ESA CCI+ supraglacial lake analysis for the Sermeq Kujalleq (Jakobshavn Isbræ) catchment

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1. Description of supraglacial lake data

1.1 Area of interest

Supraglacial lakes were identified in the catchment of Sermeq Kujalleq (SK, also known by its Danish name, Jakobshavn Isbræ) for the melt season of 2019. Here, the catchment is defined as the glacier's hydrological catchment described by Mankoff et al. (2020) (displayed in Fig. 1), covering an area of 70976.74 km^2.

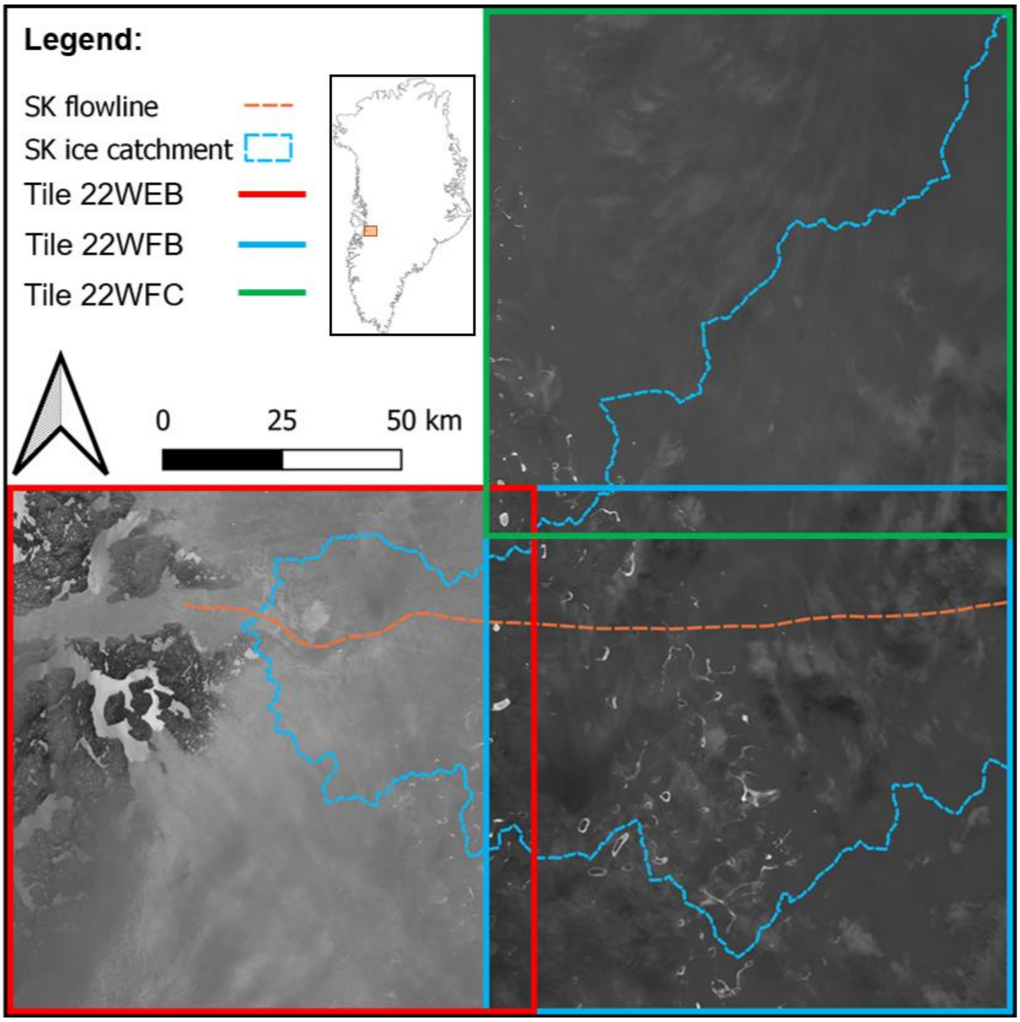

Fig. 1. The study region for identifying supraglacial lakes, consisting of three Sentinel-2 tiles that cover the Ilulissat region in West Greenland (22WEB, 22WFB and 22WFC, shown in red, blue and green, respectively). The blue dashed line signifies the hydrological catchment of SK, as defined by Mankoff et al. (2020). The orange dashed line is the SK flowline, used in subsequent velocity analyses. The example scenes shown are NDWI images, compiled from the green and NIR Sentinel-2 satellite images acquired on 25th August 2019. White regions on the ice sheet denote supraglacial lakes.

