Lateral meltwater transfer across an Antarctic ice shelf

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Abstract

Surface meltwater on ice shelves can be stored as slush, in melt ponds, in surface streams and rivers, and may also fill crevasses. The collapse of the Larsen B Ice Shelf in 2002 has been attributed to the sudden drainage of ~3000 surface lakes, and has highlighted the potential for surface water to cause ice shelf instability. Surface meltwater systems have been identified across numerous Antarctic ice shelves, however, the extent to which these systems impact ice shelf instability is poorly constrained. To better understand the role of surface meltwater systems on ice shelves, it is important to track their seasonal development, monitoring the fluctuations in surface water volume and the transfer of water across the ice shelf. Here, we use Landsat 8 and Sentinel-2 imagery to track surface meltwater across the Nivlisen Ice Shelf in the 2016-2017 melt season. Using the Fully Automated Supraglacial-Water Tracking algorithm for Ice Shelves (FASTISh), we identify and track the development of 1598 water bodies. The total volume of surface meltwater peaks on 26th January 2017 at 5.5 x 10^7 m^3. 63% of this total volume is held within two large linear surface meltwater systems, which are orientated along the ice shelf’s north-south axis and appear to migrate away from the grounding line during the melt season, facilitating large scale lateral water transfer towards the ice shelf front. This transfer is facilitated by two large surface streams, which encompass smaller water bodies and follow the surface slope of the ice shelf.

1 Introduction

The total mass loss from Antarctica has increased from 40 ± 9 Gt/y in 1979–1990 to 252 ± 26 Gt/y in 2009–2017, providing a cumulative contribution to sea-level rise of 14.0 ± 2.0 mm since 1979 (Rignot et al., 2019). Mass loss from Antarctica will likely increase in the near future due, at least in part, to the shrinkage and thinning of some of its ice shelves (Siegert et al 2019; DeConto and Pollard, 2016; Munneke et al., 2014) and the associated acceleration of inland ice across the grounding lines (Fürst et al., 2016; Gundmundsson et al., 2019). Seven out of 12 ice-shelves that bordered the Antarctic Peninsula have collapsed in the last 50 years (Cook and Vaughan, 2010). One of the most notable events was the February-March 2002 collapse of Larsen B, leading to both an instantaneous and longer-
term speedup of the glaciers previously buttressed by the ice shelf (Scambos et al., 2004; Wuite et al., 2015; De Rydt et al., 2015), and resulting in their increased contribution to sea level rise (Rignot et al., 2004).

The unforeseen catastrophic disintegration of Larsen B highlighted the unpredictable nature of ice shelf collapse, and prompted a search for the causes of ice shelf instability. Current understanding of the factors causing ice-shelf instability stems from the very limited number of airborne and satellite observations prior to and following collapse events (e.g. Glasser and Scambos, 2008; Scambos et al. 2009; Banwell et al., 2014), numerical modelling (e.g. Vieli et al. 2006, Banwell et al. 2013, Banwell and MacAyeal, 2015), and the few in-situ measurements investigating recent and current ice shelf processes (e.g. Hubbard et al. 2016; Banwell et al. 2019). It has been suggested that the chain reaction drainage of ~3000 surface meltwater lakes may have triggered the near-instantaneous break-up of Larsen B (Robel and Banwell, 2019; Banwell et al., 2013), highlighting the potential importance of surface hydrology for ice shelf instability.

Kingslake et al. (2017) identified numerous pervasive surface meltwater systems across many of Antarctica’s ice shelves. Meltwater production is often highest around grounding lines, driven by high net shortwave radiation associated with low albedo blue ice areas, high net longwave radiation around nunataks, and high sensible heat transfer from adiabatic warming of katabatic winds (Bell et al., 2018; Lenaerts et al., 2017). Ice shelf hydrological systems may then take several forms as meltwater may: (i) form surface streams and flow downslope (e.g. Liston and Winther, 2005; Bell et al. 2017); (ii) collect in surface lakes (e.g. Langley et al. 2016); (iii) percolate into the sub-surface and refreeze (Bevan et al., 2017; Hubbard et al., 2016; Luckman et al., 2014); (iv) percolate into the subsurface and flow laterally (Liston et al., 1999; Winther et al., 1996); or (v) percolate into the subsurface and form sub-surface lakes and reservoirs (e.g. Lenaerts et al. 2017). Despite the identification of pervasive meltwater systems, very little is known about their spatial and temporal evolution, both within and between melt seasons. Furthermore, while surface water ponding and the formation of lakes have been implicated in past ice shelf collapse events (Banwell et al., 2013; Scambos et al., 2003), the formation of surface water streams that route water quickly to the ice shelf front, may not necessarily cause instability but rather mitigate against potential surface meltwater-driven collapse (Bell et al., 2017). Thus, whether future projected increased surface melt on ice shelves forms lakes or flows rapidly to the ocean via streams has important implications for future ice shelf stability and potential collapse (Banwell, 2017; Bell et al., 2018). To better understand the role of these surface meltwater features on ice-shelf instability, it is important to investigate the spatial and temporal evolution of surface lakes and streams across entire ice shelves through entire summer melt seasons.

