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1 **Supraglacial rivers on the northwest Greenland Ice Sheet, Devon Ice Cap, and**  
2 **Barnes Ice Cap mapped using Sentinel-2 imagery**

3 Kang Yang<sup>1,2,3</sup>, Laurence C. Smith<sup>4</sup>, Andrew Sole<sup>5</sup>, Stephen J. Livingstone<sup>5</sup>

4 Xiao Cheng<sup>2,6</sup>, Zhuoqi Chen<sup>2,6</sup>, Manchun Li<sup>1,3</sup>

5 1. School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China

6 2. Joint Center for Global Change Studies, Beijing 100875, China

7 3. Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing  
8 210023, China

9 4. Department of Geography, University of California, Los Angeles, California, USA

10 5. Department of Geography, The University of Sheffield, Sheffield, S10 2TN, UK

11 6. State Key Laboratory of Remote Sensing Science, College of Global Change and Earth System  
12 Science, Beijing Normal University, Beijing 100875, China

13

14 **Corresponding author:** Kang Yang, Tel: +86-13814179324; Email: yangkangnju@gmail.com

15 **Abstract:** Supraglacial rivers set efficacy and time lags by which surface meltwater is routed to the  
16 englacial, subglacial, and proglacial portions of ice masses. However, these hydrologic features remain  
17 poorly studied mainly because they are too narrow (typically <30 m) to be reliably delineated in  
18 conventional moderate-resolution satellite images (e.g., 30 m Landsat-8 imagery). This study  
19 demonstrates the utility of 10 m Sentinel-2 Multi-Spectral Instrument images to map supraglacial rivers  
20 on the northwest Greenland Ice Sheet, Devon Ice Cap, and Barnes Ice Cap, covering a total area of ~  
21 10,000 km<sup>2</sup>. Sentinel-2 and Landsat-8 both capture overall supraglacial drainage patterns, but Sentinel-2  
22 images are superior to Landsat-8 images for delineating narrow and continuous supraglacial rivers.  
23 Sentinel-2 mapping across the three study areas reveals a variety of supraglacial drainage patterns. In  
24 northwest Greenland near Inglefield Land, subparallel supraglacial rivers up to 55 km long drain  
25 meltwater directly off the ice sheet onto the proglacial zone. On the Devon and the Barnes ice caps,  
26 shorter supraglacial rivers (up to 15 – 30 km long) are commonly interrupted by moulins, which drain  
27 internally drained catchments on the ice surface to subglacial systems. We conclude that Sentinel-2 offers  
28 strong potential for investigating supraglacial meltwater drainage patterns and improving our  
29 understanding of the hydrological conditions of ice masses globally.

30 **Key terms:** river remote sensing, supraglacial river, surface hydrology, Sentinel-2, Landsat-8, Greenland  
31 Ice Sheet

## 32 **1. Introduction**

33       Supraglacial river networks are one of the least studied hydrologic systems on Earth. Extensive,  
34 complex supraglacial river networks have been observed in the ablation zone of the southwest Greenland  
35 Ice Sheet (GrIS) (Thomsen et al., 1989; McGrath et al., 2011; Yang and Smith, 2013; Lampkin and  
36 VanderBerg, 2014; Poinar et al., 2015; Smith et al., 2015; Yang and Smith, 2016a; Koziol et al., 2017;  
37 Smith et al., 2017), the Antarctic Ice Sheet (Bell et al., 2017; Kingslake et al., 2017), some large ice  
38 caps/fields (e.g., Devon Ice Cap (Dowdeswell et al., 2004; Boon et al., 2010), and Juneau Ice Field  
39 (Marston, 1983; Karlstrom et al., 2014)) as well as smaller stream systems on many mountain glaciers  
40 (Stenborg, 1968; Hambrey, 1977; Knighton, 1985; Brykała, 1998; Rippin et al., 2015; Decaux et al.,  
41 2018). These surface drainage features impact the efficacy and speed of meltwater routing to the  
42 englacial, subglacial, and proglacial portions of glaciers and ice sheets (Stenborg, 1968; Marston, 1983;  
43 Smith et al., 2017; Decaux et al., 2018) and thus coupling processes of surface melt with subglacial  
44 hydrology and ice flow (Zwally et al., 2002; Bartholomew et al., 2011; Andrews et al., 2014; Poinar et al.,  
45 2015; Smith et al., 2015; Wyatt and Sharp, 2015; Karlstrom and Yang, 2016; Yang and Smith, 2016a;  
46 Smith et al., 2017). Where meltwater accumulates on ice shelves, hydrofracture of surface crevasses can  
47 trigger their rapid collapse, causing debuitressing and acceleration of upstream glaciers (Scambos et al.,  
48 2000; Scambos et al., 2003). Active drainage of supraglacial rivers across ice shelves may conversely  
49 export stored meltwater and thus prevent disintegration (Bell et al., 2017).

50       Mapping supraglacial rivers is a crucial task for understanding their hydrological and glaciological  
51 roles (Chu, 2014). However, their reliable delineation from remotely sensed imagery is complicated by  
52 narrow channel widths relative to typical image resolutions, variable contrast between supraglacial  
53 meltwater and the surrounding snow/firn/ice, and complex surface drainage patterns (McGrath et al.,  
54 2011; Yang and Smith, 2013; Smith et al., 2017; Yang et al., 2017). Landsat-7/8 images (spatial  
55 resolution 15-30 m) have been used to map trunk main-stems of large supraglacial rivers on the  
56 Greenland and Antarctic ice sheets (Lampkin and VanderBerg, 2014; Poinar et al., 2015; de Fleurian et  
57 al., 2016; Yang and Smith, 2016a; Bell et al., 2017; Kingslake et al., 2017). However, numerous

58 supraglacial rivers are just ~10 m wide (Yang et al., 2016) rendering the spatial resolution of Landsat-7/8  
59 images inadequate for reliable small river delineation. As a result, supraglacial drainage patterns of most  
60 ice masses still remain unmapped (Chu, 2014). Very high resolution (VHR) satellite or unmanned aerial  
61 vehicle (UAV) images are able to delineate extensive small supraglacial streams (Smith et al., 2017; Yang  
62 et al., 2018) but small streams are commonly ignored in most supraglacial hydrologic studies (Lampkin  
63 and VanderBerg, 2014; Poinar et al., 2015; Yang and Smith, 2016a; Kingslake et al., 2017). Furthermore,  
64 the VHR images are not freely available and are spatially and temporally sparse (McGrath et al., 2011;  
65 Yang and Smith, 2013; Rippin et al., 2015; Smith et al., 2017).

66 The launch of the Sentinel-2 satellites (spatial resolution 10 m) in 2015 and 2017 for the first time  
67 raises prospects for studying the overall drainage pattern of supraglacial river networks and derivation of  
68 detailed metrics on their distribution, form, and morphology at an appropriate spatial and temporal scale,  
69 allowing mapping across large areas with a nominal return frequency of 5-10 days.

70 This study uses 10 m Sentinel-2 satellite imagery to delineate and map supraglacial river networks  
71 on three poorly-studied ice surfaces, the northwest GrIS near Inglefield Land, the Devon Ice Cap, and the  
72 Barnes Ice Cap (Figure 1). The potential of 10 m Sentinel-2 images to map surface water masks (Du et  
73 al., 2016), and glacier extent and ice flow (Kääb et al., 2016; Paul et al., 2016) have been analyzed, but to  
74 our knowledge, this is the first attempt to use Sentinel-2 images to map supraglacial rivers. Therefore, the  
75 study's main objectives are to: (1) assess the capability of 10 m Sentinel-2 images to map supraglacial  
76 rivers; (2) compare delineations of supraglacial rivers mapped from Sentinel-2 images with those mapped  
77 from contemporaneous Landsat-8 images; and (3) characterize the supraglacial river networks on the ice  
78 surface of three poorly-studied ice masses.