Three Sentinel-2 tile scenes intersect with the lower portion of this catchment – tiles 22WFB, 22WEB and 22WFC (Fig. 1). Tile 22WEB covers the glacier terminus to roughly 44 km inland, whilst tiles 22WFB and 22WFC cover the upper part (>44 km inland) of the SK catchment. The tiles cover different subsets of the catchment, as summarised in Table I In total, the tiles cover an area of 16 039.11 km^2, approximately 22% of SK's total catchment. Supraglacial lakes were detected from this given area for each time step, subject to data availability and cloud cover.

Table I. Summary of Sentinel-2 tile extents of the SK catchment

Tile name	Catchment region covered	Maximum catchment extent (pixels)	Maximum catchment extent (km^2)	Maximum percentage of ice catchment visible
22WFB	Upper	82092374	8209.24	11.6%
22WEB	Lower	27415069	2741.51	3.9%
22WFC	Upper	50883606	5088.36	7.2%

1.2 Data structure

The supraglacial lake dataset is distributed in two forms; as a series of vector polygon shapefiles, (one for each time step), and as a combined multi vector shapefile dataset. Within this dataset, general information about the detected supraglacial lake polygons is provided, such as polygon area, source and unique identification number, which is detailed in Table II.

Table II. Metadata supplied with the distributed forms of the detected supraglacial lake shapefiles

Attribute name	Description	Data type
Identification number ('id1')	Unique identification for supraglacial lake in scene. In cases where the lake coincides with an ArcticDEM-derived sink, the ID is consistent across all time steps	Integer
Satellite source ('source')	Satellite platform that lake was detected from (S2A or S2B)	Text
Satellite tile ('tile')	Satellite tile that lake was detected from (T22WEB, T22WFB or T22WFC)	Text
Satellite relative orbit ('row')	Satellite row that lake was detected from	Text
Acquisition date ('date')	Satellite scene acquisition data (YYYYMMDD)	Text
Lake elevation ('elev')	Elevation of supraglacial lake (metres a.s.l.), as defined from ArcticDEM	Integer
Lake area ('area1')	Supraglacial lake area (km^2)	Float

1.3 General findings

We identified over 6000 lake features (±15%) over the melt season, with an average lake area of 0.4 ±0.11 km^2 (Table III). The dataset was filtered to remove abnormally high lake counts, using a linear threshold of 100-150 lakes. Minimal manual input was needed to refine this dataset, only in rare instances where saturated snow surfaces had been falsely classified. An example of supraglacial lakes detected from a select time step is shown in Fig. 2.

Table III. Summary of lake identification over the three Sentinel-2 scenes

Tile name	Total number of lakes identified (±15%)	Maximum number of lakes identified per time step (±15%)	Average number of lakes identified per time step (±15%)	Average total lake area per time step (km^2) (±22%)
22WFB	2993	99 (16/07/2019)	25	23.1
22WEB	3190	104 (27/05/2019)	29	9.3
22WFC	49	3 (27/08/2019)	3	0.1