In this paper, our objective is to develop a tool that can identify both surface lakes and streams on Antarctic ice shelves and track their evolution over individual melt seasons. We build on the work of Pope et al. (2016) and Selmes et al. (2011, 2013) and especially Williamson et al. (2017; 2018a), who developed and used the FAST algorithm for tracking...
lakes on the Greenland Ice Sheet (GrIS) using MODIS imagery. More specifically, we have 89 adapted the FASTER algorithm of Williamson, et al. (2018b) and Miles et al. (2017), who 90 adapted the FAST method to track GrIS lakes from the higher resolution Landsat-8 and 91 Sentinel-1 and -2 imagery. Here, we advance this later work to produce ‘FASTISH’, a Fully 92 Automated Supraglacial Lake and Stream Tracking Algorithm for Ice Shelves. We develop 93 the method for use with Landsat-8 and Sentinel-2 data to detect and differentiate between 94 surface lakes and streams and track them over time. We apply the technique to the Nivlisen 95 Ice Shelf, Antarctica, for the 2016-2017 melt season.

2 Study Area

The Nivlisen Ice Shelf (70.3°S, 11.3°E), is situated in Dronning Maud Land, East Antarctica, 100 between the Vigrid and Lazarev ice shelves (Fig. 1). It has a surface area of 7,600 km², and 101 is 123 km wide by 92 km long. Ice thickness ranges from 150 m at the calving front to 700 102 m towards the southeast, and it exhibits flow velocities of around 100 m a⁻¹ (Horwath et al., 104 2006). To the southeast of the Nivlisen Ice Shelf, there is a bare ice region maintained by 105 katabatic winds, which extends in a south easterly direction for approximately 100 km 106 (Horwath et al., 2006). This bare ice region is characterised by ablation, and adjoins the 107 exposed bedrock nunatak (called the Shirmacheroseas), which is positioned where the ice 108 shelf meets the inland ice (Horwath et al., 2006). The ice shelf was selected for this study 109 as: i) pervasive surface meltwater features have previously been identified here in optical 110 satellite imagery (Kingslake et al., 2017); ii) meltwater features show changes over time 111 (Kingslake et al., 2015); and iii) the ice shelf is relatively small, allowing quick and efficient 112 development and application of FASTISH, before it may be used more widely across larger 113 Antarctic ice shelves.

3 Methods

There are three main components to the FASTISH algorithm: i) detecting lake and stream 117 areas; ii) calculating lake and stream depths and volumes; iii) tracking individual lakes and 118 streams and measuring their changing dimensions over time. These will be discussed in 119 sections 3.2 to 3.5 respectively, once the pre-processing steps applied to the imagery used 120 have been outlined (section 3.1).

3.1 Images and Pre-Processing

3.1.1 Landsat 8

Between 1st November 2016 and 30th April 2017, 12 Landsat 8 scenes with minimal cloud 128 cover, each partially covering the ice shelf extent, were identified and downloaded from the 129 USGS Earth Explorer website (https://earthexplorer.usgs.gov). Each scene was 130 downloaded as a Tier 2 data product, in the form of raw digital numbers (DN). Bands 2 131 (blue), 3 (green), 4 (red) and 8 (panchromatic) were used for this study (Fig. 2). Bands 2, 3, 132 and 4 have a 30 m spatial resolution, and Band 8 has a 15 m spatial resolution. Image scene
values were first converted from DN to Top-of-Atmosphere (TOA) values, to adjust for variations in the per-pixel solar illumination angles. Each pixel was corrected for a specific solar illumination angle based on metadata stored in the .ANG file, and following the ‘Solar and View Angle Generation Algorithm’ suggested by NASA (https://landsat.usgs.gov/sites/default/files/documents/LSDS-1928_L8-OLI-TIRS_Solar-View-Angle-Generation_ADD.pdf). Converting from DN to TOA values on a per-pixel basis is imperative when mosaicking and comparing images obtained at high latitudes.

For each Landsat scene, a cloud mask was generated using the ‘Simple Cloud Score Algorithm’ (ee.Algorithms.Landsat.simpleCloudScore) in Google Earth Engine (GEE) and then downloaded. The simple cloud score algorithm assigns a ‘cloud score’ to every pixel in the image based on the following criteria: (i) brightness in bands 2 (blue), 3 (green), 4 (red); (ii) brightness in just band 2 (blue); (iii) brightness in bands 5 (near infrared), 6 (shortwave Infrared 1) and 7 (shortwave infrared 2); and iv) temperature in band 10 (thermal). The algorithm also uses the Normalised Difference Snow Index (NDSI) to distinguish between clouds and snow, which prevents snow from being incorrectly incorporated in the cloud mask. The NDSI was developed by Hall et al. (2001) to distinguish between snow/ice and cumulus clouds and is calculated from the following bands:

\[
\text{NDSI} = \frac{\text{Blue} - \text{Near Infrared 1}}{\text{Blue} + \text{Near Infrared 1}} \tag{1}
\]

Prior to implementing the FASTISH algorithm, each Landsat scene and corresponding cloud mask was clipped to the study area extent in ArcGIS using the batch clip process. This process of clipping each scene to the same extent is required when comparing images through the FASTISH algorithm. The 12 scenes formed six pairs, with two scenes per day each covering part of the ice shelf, and so each scene pair was mosaicked using ArcGIS’s ‘mosaic to new raster’ tool to produce six images. Thus, from Landsat imagery, we have near-complete coverage of the ice shelf for six days of the 2016-2017 melt season (S.4). All images were projected in the 1984 Stereographic South Pole co-ordinate system (EPSG: 3031).