79

## 80 **2. Data**

81 Sentinel-2 is a European Satellite Agency wide-swath, high-resolution, multi-spectral imaging  
82 satellite mission (Kääb et al., 2016). This mission consists of two satellites (2A launched on 23 June  
83 2015, and 2B launched on 7 March 2017) flying in the same orbit but phased at 180°, each carrying a

84 single sensor payload named Multi-Spectral Instrument (MSI). MSI includes 13 spectral bands in visible  
85 and near-infrared (VNIR) and shortwave Infrared (SWIR). The spatial resolution of these bands varies  
86 from 10 m to 60 m. The 10 m bands include blue (band 2, 490 nm), green (band 3, 560 nm), red (band 4,  
87 665 nm), and NIR (band 8, 842 nm), affording mapping of relatively narrow supraglacial rivers. The  
88 Level-1C Sentinel-2 product was obtained from the USGS EarthExplorer (<http://earthexplorer.usgs.gov/>).  
89 This product shows the top-of-atmosphere reflectance in cartographic geometry and is divided into 100  
90 km<sup>2</sup> tiles. Several concurrent Landsat-8 OLI images (30 m multi-spectral and 15 m panchromatic images)  
91 were also obtained from the USGS EarthExplorer and were used for comparison. Late July or early  
92 August images were selected because supraglacial river networks are best-developed on the surface of  
93 Arctic ice masses during this period (Table 1).

94

### 95 **3. Study area**

#### 96 *3.1 Northwest GrIS near Inglefield Land*

97 The southwest GrIS has received the most attention from ice sheet supraglacial hydrologic studies in  
98 recent years (McGrath et al., 2011; Lampkin and VanderBerg, 2014; Poinar et al., 2015; Smith et al.,  
99 2015; Gleason et al., 2016; Yang and Smith, 2016a; Yang et al., 2016; Smith et al., 2017; Yang et al.,  
100 2017). Extensive, complex supraglacial river networks have been observed and mapped from 0.5-2.0 m  
101 WorldView (McGrath et al., 2011; Yang and Smith, 2013; Smith et al., 2015; Yang et al., 2016; Koziol et  
102 al., 2017; Smith et al., 2017; Yang et al., 2017) and 15-30 m Landsat-7/8 images (Lampkin and  
103 VanderBerg, 2014; Poinar et al., 2015; de Fleurian et al., 2016; Yang and Smith, 2016a). These  
104 supraglacial river networks drain large volumes of meltwater into the ice sheet (Smith et al., 2015) with  
105 important implications for ice dynamics (Zwally et al., 2002; Bartholomew et al., 2011; Andrews et al.,  
106 2014; Wright et al., 2016).

107 Outside of southwest Greenland, the surface hydrology of other areas of the GrIS has received scant  
108 attention, resulting in a correspondingly poor understanding of the spatial distribution of hydrologic  
109 elements and couplings between surface melt and ice flow (Banwell et al., 2016; Yang and Smith, 2016a).

110 The northwest GrIS is comprised of predominantly cold-bedded (MacGregor et al., 2016) and slower  
111 moving ice (Joughin et al., 2010). Previous studies have revealed wide distributions of supraglacial lakes  
112 (mapped from low-resolution MODIS images) (Selmes et al., 2011), indicating that a supraglacial  
113 hydrologic system does develop in this area thus contributing to surface mass loss. However, a  
114 preliminary investigation of the supraglacial drainage pattern has yet to be conducted.

115 To address this knowledge gap, we selected a study area on a lobe of slow-moving ( $\sim 0 - 30$  m/year)  
116 (Joughin et al., 2017) grounded ice from  $78.1^\circ$  to  $79.0^\circ$  N,  $64.1^\circ$  to  $69.0^\circ$  W near Inglefield Land in  
117 northwestern Greenland, covering approximately  $5,239$  km<sup>2</sup> in area including the entire ablation zone and  
118 parts of the accumulation zone (equilibrium line altitude is  $\sim 1100$  m in this area (Box et al., 2004))  
119 (Figure 1 and 2). Ice surface elevation in this study area ranges from 200 to 1500 m a.s.l., sloping gently  
120 ( $\sim 0.015$  m/m) to the ice edge. A Global 30 Arc-Second Elevation (GTOPO30) digital elevation model  
121 (obtained from the USGS EarthExplorer) was used to create elevation contours.

122

### 123 *3.2 Devon Ice Cap*

124 The Devon Ice Cap (DIC) is a polythermal Arctic ice cap and one of the largest ice masses in the  
125 Canadian Arctic. It is located between  $74.5^\circ$  to  $75.8^\circ$  N,  $80.0^\circ$  to  $86.0^\circ$  W and covers an area of  $\sim 14,400$   
126 km<sup>2</sup> (Boon et al., 2010) (Figure 1). The DIC has a dome-like shape with ice divides radiating from its  
127 summit (elevation  $\sim 1921$  m) (Dowdeswell et al., 2004). We selected two study sites from the southern  
128 and western sections of the DIC (Figure 3) that are representative of the broader ice cap flow and  
129 hydrology (Dowdeswell et al., 2004; Boon et al., 2010; Wyatt and Sharp, 2015). The southern site (Figure  
130 3c) has an area of  $621$  km<sup>2</sup> with elevations ranging from 800 to 1300 m. The western site (Figure 3b) has  
131 an area of  $200$  km<sup>2</sup> and ranges in elevation from 500 to 1400 m. The southern site is drained by several  
132 large outlet glaciers and is characterized by relatively fast ice flow velocities ( $\sim 10 - 60$  m/year). Closely-  
133 spaced supraglacial river networks have been observed in this area (Dowdeswell et al., 2004) and were  
134 previously mapped for one outlet glacier using Landsat-7 ETM+ imagery (Wyatt and Sharp, 2015). The

135 western study site is flatter than the southern site and flows more slowly (~5 m/year). It has received less  
136 attention compared to its fast-flowing southern counterpart (Dowdeswell et al., 2004).

137

### 138 *3.3 Barnes Ice Cap*

139 The Barnes Ice Cap (BIC) is a remnant of the Laurentide Ice Sheet (Gilbert et al., 2016) located in  
140 central Baffin Island, Canada. It covers an area of ~5700 km<sup>2</sup> from approximately 69.5° to 70.5° N, 71.8°  
141 to 74.8° W (Figure 1). The BIC is very sensitive to Arctic climate change and is predicted to disappear in  
142 the next 300 years (Gilbert et al., 2017). Like the DIC, the BIC also has a dome-like shape but its ice  
143 divide mainly runs northwest – southeast (Figure 4). Research on the BIC has focused mainly on its  
144 accelerated melting and thinning in response to climate warming and internal dynamics (Dupont et al.,  
145 2012; Gilbert et al., 2016; Gilbert et al., 2017). BIC hydrology, in contrast, has received scant attention  
146 and to our knowledge, no study of BIC supraglacial streams and rivers has been conducted to date.

147

## 148 **4. Methods**

149 Effective delineation of supraglacial rivers from remotely sensed images requires linear feature  
150 enhancement. For this we employed the method of Yang et al. (2017), which characterizes rivers  
151 according to their Gaussian-like brightness cross sections and longitudinal continuity. First, the  
152 normalized difference water index (NDWI) was applied to enhance the spectral contrast between  
153 meltwater and background snow/ice (Yang and Smith, 2013). Second, a band-pass Discrete Fourier  
154 Transform (DFT) was used to further remove the low-frequency image background and high-frequency  
155 image noise (Yang et al., 2017). A band-pass filter ramped between 1/200 m<sup>-1</sup> and 1/40 m<sup>-1</sup> was found to  
156 effectively remove image background and high-frequency image noise, while retaining supraglacial rivers  
157 as the dominant features on the ice sheet surface (Karlstrom and Yang, 2016). Third, a Gabor filter was  
158 used to enhance supraglacial river cross sections (Yang et al., 2015a). The Gabor filter is a sinusoidally-  
159 modulated Gaussian function with optimal localization for matching river cross sections that effectively  
160 enhances supraglacial river features relative to the surrounding snow/firn/ice surface background.

161 Even after Gabor filtering, supraglacial rivers often appear intermittent owing to significant  
162 visible/near-infrared brightness variations along river courses and snow bridges (snow-filled channels,  
163 with a supraglacial stream or river actively flowing beneath). To address this problem, a flexible path  
164 opening operator (Heijmans et al., 2005) was used to lengthen the river channel continuity and to suppress  
165 noise. Rivers were consistently discerned from the image background after these steps. Finally, a global  
166 threshold was automatically determined based on the image histogram and applied to create binary river  
167 masks (Yang et al., 2015a). These supraglacial river detection codes are freely available by contacting the  
168 lead author.