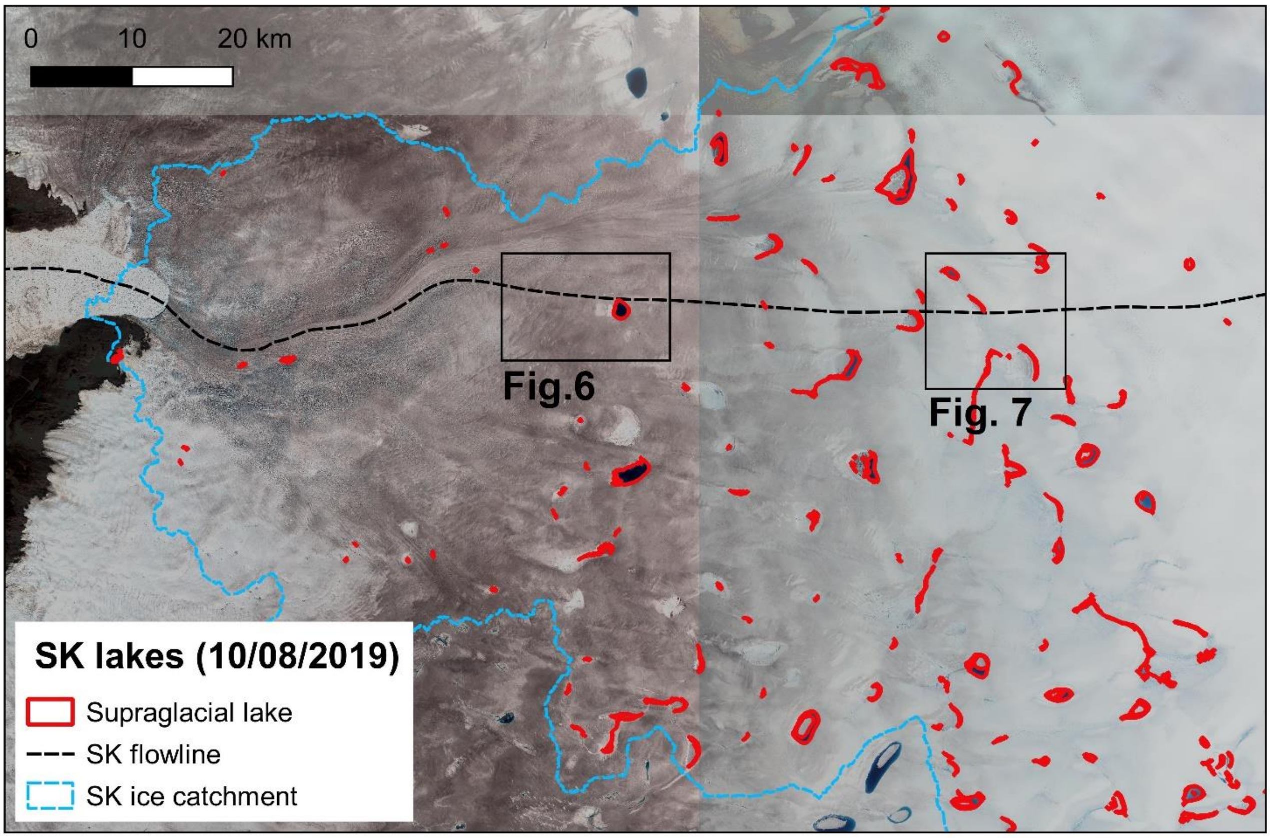

Fig. 2. An example of supraglacial lakes (red) detected from the SK catchment (blue) on 10/08/2019. The regions highlighted denote individual lakes of interest lying on the SK flowline (black dashed line), which are analysed in Fig. 6 and 7.

As expected, a high majority of these lakes were identified from tile 22WEB (3190 lakes in total), given that it covers the lower-elevation region of the SK hydrological catchment. Generally, high lake frequency is evident during the peak of the melt season in August.

2. Description of velocity data

The velocity data was downloaded as a flowline point dataset from the ENVEO Cryoportal, produced using Copernicus Sentinel-1 SAR data (Nagler et al. 2015). The resulting products were derived using offset tracking, providing an average velocity estimate for a given time interval between an image pair ranging from 6 to 12 days. The flowline extends approximately 150 km upstream, and includes 562 individual points with a spacing of 300m. *Error is introduced into the velocity data where there is poor feature matching. Mismatches are not filtered/accounted for in ENVEO's flowline velocity dataset, and therefore the associated errors remain in the velocity data presented* *subsequently. Instances where unfiltered velocity data is presented will be noted in the associated figure caption.*

The velocity data for 2019 comprised of 170,969 individual estimates from 01/01/2019 to 23/12/2019. The flowline was divided into two main components for the analysis of the supraglacial lake areal changes – the lower catchment and the upper catchment. The lower catchment is defined as the calving front to 54.6 km upstream, and the upper catchment is from 54.6 km to 184.2 km (i.e. the furthest flowline point considered in this study). ENVEO does not provide error estimates with the flowline data, and therefore error analysis is not provided as part of this study.

3. Results

3.1 Time-series analysis

Supraglacial lakes are evident in tile 22WEB (the terminus region of the catchment) at the beginning of the monitoring period, from 02/05/2019 (Fig. 3). Lakes markedly appear in the upper catchment from 16/06/2019 in 22WFB, and from 03/07/2019 in tile 22WFC. The total lake area reaches a maximum of 190.14 km^2 (±22%) on 02/08/2019, with a rapid increase in total lake area preceding this. Total lake area generally declines after 20/07/2019, largely evident in lakes detected from tiles 22WEB and 22WFB (as also reflected in lake count, Fig. 3).