### 3.1.2 Sentinel-2

20 Sentinel-2A level-1C scenes with minimal cloud cover were also downloaded between 1st November 2016 and 31st March 2017 from the Copernicus Hub web site (https://scihub.copernicus.eu). Bands 2 (blue), 3 (green), 4 (red), and 11 (short wave infrared (SWIR)) were then used. Bands 2, 3, and 4 had a spatial resolution of 10 m, and band 11 had a spatial resolution of 20 m. The Sentinel-2 data for all bands were downloaded as TOA reflectance values, but needed to be divided by the ‘quantification value’ (found in the metadata) of 10,000, to convert the numbers into values that lie within the expected zero to one range. We applied this conversion to bands 2, 3 and 4, as these are the bands used to identify water and calculate its depth, and their values need to be comparable to the values provided by Landsat 8. Each downloaded scene was clipped, mosaicked to give images with full coverage of the ice shelf, and then re-projected to the WGS 1984 Stereographic
South Pole co-ordinate system (EPSG: 3031), in line with the Landsat scenes (S.4). We computed a cloud mask for each image using a thresholding approach, and pixels were categorised as cloudy if the SWIR band value was > 10,000. This threshold was selected through visually assessing the effectiveness of various thresholds against the corresponding RGB scenes. As the resolution of the original SWIR band was 20 m, the resultant cloud masks were resampled using nearest neighbor interpolation to 10 m spatial resolution. On two image dates (14th November 2016 and 25th February 2017), this cloud masking approach was not entirely successful, and additional individual masks were manually created, to ensure all clouds were masked fully.

3.2 Delineating Water Body Areas

Lake and stream areas were determined using the Normalised Difference Water Index for ice (NDWI\textsubscript{ice}), which has widely been used previously to calculate the distribution of surface meltwater features on the GrIS and on Antarctic ice shelves (e.g. Yang and Smith 2013; Moussavi et al., 2016; Koziol et al. 2017; Macdonald et al. 2018; Williamson et al. 2018b; Banwell et al. 2019). It is calculated from the normalised ratio of the blue and red bands as:

\[
\text{NDWI}_{\text{ice}} = \frac{\text{Blue} - \text{Red}}{\text{Blue} + \text{Red}}
\] (2)

These bands were used because water has high reflectance values in the blue band, and there is a relatively large contrast between ice and water in the red band (Yang and Smith, 2013). Studies typically apply a single NDWI\textsubscript{ice} threshold to an image, to classify pixels as either ‘wet’ or ‘dry’ (e.g. Fitzpatrick et al., 2014; Moussavi et al. 2016; Miles et al. 2017). For example, Banwell et al. (2019) applied a single threshold to distinguish water covered pixels (>0.07) from ice pixels (≤0.07) on the McMurdo Ice Shelf, Antarctica. Across both Greenland and Antarctica, most studies have used a relatively strict NDWI\textsubscript{ice} threshold of 0.25 to map ‘deep’ water bodies on ice (Yang and Smith 2013, Bell et al. 2017, Williamson et al. 2018b). The same approach was applied to the Nivlisen Ice Shelf in this study in order to facilitate the detection of deep water bodies only. This is important as if too much shallow water and slush is detected, identifying and subsequently tracking individual water bodies over time becomes difficult. Having applied a 0.25 NDWI\textsubscript{ice} threshold to the available images, each resulting water mask was filtered using a two-dimensional connective threshold to remove all groups of pixels of ≤ two pixels in Landsat 8 images and ≤ 18 pixels in Sentinel-2 images, ensuring only water bodies with an area ≥ 1,800 m\textsuperscript{2} were assessed further.

3.3 Water Body Depth Calculations

As discussed above, the NDWI\textsubscript{ice} method (Equation 2) is widely used for mapping water body area, and has been used previously to provide qualitative assessments of water depths across both Greenland and Antarctica. Quantitative calculations of water depth, however, have favoured a different, more physically-based approach (Arnold et al., 2014; Banwell et al., 2019, 2014; Pope, 2016; Pope et al., 2016; Sneed and Hamilton, 2007; Williamson et al., 2017, 2018b), based on the original work of (Philpot, 1989), and this is the approach we
adopt in this study. Water depth, \( z \), is calculated from:

\[
\begin{align*}
  z &= \frac{\ln(A_d - R_w) - \ln([R_{pix} - R_w])}{g} \\
\end{align*}
\]  

(3)

where \( R_{pix} \) is the satellite-measured pixel reflectance, \( A_d \) is the lake-bottom albedo, \( R_w \) is the reflectance value for optically deep (> 40 m) water, and \( g \) is the coefficient associated with the losses made during downward and upwards travel in a water column.