169 Moulins were manually identified as the abrupt termination of a large river main-stem (Smith et al.,  
170 2015; Wyatt and Sharp, 2015; Yang and Smith, 2016a). To be conservative, only moulins close to  
171 crevasses or drained channels and that clearly terminate river networks were identified. River widths vary  
172 longitudinally so it is common for some river segments to still be too narrow in 10 m Sentinel-2 images,  
173 inducing false river terminations. Therefore, if a supraglacial river ends but then reappears a short  
174 distance downstream with similar width, the upstream river termination is not identified as a moulin. This  
175 step also mitigates for presence of snow bridges, which can conceal supraglacial rivers for tens to  
176 hundreds of meters.

177

## 178 **5. Results**

### 179 *5.1 Comparison of Sentinel-2 and Landsat-8 mapped supraglacial rivers*

180 Supraglacial river networks are better delineated in 10 m Sentinel-2 images than the 30 m  
181 multispectral or 15 m panchromatic Landsat-8 data (Figure 5) and can be efficiently detected using Gabor  
182 filtering and path opening (Figure 6). Supraglacial river networks were mapped for the northwest GrIS,  
183 the DIC, and the BIC using near-time Sentinel-2 and Landsat-8 images captured during 2016 summer  
184 (Figure 7 – 9, Table 2). The total area mapped is ~10,000 km<sup>2</sup>, with well-developed supraglacial river  
185 networks found on all three ice masses. Both Sentinel-2 and Landsat-8 images captured the overall  
186 drainage pattern of supraglacial river networks on the ice surface of the three study areas (Figure 7 – 9),

187 supporting the conclusions that moderate-resolution satellite images hold value for studying ice surface  
188 drainage patterns (Lampkin and VanderBerg, 2014; Poinar et al., 2015; Yang and Smith, 2016a; Bell et  
189 al., 2017; Kingslake et al., 2017). However, the spatial resolution of the Sentinel-2 images is three times  
190 higher than that of the Landsat-8 images and thus supraglacial drainage patterns are much better resolved  
191 in the Sentinel-derived map products (see close-up images, Figures 7 – 9). Sentinel-mapped supraglacial  
192 river networks are also more continuous, which is crucial for investigating surface meltwater routing  
193 (King et al., 2016; Yang and Smith, 2016a; Smith et al., 2017; Decaux et al., 2018; Yang et al., 2018). On  
194 all three ice masses, supraglacial rivers generally flow from high-elevation slushy zones to low-elevation  
195 bare ice ablation zones. In the slushy zones, supraglacial rivers are not clearly channelized, yet the  
196 Sentinel-2 images were nevertheless able to discern the short, often braided river networks in three areas  
197 whereas these features were difficult to identify in Landsat-8 (see Figure 7).

198 Drainage density ( $D_d$ ) was calculated to characterize the overall abundance of supraglacial rivers  
199 across the three study sites (Table 2). The derived values of  $D_d$  are highly sensor-specific, with Sentinel-  
200 derived  $D_d$  ( $2.5 - 5.6 \text{ km}^{-1}$ ) approximately two times higher than Landsat-derived values ( $1.3 - 2.7 \text{ km}^{-1}$ ).  
201 The highest  $D_d$  ( $5.6 \text{ km}^{-1}$ ) was obtained on the northwest GrIS during late July 2016, indicating a well-  
202 developed supraglacial drainage system despite having the highest latitude of the three areas (Figure 7).  
203 The western and southern areas of the DIC yielded  $D_d$  values of  $5.1 \text{ km}^{-1}$  and  $3.3 \text{ km}^{-1}$  respectively,  
204 indicating denser surface drainage in the west (Figure 8), consistent with previous studies (Dowdeswell et  
205 al., 2004; Boon et al., 2010). The BIC exhibited the lowest  $D_d$  ( $2.5 \text{ km}^{-1}$ ), mainly due to a large river-free  
206 area near the ice margin (Figure 9), but also because the Sentinel-2 images used to map the BIC were  
207 acquired in mid-August, when surface melt declines and actively flowing supraglacial river networks  
208 generally shrink (Yang and Smith, 2016a; Yang et al., 2018).

209

## 210 *5.2 Supraglacial river networks on the northwest Greenland Ice Sheet*

211 Supraglacial river networks on the northwestern GrIS near Inglefield Land drain meltwater directly  
212 off the ice surface into proglacial streams and rivers (Figure 7). These mapped supraglacial rivers are

213 subparallel (spacing ~200 m) and reach a maximum length of ~65 km, longer than the longest main-stem  
214 (~55 km) previously mapped on the southwest GrIS (Poinar et al., 2015). This subparallel drainage  
215 pattern is also very different from the generally dendritic and/or structurally controlled patterns observed  
216 in southwest Greenland (Smith et al., 2015; Karlstrom and Yang, 2016; Yang and Smith, 2016a; Yang et  
217 al., 2016) and flow continuously straight off the ice sheet surface from the interior (elevation ~1500 m) to  
218 its edge (elevation ~200 m) (Figure 7). These features originate in slush fields at high elevations (~1500  
219 m) where they are not well channelized, becoming well channelized at lower elevations on bare ice.  
220 Importantly, none of the Inglefield Land supraglacial rivers are interrupted by moulins or crevasses  
221 making this area distinctly different from southwest Greenland, where virtually all supraglacial rivers  
222 terminate in moulins before reaching the ice edge (Smith et al., 2015; Yang and Smith, 2016a).

223 Although the supraglacial drainage patterns of the two study sites are both continuous (Figure 7b and  
224 7c), notable differences can be observed. At site b, supraglacial rivers are subparallel, straight and densely  
225 distributed, and supraglacial lakes are absent (Figure 7b). At site c, supraglacial rivers flow into and out of  
226 supraglacial lakes (termed as “pathway” lakes in southwest GrIS studies (Tedesco et al., 2013; Yang et  
227 al., 2015b)) forming “lake chains” and a more sinuous supraglacial river network (Figure 7c), whereas  
228 supraglacial lakes are absent at site b. This difference is induced by broad-scale ice surface topography;  
229 elevation contours at site b are subparallel, while the contours at site c are more irregular, particularly  
230 near supraglacial lakes.

231

### 232 *5.3 Supraglacial river networks on the Devon Ice Cap*

233 The supraglacial river drainage pattern on the southern section of the DIC is strongly controlled by  
234 moulins and crevasses. At this site, most supraglacial rivers drain southwards along an outlet glacier,  
235 reaching a maximum length of ~15 km. At higher elevations (~1300-1400 m a.s.l.) most of the mapped  
236 river channels are very narrow (one pixel wide), braided, and slushy, similar to their high elevation  
237 (>1500 m) counterparts on the southwest GrIS (Yang and Smith, 2016a). The drainage density is high  
238 where meltwater channelizes but there are also large interfluves with no channels. Supraglacial rivers in

239 this area, particularly the main tributaries, are very sinuous and often turn at right angles (Figure 8).  
240 Consistent with previous findings (Dowdeswell et al., 2004), crevasses are identified in this area, which  
241 abruptly terminate supraglacial rivers to form moulins (Figure 8).

242 All of the supraglacial river networks mapped in the southern section of the DIC are captured by  
243 moulins, similar to the southwest GrIS (Smith et al., 2015). For example, 16 moulins (density 0.08  
244 moulin/km<sup>2</sup>, calculated as moulin count / study site area) in the lower-middle part of the study site  
245 correspond to a ~3 km long west-east orientated linear crevasse. Another isolated moulin was found  
246 nearby draining a very large supraglacial river network (see the right yellow box in Figure 8). These  
247 widely distributed moulins drain large volumes of meltwater into the ice cap and likely play a significant  
248 role in coupling surface melt with the subglacial hydrological system and ice flow (Zwally et al., 2002;  
249 Banwell et al., 2013; Andrews et al., 2014; Clason et al., 2015; Wyatt and Sharp, 2015) of the DIC. The  
250 resultant moulin density (0.08 moulin/km<sup>2</sup>) is similar to the density reported for low-elevation (<1400 m)  
251 southwestern GrIS (>0.06 moulin/km<sup>2</sup>) (Yang and Smith, 2016a), indicating that moulins on the southern  
252 section of the DIC are as abundant as their southwest GrIS counterparts in general.