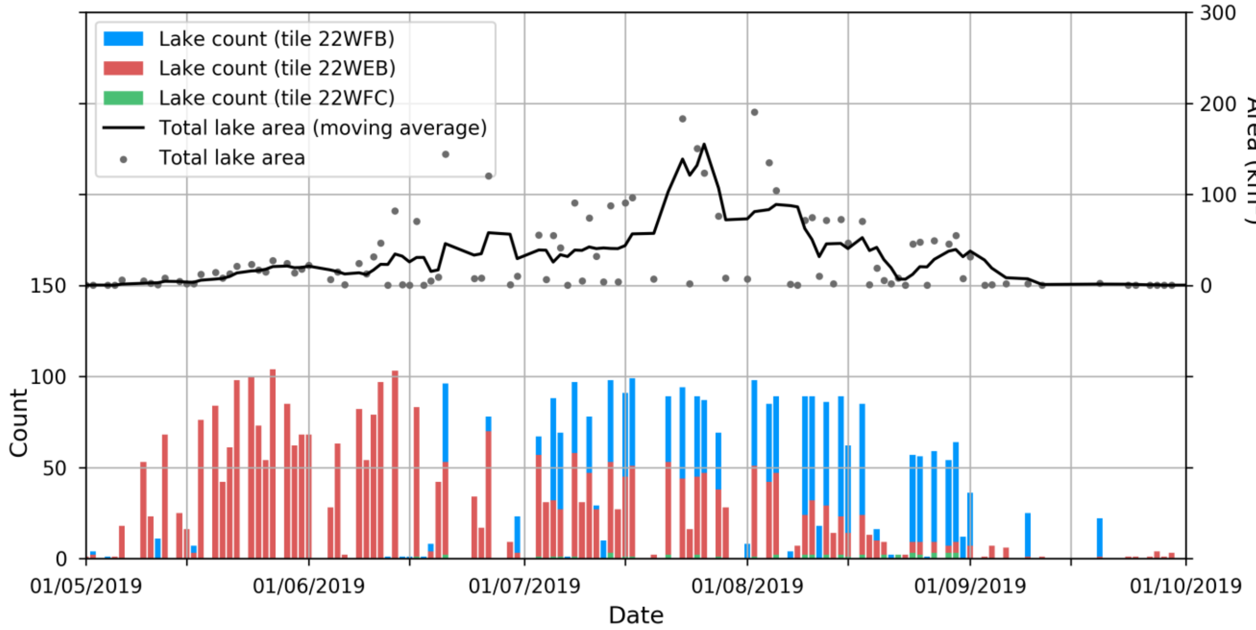

Fig. 3. Time-series showing lake count and total lake area over the 2019 melt season. Lake count is divided by Sentinel-2 tile (as indicated by the bar colour), whilst the total lake area is the cumulative sum of lake area over all tiles. The point data denotes total lake area per time step, and the line plot signifies total lake area as a moving average over a ten-step window.

Surface velocities along the flowline of the SK catchment average approximately 7 m/day over the course of the 2019 melt season (Fig. 4, panel 1). As expected, surface velocities across the lower region of the flow line are higher than those in the upper region. Ice flow trends in the lower region are seldom observed in the upper region; the only apparent instance being the increase in velocity in both the upper and lower regions of the flow line from 01/06/2019 to 15/06/2019.

Lakes first drain in the terminus area of the catchment from approximately 27/05/2019 (22WEB, Fig. 4, panel 2), with a 40% decrease in the number of lakes between 27/05/2019 and 19/06/2019. Lakes in the upper catchment become abundant later in the season, with a significant increase in lake appearance for tile 22WFB spanning 08/06-20/07/2019 (Fig. 4, panel 3), and the presence of lakes largely from 03/07/2019 for 22WFC (Fig. 4, panel 4). Lakes reach their maximum area and abundance in 22WFB in the latter half of July, followed by a decline throughout August; with surface area decreasing from 172.6 km^2 (02/08/2019) to 24.9 km^2 (01/09/2019), and lake abundance changing from 98 to 36 visible lakes.