For the Landsat 8 images, water depths were calculated for each water pixel in each water body using TOA reflectance data for both the red and panchromatic bands separately, and then these values were averaged to give a single final value (Pope et al., 2016; Williamson et al., 2018b). The average error associated with lake depths using this method has previously been calculated to be zero, as the negative and positive errors cancel out (Pope et al., 2016; Banwell et al., 2019). In our study, the panchromatic band was first resampled using bilinear interpolation from 15 m to 30 m spatial resolution to match the resolution of the red band. For the Sentinel-2 images, water body depths were calculated using the TOA reflectance values in the red band only, as there is no equivalent panchromatic band (Williamson et al. 2018b). To calculate \( A_d \), the average reflectance value of the second (Landsat) and sixth (Sentinel) ring of pixels surrounding each water body was calculated (following a similar approach used by Arnold et al., 2014 and Banwell et al., 2014). The second or sixth ring of pixels surrounding each lake was used to avoid calculating \( A_d \) from slushy areas that border each water body; sixth-pixel rings were used for Sentinel-2 images as these represent the same distance away from the water body as two-pixel rings in Landsat images. Values for \( R_w \) were assessed on an image-by-image basis, by taking the minimum reflectance value found over optically deep water (the ocean). For Landsat 8 imagery we used a \( g \) value of 0.7507 for the red band, and 0.3817 for the panchromatic band (Pope et al., 2016), and for Sentinel-2 imagery, we used a value of 0.8304 (Williamson et al., 2018b). Individual water body volumes were calculated by multiplying each pixel area by its calculated water depth, and then summing across the water body. To facilitate comparisons between Landsat 8 and Sentinel-2 data, area and depth arrays generated from Landsat 8 images were then resampled to 10 m spatial resolution using nearest neighbour interpolation.

### 3.4 Classifying Water Body Types

Having produced area and depth masks for each date, each identified water body was categorised as either a lake or stream. This classification reflects only the morphology of each water body, and does not imply anything about the rate of water flow. To distinguish between lakes and streams we classified each water body based upon its solidity (defined as the proportion of pixels of the water body that fall within its convex hull), which was calculated using the ‘regionprops’ function in MATLAB. Water bodies with a solidity score \( \geq 0.45 \) were classified as individual lakes, and water bodies with a solidity score < 0.45 were classified as streams. This threshold was selected by visually assessing the masks.
generated from thresholds ranging between 0.42 and 0.49, in increments of 0.01, and selecting the threshold that appears to best distinguish between more rounded lakes and more linear streams.

3.5 Tracking Water Bodies

To track changes in the area and volume of surface meltwater bodies throughout the 2016-2017 melt season, a maximum extent mask showing the maximum extent of all water bodies during the melt season was generated by superimposing the areas of all water bodies identified in each image (Williamson et al., 2018b). The maximum extent mask was then used to guide the tracking process, and each individual water body within the maximum extent was prescribed an ID, and changes to the area and volume of each individual water body over time were tracked within its maximum extent (Williamson et al., 2018b).

In addition to tracking changes in the area and volume of each water body, the FASTISh algorithm also tracks the water body type. To achieve this, a 3D matrix of all water bodies was compiled, recording the area and volume of each water body over time, as well as whether the water body is a lake or a stream. From this tracking process, four categories were defined: (i) always a lake, (ii) always a stream, (iii) ‘simple transitions’ where a water body is defined as either a lake or a stream and switches between the two categories (either once or more than once, and in either direction), and (iv) ‘envelopment transitions’ where water bodies spread and merge with neighbouring lakes and streams to form new, larger bodies, or where larger bodies split into smaller lakes and streams. This final category allows us to track the development of large surface water bodies across the ice shelf surface as it identifies smaller water bodies being subsumed by larger water bodies as the melt season progresses.

3.5.1 Tracking volume loss from surface lakes

Following previous studies (e.g. Fitzpatrick et al., 2014; Miles et al., 2017; Williamson et al., 2018b), we identified and track volume losses from each water body in the ‘always a lake’ category to better understand the local loss of surface melt water in seemingly isolated and stationary water bodies. Previous studies have attempted to identify rapid drainage events, defined as events where lakes lose > 80 % of their maximum volume in ≤ four days (e.g. Fitzpatrick et al., 2014; Miles et al., 2017; Williamson et al., 2018b), however, the temporal resolution of available imagery for the Nivlisen Ice Shelf is not great enough to facilitate this. Therefore, we used our calculated volume time series to identify any lakes that lost > 80 % of their maximum volume over the full melt season (referred to as ‘loss events’ hereafter).

3.8 Digital Elevation Model

To aid interpretations of the tracking results produced by the FASTISh algorithm, we used surface elevation data from the REMA database (Howat et al., 2019). Figure 3a shows a mosaic DEM product at 8 m resolution, which was used to visualize the topography of the
ice shelf and to plot the elevation distribution of some of the main water bodies identified. In addition, a single 2 m data strip acquired on 31st January 2016, was used to extract the elevation profiles along some of these main water bodies.

3.7 Meteorological Data

To put the calculations of meltwater volume into the context of seasonal variations in surface meltwater production rates, we used surface air temperature and ground surface temperature data for Novolazarevskaya station (70°46'04" S and 11°49'54"E), Nivlisen, downloaded from the Russian Federation NADC, Arctic and Antarctic Research Institute (AARI) (http://www.aari.aq). The station is positioned on the southeastern edge of the Shirmacheroase, and is 80 km inland from the Lazarev Sea Coast. Monthly mean averages were plotted for the duration of the melt season (1 November 2016 - 30 April 2017).