253 Supraglacial river networks are well developed on the western section of the DIC, with most rivers  
254 flowing continuously toward the ice margin (Figure 8). At high elevations, we mapped numerous  
255 supraglacial rivers yielding correspondingly high drainage densities ( $D_d = 5.1 \text{ km}^{-1}$ ). These supraglacial  
256 rivers are straighter than their counterparts in the southern section of the DIC. At lower elevations (<900  
257 m), supraglacial rivers become sinuous and are captured by ~10 main-stems, forming a limited number of  
258 large supraglacial river networks (Figure 8). A large, previously unreported low albedo zone is found in  
259 this low-elevation area (Figure 3 and 8). A previous field study during 1998 also observed well-developed  
260 supraglacial rivers with long main-stems in this area and thereby assumed surface-to-bed meltwater  
261 connections were limited (Lamoureux et al., 2002; Boon et al., 2010). However, we mapped a total of 16  
262 moulins (density 0.03 moulin/km<sup>2</sup>) and most moulins are located close to the ice margin (<3 km), thus  
263 terminating relatively large river networks (10–20 km long main-stems). This new finding indicates a  
264 considerable volume of meltwater can be drained into the lower ice margin of the western section of the

265 DIC, which is contrary to previous assumptions and implies either recent moulin formation or spatial  
266 limitations of the field observations.

267

#### 268 *5.4 Supraglacial river networks on the Barnes Ice Cap*

269 Supraglacial river networks were mapped across the entire BIC using both Sentinel-2 and Landsat-8  
270 (Figure 9). Supraglacial rivers drain ~30 km towards the southwestern and ~22 km towards the  
271 northeastern portions of the ice cap, flowing away from the 128 km long northwest-southeast trending ice  
272 divide. The longest supraglacial river on the western side is ~35 km, and the longest on the eastern side is  
273 ~25 km, both governed by the distances from the ice margins to the ice divide (Figure 9).

274 There are noticeable differences between the drainage patterns on either side of the BIC ice divide.  
275 On the eastern side, supraglacial rivers are relatively straight and subparallel, similar to the northwestern  
276 GrIS (Figure 7) and the western section of the DIC (Figure 8). On the western side, they are more  
277 dendritic (similar to the southern section of the DIC, Figure 8). On both sides numerous supraglacial  
278 rivers drain directly into proglacial lakes and rivers. However, some also terminate abruptly in moulins  
279 (Figure 9), indicating that some meltwater does reach the BIC bed. A total of 66 moulins (density 0.01  
280 moulin/km<sup>2</sup>, calculated as moulin count / BIC area) were identified from the Sentinel-2 images, of which  
281 27 (density 0.01 moulin/km<sup>2</sup>, calculated as moulin count / the western BIC area) were detected west of  
282 the divide and 39 (density 0.02 moulin/km<sup>2</sup>, calculated as moulin count / the eastern BIC area) east of the  
283 divide. Most moulins are located close to the BIC ice margin (5–7 km) and thus terminate relatively large  
284 supraglacial river networks (15–25 km long main-stems) relatively close to the proglacial zone.

285

## 286 **6. Discussion**

### 287 *6.1 Scientific implications of observed supraglacial drainage patterns*

288 This study maps supraglacial river networks on three poorly-studied ice masses, the northwestern  
289 GrIS near Inglefield Land, the Devon Ice Cap, and the Barnes Ice Cap using 10 m Sentinel-2 and  
290 Landsat-8 satellite imagery. A variety of supraglacial drainage patterns is revealed. On the northwestern

291 GrIS, on high-elevation areas of the western sections of the DIC and the BIC, and on the eastern section  
292 of the BIC, supraglacial rivers are straight, subparallel, and densely distributed (Figure 7-9) indicating  
293 limited variations in surface relief (Karlstrom and Yang, 2016; Crozier et al., 2018; Ignéczi et al., 2018).  
294 In contrast, the southern section of the DIC and the low-elevation areas of the western sections of the DIC  
295 and the BIC have supraglacial river drainage patterns that are more dendritic, (Figure 8 and 9), similar to  
296 the southwest GrIS (Smith et al., 2015; King et al., 2016; Yang et al., 2016; Smith et al., 2017) and many  
297 terrestrial river systems (Dingman, 2015), indicating relatively large variations in surface relief and  
298 greater transfer of basal roughness and slipperiness (Crozier et al., 2018; Ignéczi et al., 2018). There is  
299 also considerable variation within some of the study sites. For example, on the western sections of the  
300 DIC and the BIC, subparallel supraglacial rivers developed at high elevations become more sinuous and  
301 dendritic downstream and are eventually captured by highly sinuous main-stems (Figure 8).

302         Supraglacial drainage patterns are primarily determined by ice surface topography, which is  
303 influenced by variations in bed roughness and slipperiness and the differing transmission of that  
304 variability to the ice surface (Crozier et al., 2018; Ignéczi et al., 2018). Therefore, inversely, satellite-  
305 mapped supraglacial river networks hold useful information for inferring subsurface topography and basal  
306 transfer characteristics. Regional and local variations in supraglacial river pattern are consistent with  
307 theory and observations that the transfer of basal variability is enhanced by thinner ice, steeper ice surface  
308 slopes and higher slip ratios prevalent in ice-marginal and fast-flowing regions (Gudmundsson, 2003;  
309 Crozier et al., 2018; Ignéczi et al., 2018). More generally, there is a propensity of all natural rivers to  
310 adjust their own slope (i.e. to decrease it, in this case) through increasing their sinuosity (Charlton, 2007).  
311 Finally, crevasses, which tend to be associated with faster flowing and thinner ice (Colgan et al., 2011),  
312 fragment supraglacial rivers networks and generate moulins (Yang and Smith, 2016a). As a result, low-  
313 elevation supraglacial rivers near the ice edge are not well channelized for the DIC and the BIC, yielding  
314 short river segments and moulins (Figure 8 and 9). In contrast, on cold bedded northwestern GrIS with  
315 slow ice flow (Joughin et al., 2010), crevasses are rare and therefore long supraglacial rivers flow  
316 continuously straight off the ice sheet surface (Figure 7).

317

318 *6.2 Implications for surface meltwater routing*

319       The supraglacial drainage patterns mapped in this study have important implications for surface  
320 meltwater routing. Supraglacial river networks and their corresponding ice surface catchments determine  
321 the timing and magnitude of peak supraglacial river discharge and corresponding inputs to englacial and  
322 subglacial drainage systems through moulins (Smith et al., 2017; Decaux et al., 2018; Yang et al., 2018).  
323 Various factors control how a supraglacial river's hydrograph responds to ice surface melt, including  
324 catchment shape, contributing area, drainage density, ice surface properties (snow/firn/weathering  
325 crust/ice), surface melt rate, and surface topographic gradient (Arnold et al., 1998; Leeson et al., 2012;  
326 Banwell et al., 2013; Clason et al., 2015; Smith et al., 2017; Yang et al., 2018). Integration of regional  
327 climatic models (RCMs), satellite observations, high-quality DEMs and fieldwork are required to conduct  
328 a comprehensive investigation of catchment hydrological responses (Smith et al., 2015; Yang and Smith,  
329 2016a; Smith et al., 2017), which is outside the scope of this study. However, of these controlling factors,  
330 catchment area and shape are the most straightforward to acquire and most stable over time (Yang and  
331 Smith, 2016a; Smith et al., 2017). Therefore, a basic understanding of catchment hydrological responses  
332 to catchment shape can be obtained from remotely sensed mapped supraglacial river networks, if other  
333 controlling factors are assumed to be constant. We acknowledge that this may oversimplify reality but  
334 argue it provides a preliminary understanding of catchment hydrological response to meltwater generation  
335 on ice surfaces.