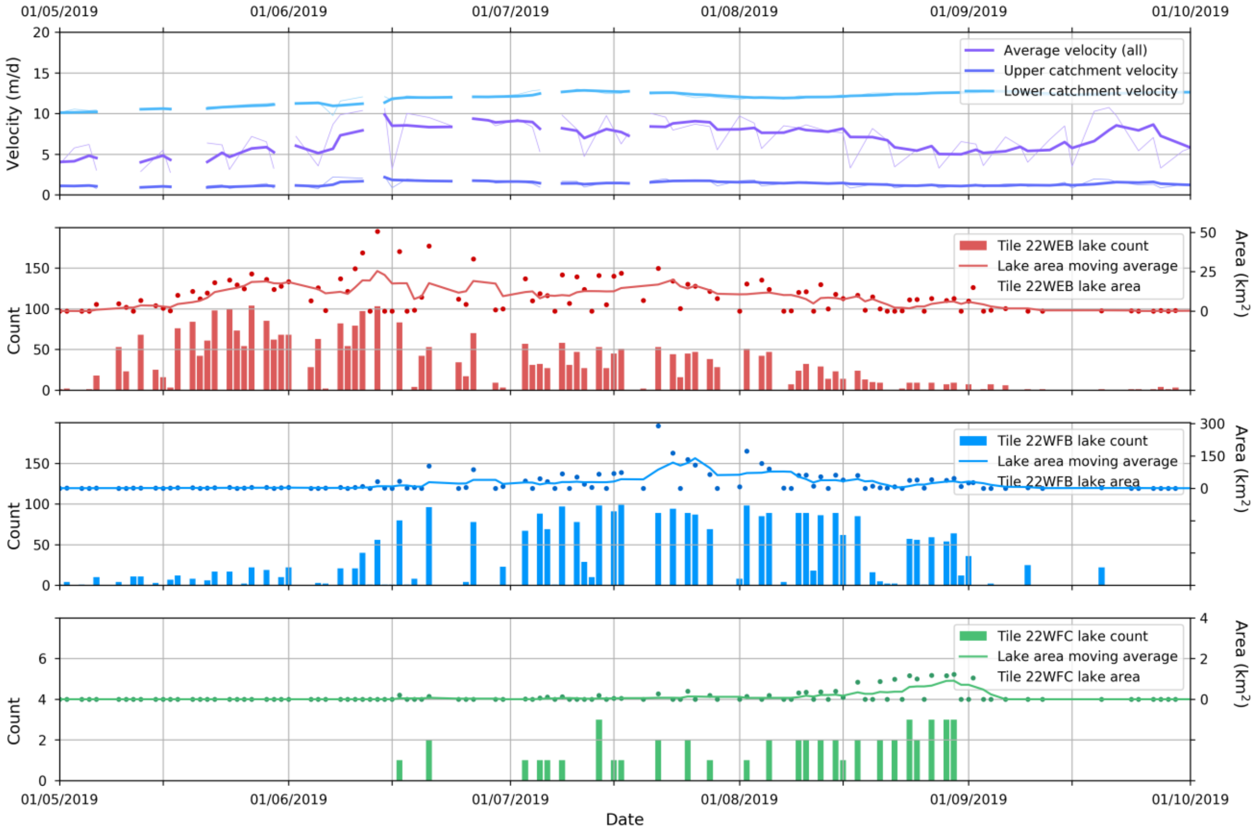

Fig. 4. Time-series analysis of surface velocity and supraglacial lakes (divided by Sentinel-2 tile detected from) at SK. Panel 1 (top) shows average velocity (unfiltered) along the glacier flowline as raw data (faint lines) and with a moving average (strong lines). Panels 2, 3 and 4 show lake count and total lake area in each Sentinel-2 tile through time. The point data denotes total lake area in the scene, and the line plots signify total lake area as a moving average over a five-step window.

An upglacier-propagating drainage trend is evident from Fig. 4, with lakes in the lower catchment tile (22WEB, Fig. 4, panel 2) filling and draining before the upper catchment tiles (22WFB and 22FC, Fig. 3, panels 3 and 4). This spatial trend in lake drainage is similar to those documented in previous years at SK (Stevens et al., 2015; Miles et al., 2017) and adjacent catchments (e.g., Sermeq Avangnardleq, Morriss et al., 2013), and at other major Greenland outlet glaciers such as Store Glacier (Qarassap Sermia) (Williamson et al., 2018; Chudley et al., 2019) and Russell Glacier (Sundal et al., 2009; Doyle et al., 2013; Fitzpatrick et al., 2014).

It is unclear whether there are causal links between surface velocity and supraglacial lake activity, likely because of the analysis of large-scale trends in Fig. 4 rather than local analysis (e.g. the effect of lake drainage on ice flow at a discrete area of the catchment). The subsequent sections will examine individual lake dynamics and their relation to localised ice flow patterns and elevation, in order to address the limitations with large-scale analysis of lake-velocity trends.

3.2 Elevation analysis

Supraglacial lakes are evident between 250 m and 2000 m a.s.l. within the SK catchment, spread evenly across the elevation range (Fig. 5). Generally, lakes are smaller at lower elevations, with few lakes below 1000 m a.s.l. reaching an larger than 0.5 km^2. Lakes tend to reach a larger maximum extent at higher elevations, with the largest lake (located at approximately 1700 m a.s.l.) reaching a maximum area of 81 km^2 on 25/07/2019.