4 Results

4.1 Spatial Extent and Distribution of Surface Water Bodies

The seasonal evolution of meltwater occurrence during the 2016-2017 summer is shown in Figure 4. On 11th December 2016, few meltwater bodies exist, and they are predominantly clustered towards the grounding line in the south-west, where the ice shelf surface is relatively flat and the winter snow cover is thin (Fig. 4A). The majority of these water bodies exist as distinct entities, and do not connect to one another. Some meltwater ponds are identified in close proximity to the nunatak. The mean water depth on 11th December is 1.0 m, and the maximum water depth is 3.4 m.

By 17th December (Fig. 4B), there has been a marked increase in the area and volume of surface meltwater, held in both surface lakes and streams; the mean water depth is 0.7 m and the maximum water depth is 3.1 m. Several of the previously isolated ponds have coalesced in some of the main topographic lows. The spatial extent of the surface water bodies extends ~ 2 km further towards the ice shelf front. In addition, some water bodies have begun to develop towards the eastern edge of the grounding line in a blue ice region.

By 27th December (Fig 4C), there is a marked development in the surface meltwater system, as two surface streams have formed along the north-south axis (labelled a and b in Fig. 4C). The Western stream (a) is ~ 6.5 km long and ~ 10 km from the Eastern stream (b), which is ~ 8.5 km long and proximal to the surface lakes on the ice shelf's eastern margin. Overall, there are fewer isolated lakes towards the grounding line, and the majority of the surface meltwater is proximal to the two large surface streams, at elevations of ~ 60 m to 65 m (Fig. 3). The mean water depth of all identified water bodies is 0.9 m and the maximum water depth is 4.7 m.

On 26th January 2017 (Fig. 4D), the area and volume of surface meltwater reaches a peak for the summer, facilitated by the enlargement of the two large surface streams, which involve the flooding of topographic lows, as water appears towards the firn further north on the ice shelf. These streams are now (a) ~ 20.5 km and (b) ~ 16.9 km in length, and have a mean depth of (a) 0.8 m and (b) 0.7 m. The mean depth of all water on 26th January 2017 is 0.6 m and the maximum water depth is 3.3 m.
On 13th February (Fig 4E), the two large streams remain prominent on the ice shelf, however they have lost area, depth and volume at their southern ends. The mean water depth of all water is 0.6 m and the maximum water depth is 4.3 m.

### 4.2 Tracking Results

Of the 1598 water bodies identified and tracked within the maximum extent matrix, 1458 (91%) are defined as always a lake, 42 (3%) are identified as always a stream, 51(3%) are defined as simple transitions, and 47 (3%) are categorised as envelopment transitions. Water bodies that are always a lake are predominantly clustered further south on the ice shelf towards the grounding line, while water bodies defined as envelopment transitions are found further north, towards the ice shelf front (Fig. 5).

#### 4.2.1 Total Area and Volume of Tracked Surface Water Bodies

For each of the tracked water body categories, Table 1 shows the maximum area and volume, and the corresponding dates on which these maxima were reached. The minimum area and volume for all tracked categories is zero on 14th November 2016, as no deep surface melt water was detected on that date. Although 91% of water bodies identified are classified as lakes, lakes do not dominate the total area or volume of surface meltwater (Table 1, Fig. 6). Conversely, the envelopment transitions, of which there are only 47 in total, peak at 8.0 x 10^7 m^2 in area and 4.5 x 10^7 m^3 in volume on 26th January 2017, which is over a month later than the peaks in area and volume recorded for the other three categories. These envelopment transitions dominate the total area and volume signals for ‘all water bodies’ (Table 1), which also reach their maxima on 26th January (Table 1, Fig. 6).

#### 4.2.2 Tracking Individual Water Bodies

In addition to producing a time series of total surface water area and volume for each of the four water body categories, the FASTIsh tracking algorithm also produces time series of individual water body areas and volumes. Over the 2016-2017 melt season, the two largest envelopment transitions, referred to as the Western System (WS) and the Eastern System (ES) hereafter (Fig. 5), propagate towards the ice shelf front as the melt season progresses, and contain 62.6 % of the total surface water volume on 26th January 2017.

The volume of meltwater within the WS increases from zero on 11th December 2016 to a maximum of 2.5 x 10^7 m^3 on 26th January 2017, before declining to zero again by 24th March 2017 (Fig. 7). The ES has a shorter lifespan, and is active between 27th December 2016 and 25th February 2017 (Fig. 7). Its volume peaks at 9.6 x 10^6 km^3 on the 26th January 2017 (Fig. 7). In line with the trends described in section 4.1, both the ES and WS migrate north towards the ice shelf front as the melt season progresses.

Figure 7 shows the elevation distribution for each meltwater system on three dates: 27th December 2016, 26th January 2017 and 13th February 2017. Overall, the WS occupies a total elevation range of just 59 to 66 m (Fig. 7a). On 27th December 2016, the majority of this surface water is held in the 62 to 63 m range, accounting for 5.4 x 10^6 m^2 (Fig. 7a). This is also true at the height of the melt season, when 1.1 x 10^7 m^2 of water is within the 62 to 63 m bin on 26th January 2017. However, by 13th February 2017, the majority of the surface water is held in the slightly lower 61 to 62 m elevation range, which accounts for 7.9 x 10^6 m^2 of surface melt (Fig. 7a). Over the three dates, the ES occupies a total elevation range
of 51 to 65 m (Fig. 7b). On 27\textsuperscript{th} December 2016, the majority of the water (1.9 x 10\textsuperscript{6} m\textsuperscript{3}) is clustered at an elevation of 63 to 64 m, whilst on 26\textsuperscript{th} January and 13\textsuperscript{th} February 2017, 3.1 x 10\textsuperscript{6} m\textsuperscript{3} and 2.6 x 10\textsuperscript{6} m\textsuperscript{3} of water respectively is clustered within the 58 to 59 m bin.