336       On the northwestern GrIS and eastern section of the BIC, the straight and subparallel supraglacial  
337 river networks yield unusually long and narrow catchments (Yang and Smith, 2016a). As a result, it takes  
338 longer on average for meltwater to travel to the catchment outlet and the supraglacial catchment output  
339 runoff hydrograph will be more subdued with a longer rising limb (Karamouz et al., 2013). Because these  
340 supraglacial rivers flow directly onto the proglacial zone (Figure 2 and 7) discharge into terrestrial  
341 streams and rivers directly reflects the timing and intensity of ice surface runoff influenced by catchment  
342 routing, with no modulation by en- and/or subglacial processes. In contrast, the dendritic supraglacial

343 river networks on the southern section of the DIC, similar to their counterparts on the southwest GrIS  
344 (Yang and Smith, 2016a), have more compact (more circular rather than long and narrow) catchment  
345 shapes and the resultant runoff hydrograph will be more flashy with a greater peak and shorter rising limb  
346 (Smith et al., 2017). On the western sections of the DIC and the BIC, where subparallel and dendritic  
347 drainage patterns both exist, the runoff hydrographs are expected to be complex composites of the  
348 aforementioned subdued and flashy hydrographs (Karamouz et al., 2013).

349 Drainage density ( $D_d$ ) of supraglacial rivers also controls the hydrological responses of supraglacial  
350 catchments but  $D_d$  varies significantly over a melt season (Yang et al., 2017). For a given catchment, high  
351 drainage density will lead to flashy drainage since open-channels route surface meltwater much more  
352 efficiently ( $10^{-1}$  m/s) than hillslope overland/subsurface flow ( $10^{-3}$ - $10^{-4}$  m/s) (Yang et al., 2018). However,  
353 10 m Sentinel-2 mapped drainage density cannot detect small supraglacial streams and thus likely  
354 underestimates the extent of high drainage density, hydraulically efficient catchment. Moreover, it is  
355 inappropriate to directly compare  $D_d$  derived for different ice masses during different time periods.  
356 Further study is needed to determine the usefulness of Sentinel-2 mapping of drainage density and surface  
357 meltwater routing studies more generally.

358

### 359 *6.3 Implications for coupling with subglacial systems*

360 Remotely sensed supraglacial drainage patterns provide improved understanding of the coupling  
361 between supraglacial hydrology and subglacial systems. The long, subparallel supraglacial rivers of the  
362 northwest GrIS are very different from those in the southwest, which are characterized by numerous  
363 segmented river networks terminating at moulins (Poinar et al., 2015; Smith et al., 2015; King et al.,  
364 2016; Yang and Smith, 2016a; Yang et al., 2016; Ignéczi et al., 2018). We suggest relatively cold, thick,  
365 and broadly impermeable ice, slow flow, and low strain rates (Rignot and Kanagaratnam, 2006; Joughin  
366 et al., 2016) all contribute to the absence of moulins and crevasses in northwest Greenland. As a result,  
367 the coupling between surface hydrology and ice flow is likely weak, with ice motion in this region

368 dominated by internal deformation (Boon et al., 2010), similar to findings reported for the Antarctic Ice  
369 Sheet (Bell et al., 2017; Kingslake et al., 2017).

370         Considerable numbers of moulins are found on the western sections of the DIC and the BIC, places  
371 where moulins have previously been considered rare and the coupling between surface hydrology and ice  
372 flow remains unstudied (Dowdeswell et al., 2004; Boon et al., 2010; Gilbert et al., 2016). This new  
373 finding indicates that non-trivial volumes of meltwater drain into the two ice caps each summer. Wyatt  
374 and Sharp (2015) mapped moulins for an outlet glacier (<600 m) in the south sector of the DIC and found  
375 that ice velocity variability is greater near moulins. Through our expanded mapping, we find that moulins  
376 are widely distributed in the high-elevation (>800 m) interior of the southern section of the DIC. This is  
377 similar to southwestern GrIS, where moulins are widely distributed inland (e.g., >100 km to the ice  
378 margin) (Yang and Smith, 2016a) and drain short supraglacial rivers near the ice margin (~4 km long  
379 main-stems) (Poinar et al., 2015). In contrast, most moulins identified for the western sections of the DIC  
380 and the BIC are located close to the ice margin (~5 km) and drain long supraglacial river networks (10-25  
381 km long main-stems), indicating substantial ability to drain meltwater into the ice cap but limited overall  
382 coupling with ice dynamics given the relatively small area of the bed that is hydraulically connected to  
383 the ice surface. This unique coupling may lead to a strong response of marginal ice flow to surface  
384 meltwater inputs but the effect of supraglacial meltwater on inland ice flow may be weak.

385

#### 386 *6.4 Limitations and future potential of Sentinel-2 for supraglacial river mapping*

387         Although higher-resolution satellite (e.g., WorldView-1/2) (McGrath et al., 2011; Joughin et al.,  
388 2013; Yang and Smith, 2013; Smith et al., 2015; Smith et al., 2017; Yang et al., 2017) and UAV images  
389 (Rippin et al., 2015; Smith et al., 2017) can detect very small supraglacial streams, Sentinel-2 images  
390 provide a promising spatial scale to map larger supraglacial river networks over large areas (Figure 7-9).  
391 This is crucial for accurately delineating internally drained catchments (IDCs) (Yang and Smith, 2016a;  
392 Smith et al., 2017), which directly control the timing and magnitude of surface meltwater inputs into ice  
393 masses (Banwell et al., 2013; Clason et al., 2015; Smith et al., 2015; Smith et al., 2017) and cannot be

394 readily determined from DEMs (Yang and Smith, 2016b). Furthermore, as reported in Yang and Smith  
395 (2016a), supraglacial rivers as narrow as ~3 m are sometimes distinguishable in 15 m Landsat-8 images if  
396 the surrounding ice surface is bright and clean, creating strong contrast with dark supraglacial rivers.  
397 Under such conditions, Sentinel-2 images may therefore detect even narrower, higher-order supraglacial  
398 streams (Yang et al., 2016), thus characterizing ice surface drainage patterns more comprehensively.

399 The distribution of dark dust (low albedo) zones influences the quality of Sentinel-2 supraglacial  
400 river maps. These zones are typically found <10 km from the western ice margin of the DIC and pose a  
401 challenge for distinguishing supraglacial rivers against the surrounding dark background (Figure 3b).  
402 Supraglacial rivers are not well channelized in this area and thus cannot be enhanced by the river  
403 detection algorithm presented here. For this reason, low-elevation (<900 m) supraglacial rivers are not  
404 well detected and drainage density at low elevations appears to decrease dramatically after flowing into  
405 the dark dust zone (Figure 10), which is likely erroneous. We therefore suggest caution when mapping  
406 supraglacial rivers or drainage densities using moderate-resolution Sentinel-2 imagery in areas of dark  
407 ice.

408 Integrating remotely sensed river mapping with DEM data will further improve our understanding of  
409 supraglacial drainage patterns. Moderate-resolution (30 m) DEMs have been integrated with remotely  
410 sensed mapping to study the fluvial-morphometry of supraglacial meltwater channels in southwestern  
411 Greenland (Yang et al., 2015b; Yang et al., 2016). The availability of high spatial resolution (~2-5 m)  
412 DEMs (e.g., ArcticDEM (Noh and Howat, 2015, 2017) ) raises prospects for studying surface meltwater  
413 channel morphometry in unprecedented detail. In Yang et al. (2018), a 3 m resolution DEM was utilized  
414 to simulate seasonal evolution of supraglacial river networks with a series of cumulative contributing area  
415 thresholds. By integrating ArcticDEM-simulated continuous drainage networks with image-mapped  
416 supraglacial river networks it becomes possible to create a single river product containing numerous  
417 hydraulically useful channel characteristics (e.g., length, width, slope, sinuosity, and stream order). A  
418 preliminary example is shown in Figure 11. ArcticDEM-simulated drainage networks are more  
419 continuous than Sentinel-2 supraglacial river networks but the method struggles to reproduce river

420 distribution (overestimating high-elevation rivers, underestimating low-elevation rivers, and failing to  
421 identify moulins).