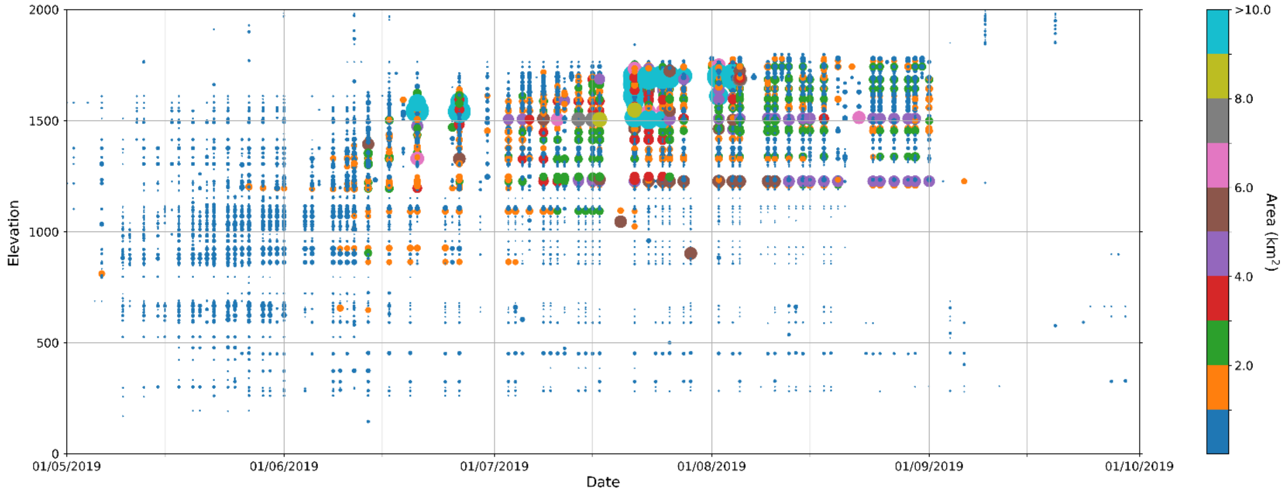

Fig. 5. Change in supraglacial lake frequency and area over time, in relation to elevation. Each plotted point represents a single lake at a given time step, where its colour and size denote lake area (km^2) and its position on the y-axis represents elevation. The abundance of points for each time step (x axis) provides an indication of lake frequency. Gaps in the dataset at the beginning of the record largely denote poor conditions for detecting supraglacial lakes due to saturated snow, and therefore lakes are highly likely to be present at lower elevations (<1000 m a.s.l.) at the beginning of the record (i.e. 01-15/05/2019).

Generally, supraglacial lakes at lower elevations (i.e. <1000 m a.s.l) fill and drain from 01/05-01/07/2019, with a gradual increase in lake area followed by an abrupt reduction (Fig. 5). As lakes begin to develop and grow at higher elevations (i.e. >1000 m a.s.l.) from 05/06/2019, those at lower elevations reach their maximum area and drain. Few low-elevation lakes are distinguishable beyond 17/08/2019, which is likely to be because they are empty, freeze over, or are undetectable. Lakes at higher elevations tend to reach their maximum later on in the melt season, between 23/07-05/08/2019, and remain present until 01/09/2019. Few lakes are detected beyond 07/09/2019, with none exceeding 1.0 km^2.

3.3 Individual lake analysis

Examination of individual supraglacial lake changes and dynamics for a portion of the lower catchment (as defined in Fig. 2) shows two regimes of lake filling and drainage, as highlighted in Fig 5A. Two sets of lakes are shown in the first of these regimes (Fig. 4B, lake IDs 108590 and 124237), one of which (lake ID 124237) is shown in the images as two separate water bodies (but lies within the same surface sink in the DEM). The lakes shown in Fig. 5B appear to drain simultaneously over the same time period (26/06 – 03/07/2019) in a rapid manner (< 8 days). The second regime highlighted in Fig. 5 consists of three sets of lakes (Fig. 5C, lake IDS 86279, 87379 and 102242), which drain much less rapidly (< 15 days) and occur earlier in the melt season (from 15/05/2019) than the former described regime. These observations further suggest an upglacier-propagating drainage pattern in the region, as the lakes in Fig. 5C lie downglacier of those in Fig. 5B, draining up to 35 days prior to those upglacier.