Figure 8 shows the surface elevation profiles for the WS and the ES, which are extracted from the maximum extent matrix (a composite image made by superimposing the areas of all water bodies identified in each image, to retrieve the maximum extent of each water body). Both systems are characterised by a downward sloping surface towards the ice shelf front. The WS has a very shallow slope, with the elevation decreasing by \textasciitilde 2 m over the full 25.7 km profile (Fig. 8a), the ES is slightly steeper, showing a \textasciitilde 6 m decrease in elevation over its full 27 km profile (Fig. 8b). While the overall trends for both profiles show a decrease in elevation, both are also characterised by rhythmic variance and high frequency variability over short distances (Fig. 8).

4.2.2 Identifying Individual Lake Freeze Through/Drainage Events.

Figure 9 shows the loss in water volume through freeze-through or drainage for the ‘always a lake’ category over the melt season, together with the ground surface temperatures and surface air temperatures from the Novolazarevskaya Station. 805 lakes have a ‘loss event’ by 27\textsuperscript{th} December 2017, losing a total volume of 1.5 x 10\textsuperscript{7} m\textsuperscript{3}, despite increasing air surface and ground surface temperatures (Fig. 9).

5 Discussion

Spatial and Temporal Distribution of Surface Meltwater Bodies

In the early melt season, surface meltwater on the Nivlisen Ice Shelf ponds in small surface lakes that form in relatively flat areas towards the grounding line, in close proximity to the Shirmacheroasen and blue ice regions (Figs. 3 and 4). This initial generation of surface meltwater is likely driven by regional wind patterns and the effects of local ice-albedo, as the relatively low albedo of the blue ice can lead to increased local melt rates (Bell et al., 2018; Lenaerts et al., 2017; Stokes et al., 2019). Furthermore, areas of lower elevation towards the grounding line are likely to be exposed to katabatic winds, which can result in near-surface temperatures that are 3 K greater than temperatures further up-ice and down-ice (Lenaerts et al. 2017). These persistent katabatic winds can also result in the production of blue ice regions, as snow is eroded from the ice shelf surface (Lenaerts et al., 2017). Our results for the early melt season on the Nivlisen Ice Shelf therefore support the findings of Kingslake et al. (2017) who found, for a variety of ice shelves around Antarctica, that 50 % of the ice shelf drainage systems are either within 8 km of rock exposures, or within 3.6 km of blue ice surfaces.

Seasonal variations in the amount of surface meltwater on the Nivlisen Ice Shelf are driven by weather, with increases in surface water area and volume corresponding with rising ground and air surface temperatures (Fig. 9). However, as the melt season progresses, there is a transition to a connected surface drainage network, which facilitates a progressive transfer of surface meltwater away from the grounding line towards the ice shelf front. As temperatures rise and surface water bodies increase in area and volume, they grow, merge with nearby water bodies, and form new extended networks of surface lakes and streams on the ice shelf surface. While rising ground and air temperatures are a strong control on
the amount of surface meltwater, the direction and extent of the identified lateral water transfer is controlled by the ice shelf's surface topography (Fig. 3b). Over the course of the melt season, the area and volume of surface meltwater decrease in the regions close to the grounding line, and increase in more distal parts of the ice shelf.

The development of the two largest enveloping water bodies (WS and ES) dominate the transition to a generally more connected drainage network. This is because these systems facilitate large-scale transfer of water across the shelf, as water flows along linear depressions from high to low elevations (Figs. 8 and 9). The ES and WS appear to be fed by smaller surface lakes and streams, both above and below the grounding line, and as the area and volume of the ES and WS increases, they spread and envelope nearby water bodies, likely as water ponds up and flows over impermeable ice, which is refrozen surface or shallow subsurface meltwater from previous years. Such processes were also observed by Kingslake et al. (2015). The ‘pulse’ forward of the ES and WS between 27th December 2016 and 26th January 2017 does not appear to be controlled by a topographic ‘lip’ or ‘dam’, and is therefore more likely to be the result of increased meltwater production, resulting in saturation of the surrounding firn pack, which may bring it up to isothermal conditions, thereby facilitating further melt and lateral transfer. By 26th January 2017, the ES and WS are the dominant features within the entire Nivlisen Ice Shelf meltwater system, holding 62.6% of the surface meltwater volume. On this date, the ES and WS reach a length of ~16.9 km and ~20.5 km respectively, although unlike observations on the Nansen Ice Shelf (Bell et al., 2017), they do not facilitate the export of surface meltwater off the ice shelf front via a waterfall. Instead, both systems always terminate at least ~35 – 55 km from the ice shelf front, suggesting that the water percolates into the surrounding firn in that area of the ice shelf. Whilst the drainage system currently observed on the Nivlisen Ice Shelf does not transfer surface meltwater all the way to the ice shelf front, it is plausible that such a system will develop in the future, as the quantity of surface meltwater produced increases. Whilst the water may pond, (possibly resulting in eventual hydrofracture and ice shelf collapse), the ES and WS may also evolve quickly and sufficiently to allow water to flow off the ice shelf front, effectively exporting the excess meltwater and mitigating some of the threats to the ice shelf stability (Bell et al., 2017; Banwell, 2017).

