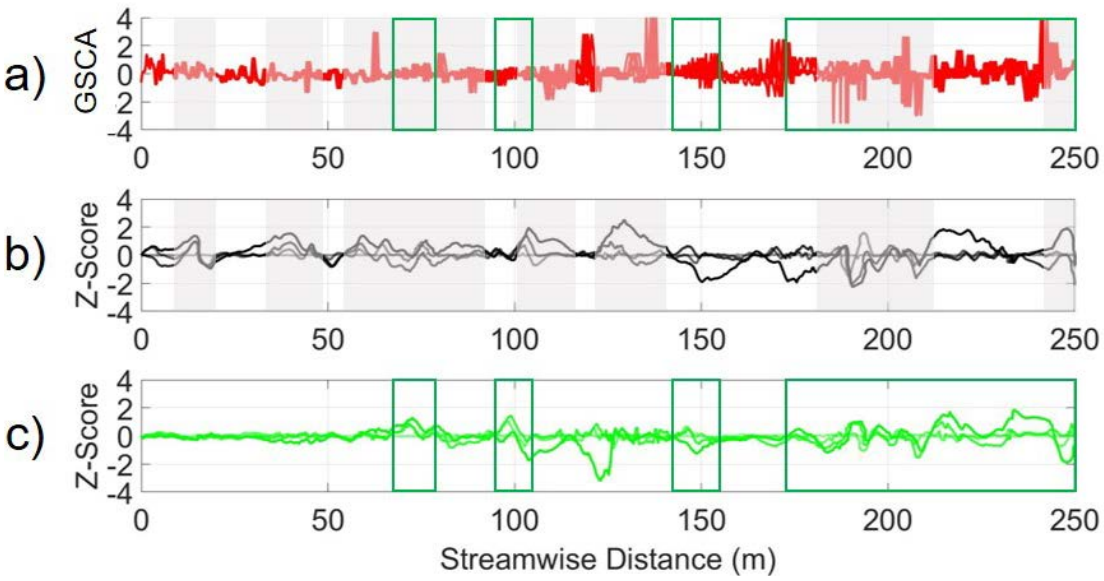

Figure 4. a) Groundspeed and acceleration magnitude covariance (GSCA). b) Multiscale lateral deviations along the streamwise axis using channel-fitted coordinates. Bend regions appear as persistent deviations across multiple scales and are shaded in gray. c) Multiscale vertical deviations, step-riser regions are detected as persistent multiscale deviations and are outlined in green.

3.2 *Groundspeed and magnetometer covariance*

The multiscale comparison of the GSCM to channel bend regions revealed a very co-occurrence pattern than the GSCA. Specifically, the largest changes in the GSCM tended to be out of phase with bend regions. Two clear examples are the initial low-high shift in the GSCM which precedes the first bend region (20 m) as well as the fourth bend region which begins at 100 m along the streamwise axis. There was no relationship between changes in the GSCM and the second bend region (40 m), indicating that unlike the GSCA, the GSCM may be less sensitive to local gradients in the flow regime caused by abrupt changes in the channel geometry.

A comparison of GSCM with vertical multiscale deviations indicates that the relationship is similar to the lateral results. Interestingly, the peak observed in the 20 m spacing vertical deviation from 116 to 127 m corresponds with a clearly-defined peak in the GSCA. This may be caused by a local variation in geological conditions (e.g. higher percentage of metal) as a rapid change in the flow parameters at this location was not observed. In general, the interpretation of the GSCM is much more challenging because the relationship between local variations in the magnetic field are not simply defined based on channel geometry and flow characteristics. Despite this challenge, the GSCM may provide new and potentially useful observations of the supraglacial environment.