422

## 423 **7. Conclusions**

424 As satellite sensor spatial and temporal resolutions continue to improve, supraglacial streams and rivers  
425 are increasingly discernible on various different snow, firn and ice surfaces. The twin Sentinel-2 satellites  
426 (2A and 2B) began accumulating global coverage in 2017 with a short revisit time (~5 days) and 10 m  
427 spatial resolution. This paper has provided a first synoptic mapping of supraglacial river drainage  
428 networks on the northwest Greenland Ice Sheet near Inglefield Land, the Devon Ice Cap, and the Barnes  
429 Ice Cap using these data. Based on this demonstration, we conclude that the growing Sentinel-2 archive  
430 will enable mapping of supraglacial river drainage networks, their termination points, and seasonal and  
431 inter-annual evolution for ice masses globally. Remotely sensed drainage networks will advance  
432 understanding of meltwater source areas and routing pathways on large ice masses, while their  
433 termination locations will help to identify areas of hydrological coupling between ice surfaces and  
434 subglacial systems.

435

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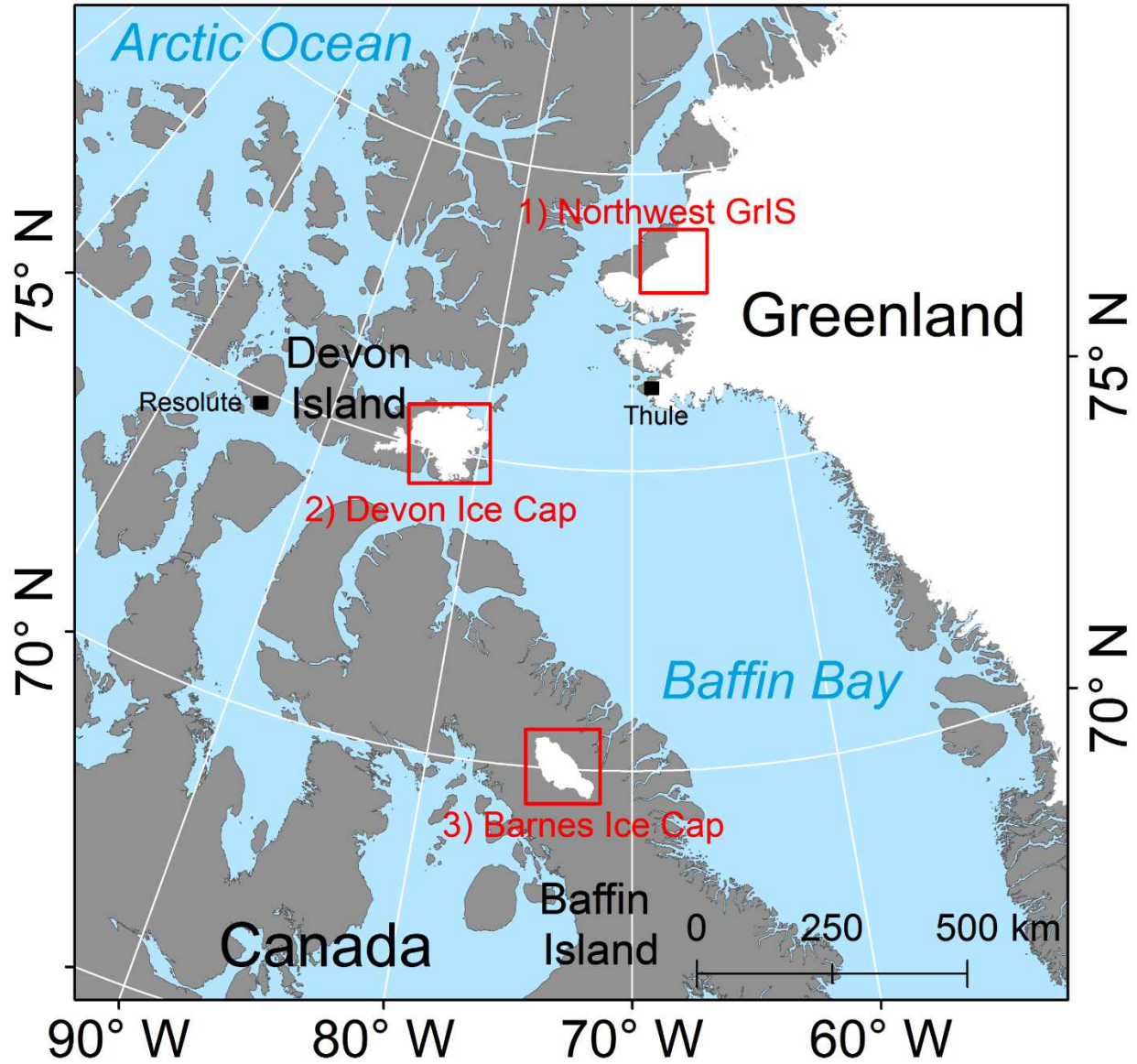
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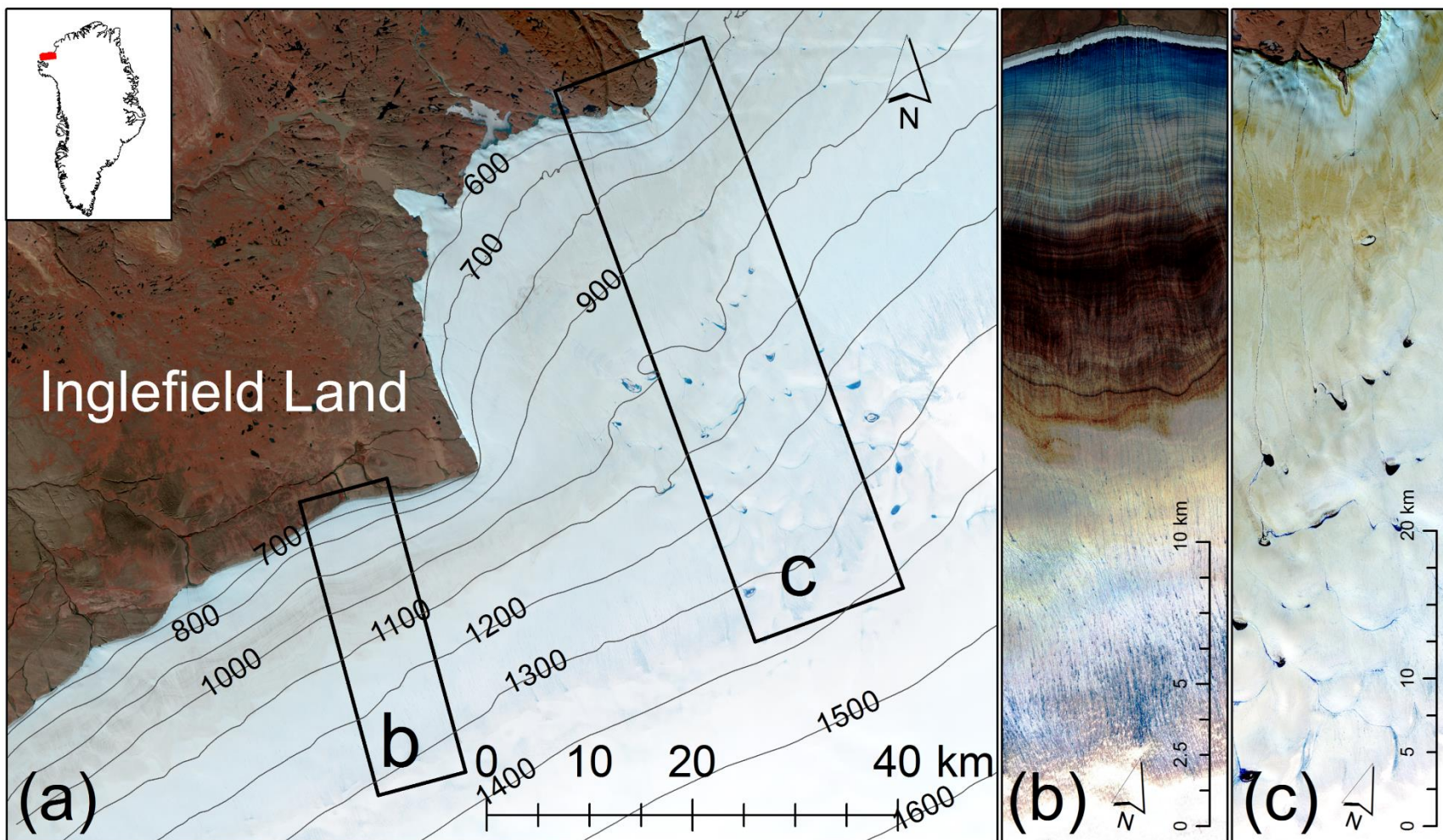
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616

617 **Figure 1.** Locations of the three study areas: 1) northwest Greenland Ice Sheet (GrIS), 2) Devon Ice Cap

618 (DIC), and 3) Baffin Ice Cap (BIC).