Overall, 1.6 % of the Nivlisen Ice Shelf is occupied by a surface meltwater body at some point during the 2016-2017 melt season, and over those areas, the mean water depth is 0.85 m. Comparatively, prior to its collapse, 5.3 % the Larsen B Ice Shelf was covered by a surface meltwater body, and the mean water depth was 0.82 m (Banwell et al., 2014). Whilst the mean water body depths between the Larsen B and Nivlisen Ice Shelves are comparable, the spatial distributions of these water bodies, and the proportion of the ice shelf that they cover, are different. Surface lakes were distributed relatively evenly across the entire surface of Larsen B before it collapsed, whereas surface lakes are predominantly clustered towards the grounding line on the Nivlisen Ice Shelf, and the transfer of surface melt towards the ice shelf front and across snow/ firn covered regions is predominantly facilitated by the WS and ES. The relatively extensive snow and firn cover on the Nivlisen Ice Shelf likely prevents the development of a similar meltwater distribution to that observed on the Larsen B Ice Shelf, as much of the surface meltwater is able to percolate into available pore space.
Loss in Water Volume from Surface Lakes

The loss of $1.5 \times 10^7 \text{ m}^3$ of surface water from surface lakes by 27th December 2017, despite increasing air surface and ground surface temperatures (Fig. 9), coincides with an increase in the volume of water held within the enveloping water bodies, which continues to increase up to a maximum of $4.5 \times 10^7 \text{ m}^3$ on 26th January 2017. It is likely, therefore, that the loss of water from surface lakes at such an early stage in the melt season signifies the lateral transfer of water, away from the small ‘isolated’ lakes near the grounding line, and into the large enveloping water bodies, which hold and transport the surface meltwater across the ice shelf in more distal regions. This lateral transfer of water may be occurring through two mechanisms, (i) the over-topping of surface lakes, which results in the formation of shallow channels that connect water bodies and facilitate the transfer of water towards the ice shelf front (e.g. Banwell et al., 2019), or (ii) the gradual percolation of surface meltwater into the cold firm pack, which reduces the firm air content (FAC) of a region, therefore creating an impermeable surface over which water can flow (e.g. Kingslake et al., 2015). The firm may also become saturated enough to be isothermal, therefore melting and facilitating the flow of upstream ponded meltwater. This is particularly likely to occur near surface depressions such as those that are later occupied by the WS and ES. The FAC is determined by the melt to accumulation ratio, and if the surface melt on an ice shelf increases relative to precipitation, its FAC will drop, reducing the available pore space for meltwater storage (Lenaerts et al., 2017).

Potential Implications for Ice Shelf Stability

It is expected that the area of coverage and volume of surface meltwater on Antarctic ice shelves will increase into the future, in line with rising atmospheric temperatures (Bell et al., 2018; IPCC, 2019; Kingslake et al., 2017; Siegert et al., 2019). This surface water may have significant implications for ice shelf stability, as meltwater accumulation can lead to hydro-fracture, which could subsequently result in the collapse of an ice shelf, as seen on the Larsen B Ice Shelf in 2002 (Robel and Banwell, 2019; Banwell et al., 2013). An ice shelf may become increasingly vulnerable to hydrofracture if its FAC is reduced (Lenaerts et al., 2017). On ice shelves like the Nivlisen, where large scale lateral water transfer prevails, meltwater is delivered to locations that may otherwise not receive or experience much melt (Bell et al., 2017), and the FAC of these locations will, in turn, be reduced, increasing their susceptibility to surface meltwater ponding and hydrofracture. Surface meltwater re-freezing at the end of the melt season will also act as a significant source of heat, and the lateral transfer of surface melt could cause increased warming of the ice shelf and possible weakening in areas which currently do not experience significant summer melt. Were the maximum volume of surface meltwater we observe on the Nivlisen Ice Shelf in the 2016-2017 melt season ($5.5 \times 10^7 \text{ m}^3$) to re-freeze over the maximum area of surface meltwater ($9.1 \times 10^7 \text{ m}^3$), it would release an amount of energy equivalent to 49 days of potential solar energy receipts (Arnold and Rees, 2009), assuming an ice surface albedo of 0.86 (the mean value we observe over water-free distal areas of the ice shelf). Furthermore, large scale lateral water transfer and subsequent ponding may lead to ice shelf flexure (and therefore potential fracture) at locations that may otherwise not been affected by flexure in response to meltwater loading (Banwell et al., 2013, 2019; Macayeal and Sergienko, 2013). However, evidence of lateral water transfer and export off the Nansen Ice Shelf has highlighted the potential for surface drainage systems to mitigate some of these meltwater driven instabilities (Bell et al., 2017).
6 Conclusions