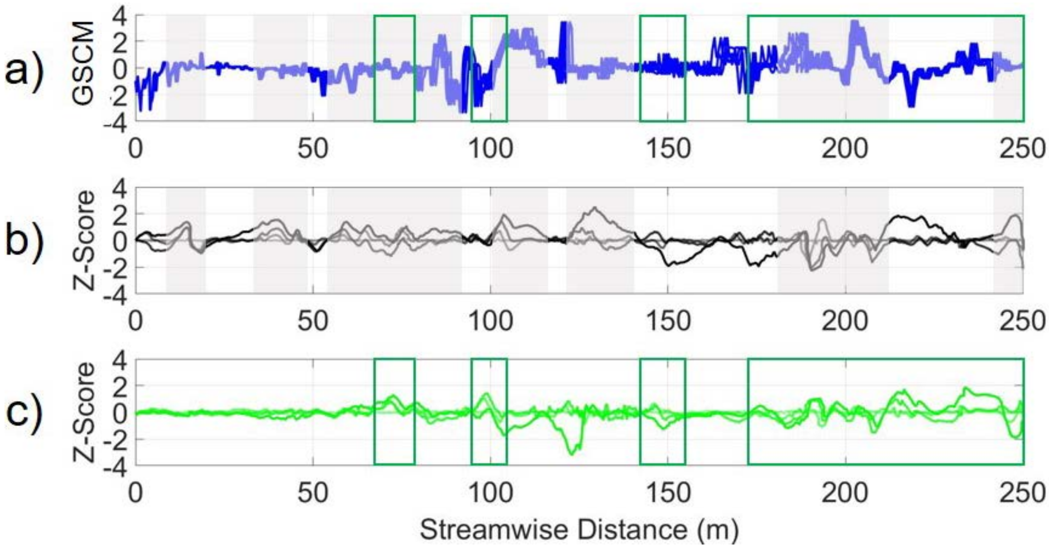

Figure 5. a) Groundspeed and magnetic field intensity magnitude covariance (GSCM). b) Multiscale lateral deviations along the streamwise axis using channel-fitted coordinates. Bend regions appear as persistent deviations across multiple scales and are shaded in gray. c) Multiscale vertical deviations, step-riser regions are detected as persistent multiscale deviations and are outlined in green.

4 CONCLUSIONS

Motivated by the lack of supraglacial field measurements, we constructed and deployed custom multimodal surface drifters which recorded the position, groundspeed, acceleration and magnetic field data. The data were used to investigate multiscale (1, 5, 10 and 20 m) changes in the river planform and vertical geometry. Persistent regions of multiscale horizontal deviations corresponded to bends, and vertical deviations to step-risers. A simple data-driven approach comparing the covariance between drifter groundspeed and the acceleration (GSCA) or magnetic field intensity magnitudes (GSCM) was developed. It was found that peaks and large fluctuations from both corresponded to bend and step-riser regions. However, it remains to be established if the observed co-occurrence patterns are repeatable and can be used to predict and define geometric changes in supraglacial streams. Establishing the accuracy of the drifters as well as detecting the exact positions of step-risers and small-scales morphological features would be possible using high-resolution imagery collected by unmanned aerial vehicles. In addition, more advanced filtering and clustering algorithms may be required to disambiguate changes in the GSCA and GSCM. Another important step is to investigate data from multiple drifter tracks obtained on the same day. These data can then be cross-compared to tune and validate statistical models to predict geometric change using drifter parameter covariance.

Future work to improve both the drifter electronics as well as data processing is ongoing. A new electronics design is now being tested which will reduce the drifter's length scale by a factor of five (5 cm vs. 25 cm), increase the sampling rate twentyfold (100 Hz vs. 5 Hz) and reduce the unit cost to 150 EUR. Onboard processing of the data will allow each device to export multiscale sensor covariance via radio modules in real-time. This will provide future field campaigns with higher-level analytical representations of the drifter data, ideally in larger and more complex supraglacial streams. We are cautiously optimistic that the data-driven method proposed in this work can be applied in unexplored subglacial channels where the direct observation of planform morphological features is currently impossible.

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