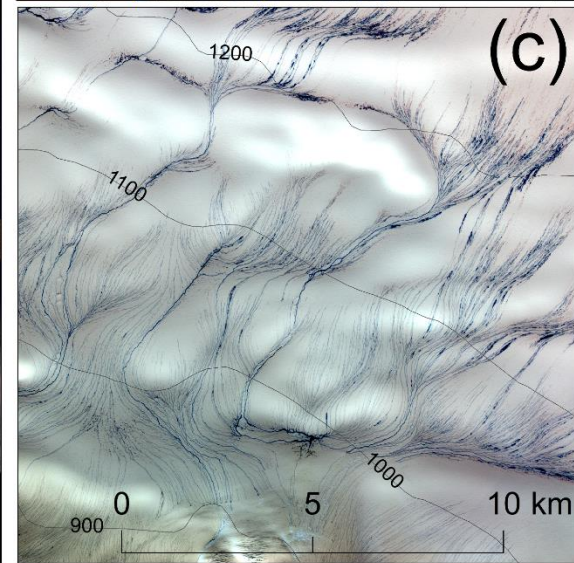
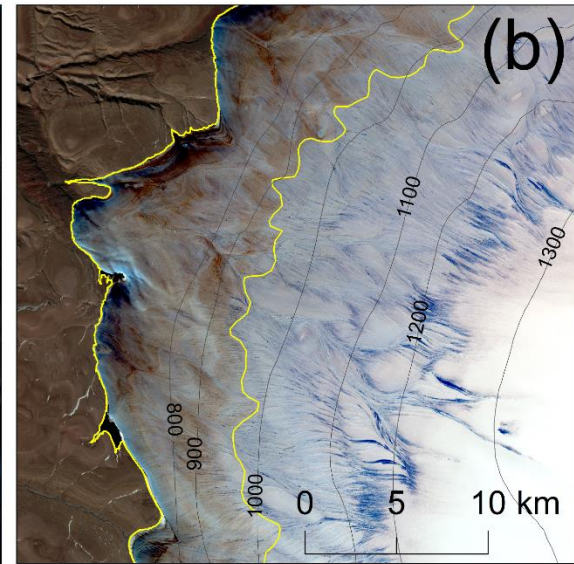
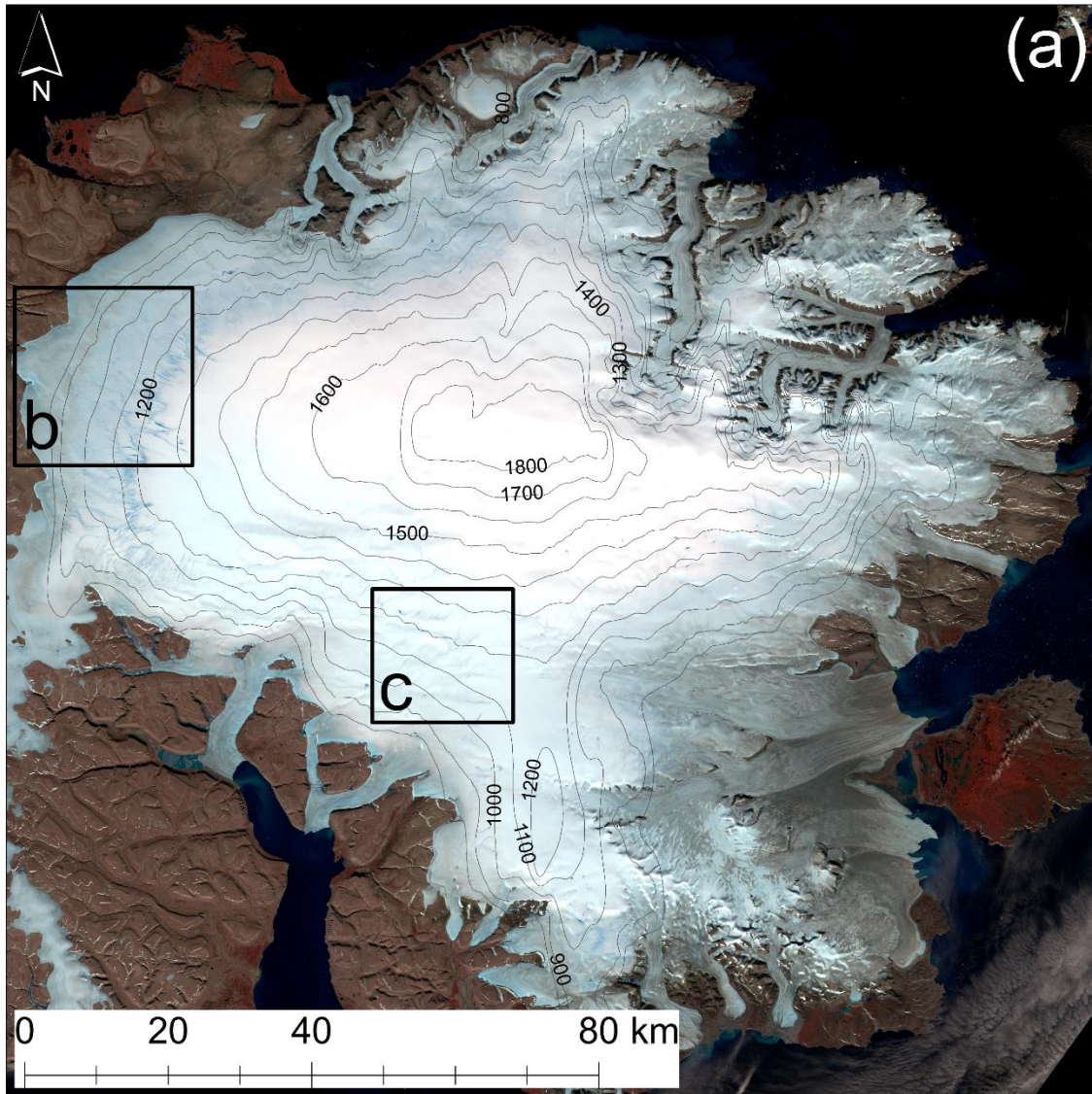