We have adapted the pre-existing FASTER algorithm, developed for studying lakes on the GrIS (Williamson et al., 2018b), so that we can identify and track the area, depth and volume of both surface lakes and surface streams across Antarctic ice shelves. We refer to this new algorithm as FASTIsh, and have used it to study the changing spatial patterns of lakes and streams across the Nivlisen Ice Shelf in the 2016-2017 melt season. In total, we identify and track 1598 water bodies on the ice shelf over the course of the melt season. Surface water is initially generated towards the nunatak and blue ice region, in proximity to the grounding line. This region is relatively flat and has a low albedo, and we therefore observe localised ponding of surface meltwater. As the melt season progresses and air and ground surface temperatures increase, we see a transition from isolated localised ponding towards the grounding line to a more connected drainage system, that is influenced by the ice shelf topography. The middle of the melt season (e.g. 27th December 2016) is characterised by the progression of surface melt water bodies towards the thin snow band and firm-pack, as two large extensive drainage systems (the East System (ES) and West System (WS) develop in long linear surface depressions. By the 26th January 2017, the ES and WS have fully developed, and facilitate the lateral transfer of surface melt up to 16.9 and 20.5 km north into the firm pack, and towards the ice shelf front. The transfer of surface meltwater to regions on the ice shelf that otherwise experience little surface melt may have implications for the structure and stability of the ice shelf in the future.

Code and Data Availability

The satellite imagery, REMA DEM, and meteorological data are all open access (see section 3). The MATLAB scripts used to process the data are available from the corresponding author upon request.

Author Contributions

RLD developed the methodology and scripts, building upon the prior work of AGW. NSA developed a script to convert Landsat DN values to per-pixel TOA values. RLD conducted the analysis and wrote the draft manuscript, under the supervision of all other authors. All authors discussed the results and were involved in editing of the manuscript.

Competing Interests

The authors declare no competing interests

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Figure 1: RGB Landsat image of the Nivlisen Ice Shelf acquired on 26th January 2017. The solid black line marks the grounding line, according to the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Antarctic boundaries dataset (Mouginot et al., 2017). The solid orange line shows the study area extent used for this study, and the solid red line marks the area shown in all subsequent figures. The red star on the inset shows the location of the Nivlisen Ice Shelf in the context of an image of Antarctica, which is a mosaic product based on sources from USGS, NASA, National Science Foundation, and the British Antarctic Survey (https://visibleearth.nasa.gov/view.php?id=78592).
Figure 2: A workflow detailing the methods applied to both the Landsat 8 and Sentinel-2 images through the FASTISh algorithm in MATLAB. Dashed lines indicate steps that were applied to Landsat 8 images only, whereas solid lines indicate steps that were applied to both sets of image types. Modified from Williamson et al. (2018b).
Figure 3: (a) DEM mosaic of the Nivlisen Ice Shelf, (b) DEM mosaic of the Nivlisen Ice Shelf overlain with the maximum extent matrix for the 2016-2017 melt season in white. DEM data sourced from the REMA dataset (Howat et al., 2019).
Figure 4: Five of the eleven dates studied in the 2016-2017 melt season (represented by labels A-E), and their corresponding (i) RGB images, (ii) lake and stream area masks, (iii) depth masks. See S.1 for all RGB images, S.2 for all lake and stream area masks and S.3 for all depth masks produced in this study.
Figure 5: The maximum extent of all identified water bodies on the Nivlisen Ice Shelf for the 2016-2017 melt season, colour coded by water body type. ‘WS’ denotes ‘Western System’, and ‘ES’ is ‘Eastern System’.

Figure 6: The total area and volume held in each water body category over the 2016-2017 melt season on the Nivlisen Ice Shelf. Volumes are indicated by the solid lines, and areas by the dashed lines.
Figure 7: Elevation Distribution Plots for (a) the Western System (WS) and (b) the Eastern System (ES) on the Nivlisen Ice Shelf for three dates in the melt season. Data points are plotted at the midpoint of their elevation bins along the X axis.

Figure 8: Elevation profiles for (a) the WS and (b) the ES, fitted with quadratic trendlines (in red). These data are extracted from REMA (Howat et al., 2019) and the path of data extraction was guided using the maximum depth matrix of both the WS and ES over the full 2016-2017 melt season (see S.6).
Figure 9: The total volume lost in ‘loss events’ from water bodies in the ‘always a lake’ category, plotted as bars. The total number of loss events for each date is indicated above each bar. Ground surface temperatures (purple) and air surface temperatures (dashed) are also plotted as dashed lines.

Table 1: Maximum Area and Volume and the corresponding dates for each water body category on the Nivlisen Ice Shelf in the 2016-2017 melt season.

|                  | Maximum Volume (m$^3$) | Maximum Area (m$^2$) | Date of Maximum Volume | Date of Maximum Area |
|------------------|------------------------|-----------------------|------------------------|----------------------|
| All Water Bodies | $5.5 \times 10^7$      | $9.1 \times 10^7$     | 26th January 2017      | 26th January 2017    |
| Always Lakes     | $1.4 \times 10^7$      | $1.5 \times 10^7$     | 17th December 2016     | 17th December 2016   |
| Always Streams   | $3.9 \times 10^5$      | $1.3 \times 10^6$     | 17th December 2016     | 17th December 2016   |
| Simple Transitions| $3.2 \times 10^6$     | $3.2 \times 10^6$     | 17th December 2016     | 17th December 2016   |
| Envelopment Transitions | $4.5 \times 10^7$ | $8.0 \times 10^7$ | 26th January 2017 | 26th January 2017 |

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