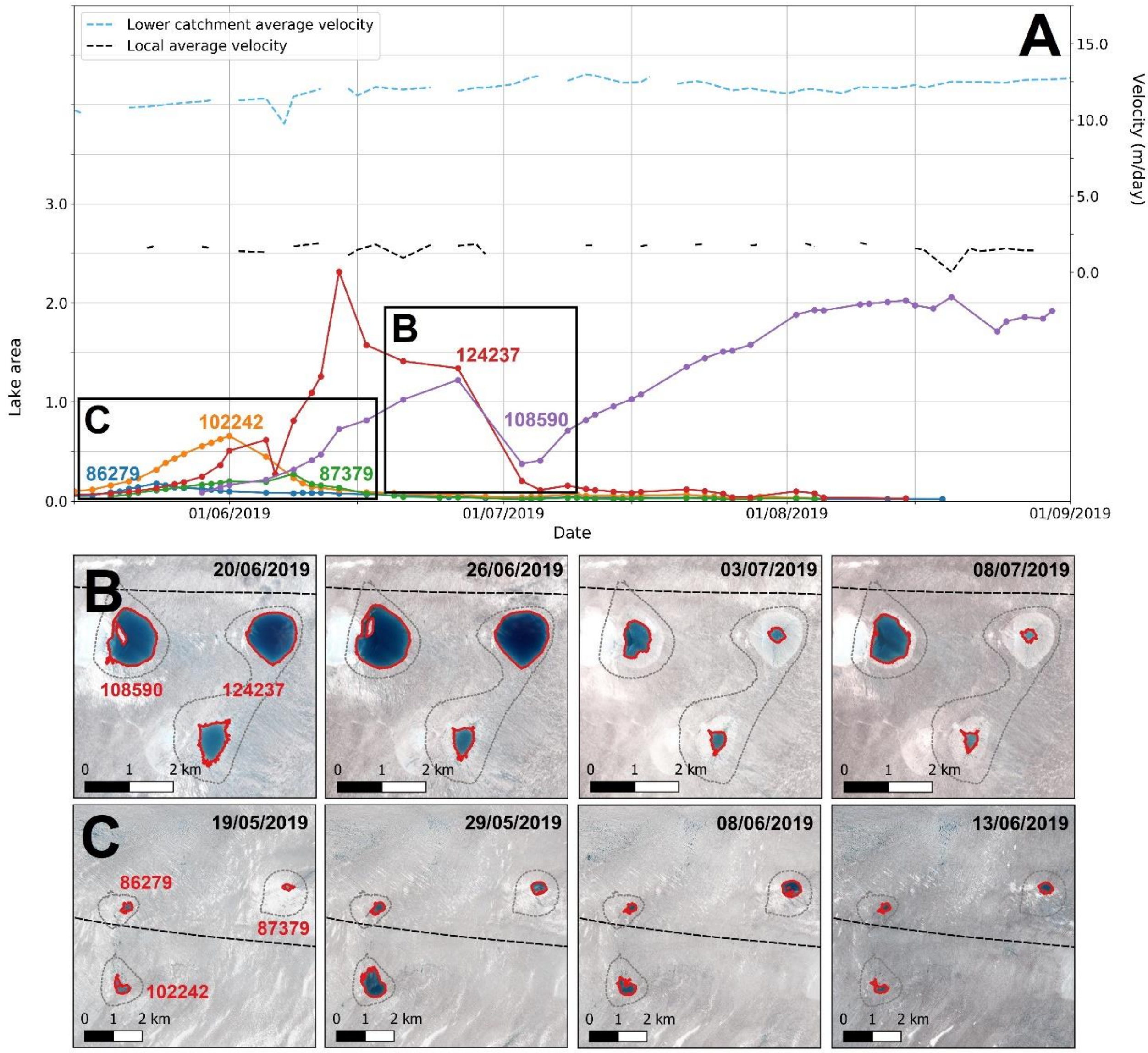

Fig. 6. Detailed look at a cluster of supraglacial lakes detected on the SK flowline, in the lower ice catchment (location of this subset shown in Fig. 2). A shows changes in surface area of the five selected lakes (lake IDs 86279, 87379, 102242, 108590 and 124237) along with local unfiltered flowline velocity (black dashed line) and the average unfiltered lower catchment velocity (blue dashed line, as in Fig. 3). B depicts select Sentinel-2 images of the two larger lakes from A (20/06-08/07/2019), whilst C depicts Sentinel-2 images of the three smaller lakes (19/05-13/06/2019). The overlaid red outlines denote the extent of the detected supraglacial lakes, the black dashed line is the coinciding sections of the SK flowline, and the grey dashed lines signify potential sinks in the surface hydrology (derived using ArcticDEM).

Three lakes from the upper catchment were selected for individual examination, as shown in Fig. 7. These lakes are relatively small compared to those at higher elevations, on average, fluctuation up to ~0.75 km^2. Generally, these lakes reach their maximum extent at the beginning of August, with the larger of the three (lake ID 180551, Fig. 7) surpassing an area of 0.7 km^2 on 01/08/2019, followed by the latter two reaching their maximums on 03/08/2019. The larger two lakes (lake ID 1290819 and 180551, Fig. 7) drain rapidly, losing approximately 30% of the total surface area in one day. The smallest of the three lakes (lake ID 159515, Fig. 7) drains much more gradually, leaving it practically empty (< 0.1 km^2) on the 14/08/2019.

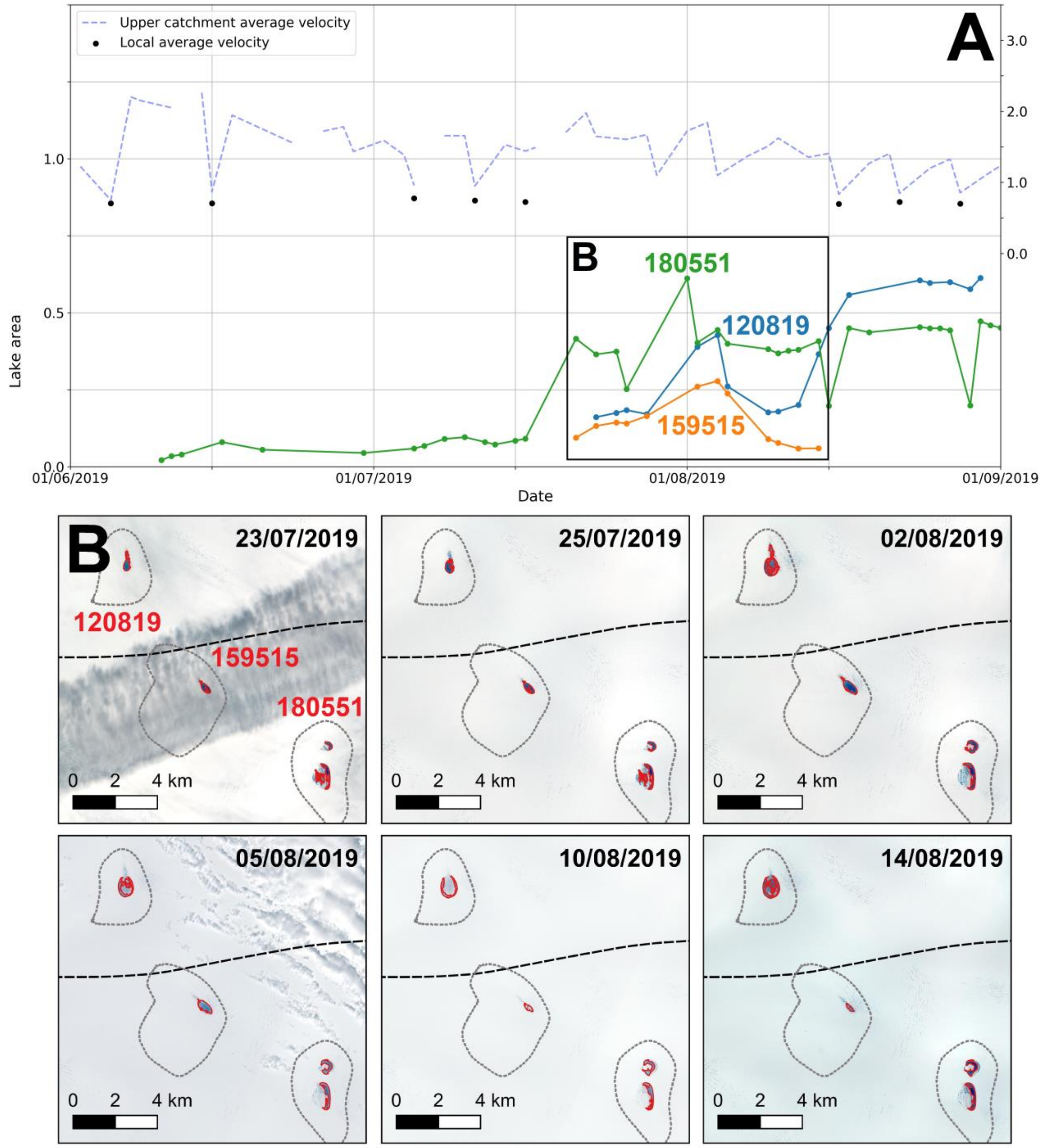

Fig. 7. Detailed look at a cluster of supraglacial lakes detected on the SK flowline, in the upper ice catchment (location of this subset shown in Fig. 2). A shows changes in surface area of the three selected lakes (lake IDs 120819, 159515 and 180551) along with the average unfiltered lower catchment velocity (lilac dashed line, as in Fig. 3) and the local unfiltered flowline velocity (black points). The local unfiltered flowline velocity could not be derived in this instance, as a complete time series due to poor tracking in the vicinity. B shows select Sentinel-2 images from the time-series (21/07-14/08/2019, subset shown in A), with overlaid red outlines denoting the extent of the detected supraglacial lakes, the black dashed line showing the coinciding sections of the SK flowline, and the grey dashed lines signifying surface hydrology sinks (derived using ArcticDEM).

Generally, the examples shown in this section (Fig. 6 and 7) demonstrate complex and intricate supraglacial lake processes. As shown by the subsets in Fig. 2, the lakes within these select clusters are adjacent to one another (within approximately 5 km), highlighting the diverse dynamics of supraglacial lakes, even over small areas within an ice catchment. It is therefore of utmost importance to consider examining supraglacial lakes across small subsets of an ice catchment, as well as glacier- and ice sheet wide

4. References

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