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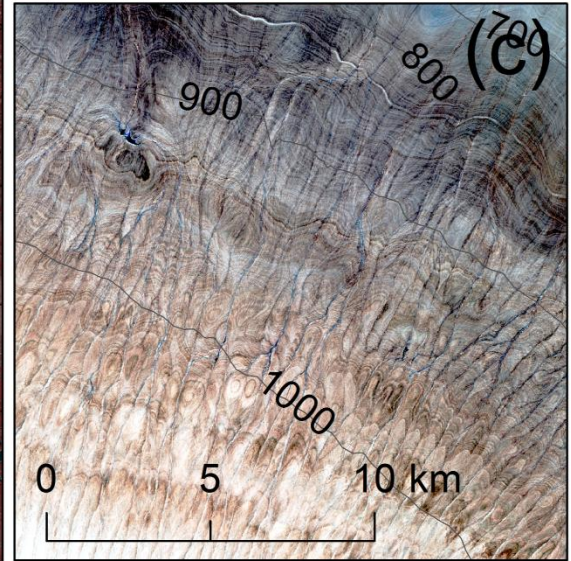
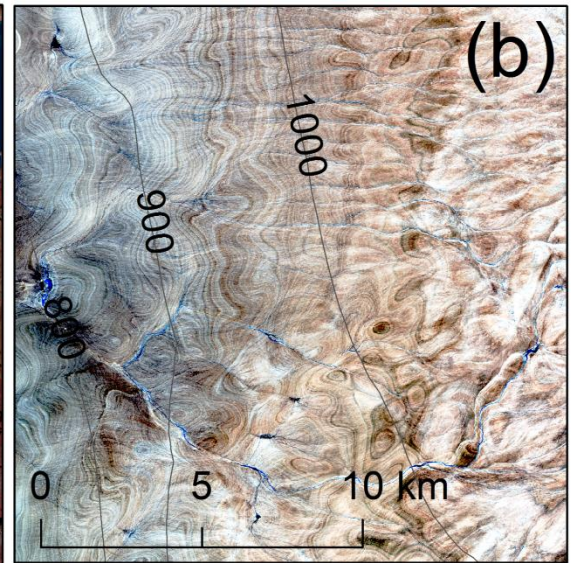
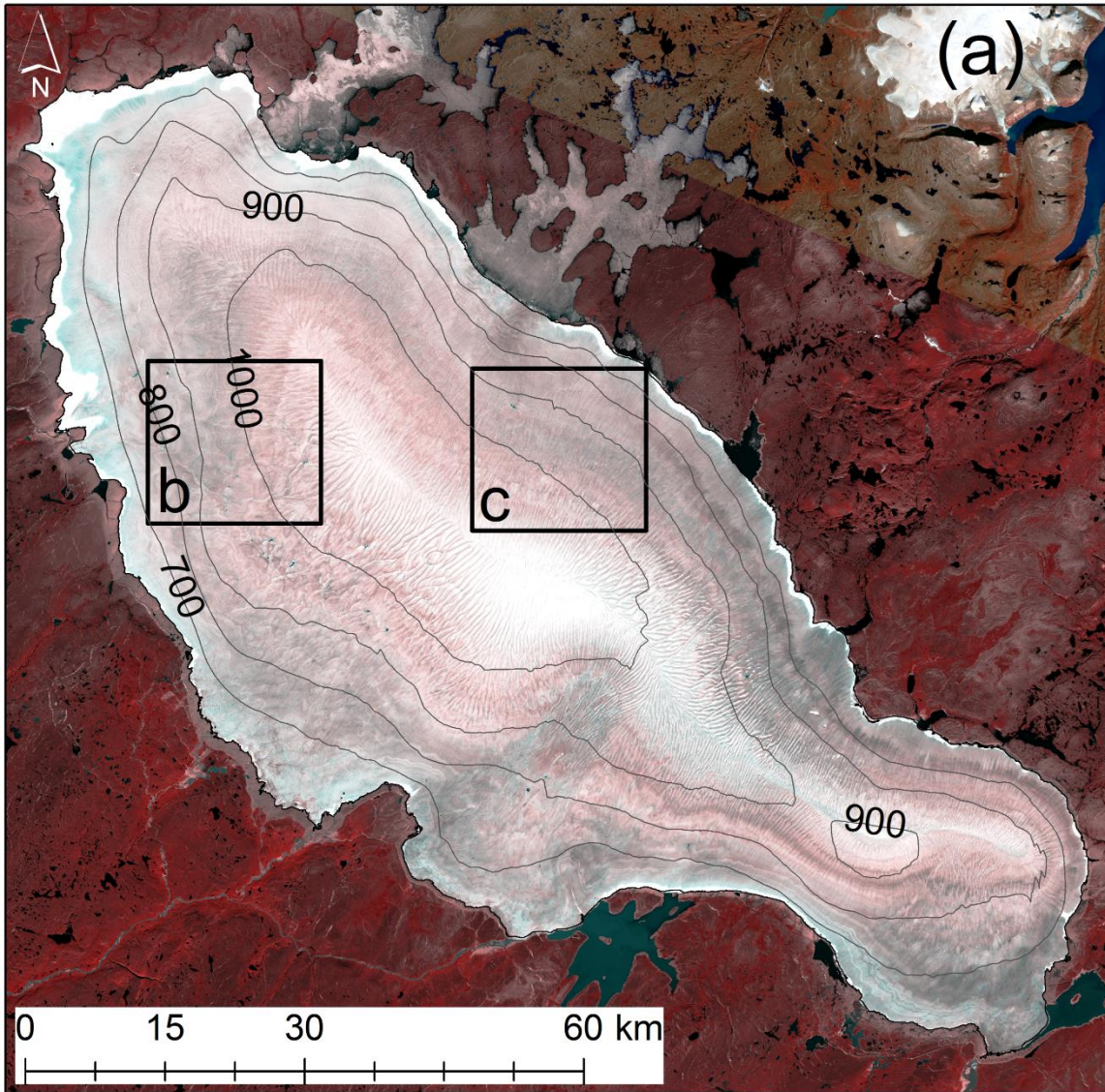
620 **Figure 2.** (a) Landsat-8 image (acquired on 30 July 2016, RGB: bands 5 (NIR), 4 (Red), 3 (Green)) of the northwest GrIS. Sentinel-2 images

621 (acquired on 23 July 2016, RGB: bands 8 (NIR), 4 (Red), 3 (Green)) of two typical sites are shown in (b) and (c), indicating continuous

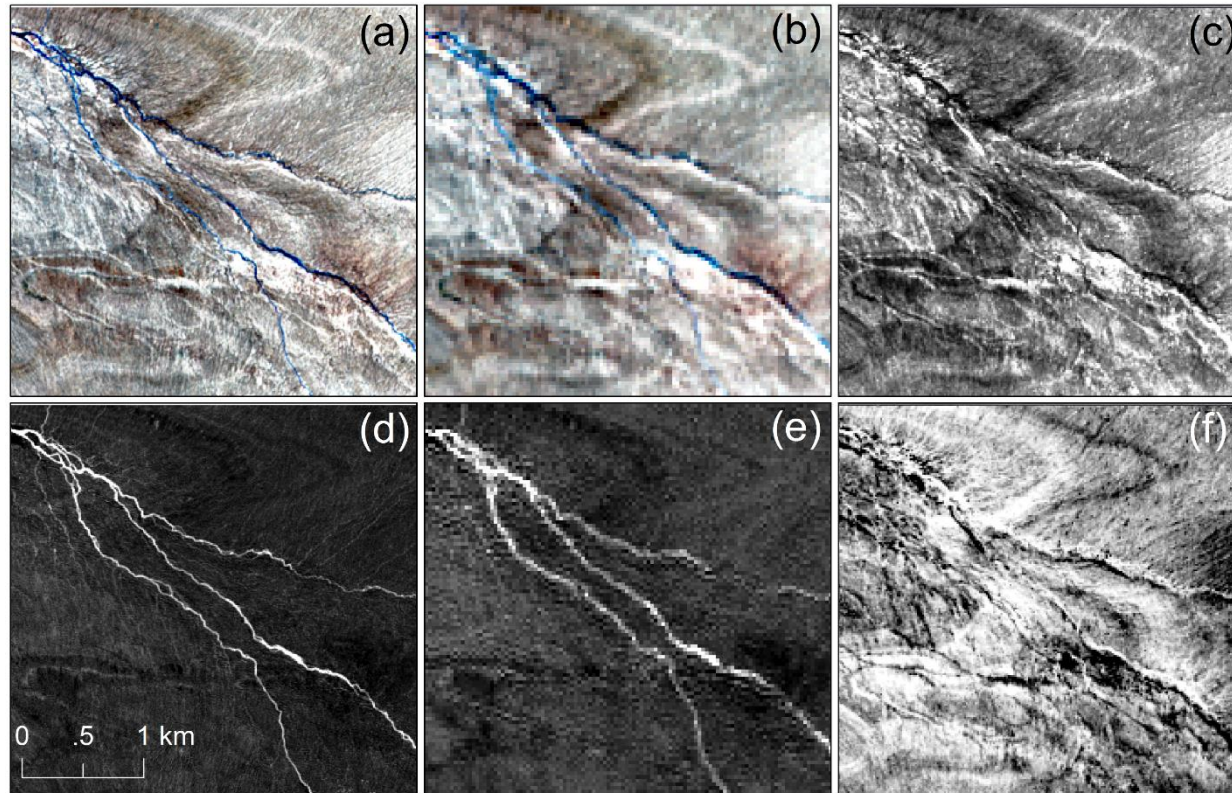
622 supraglacial rivers directly drain meltwater off the ice margin and into proglacial rivers.



624 **Figure 3.** (a) Landsat-8 image (acquired 28 July 2016, RGB: bands 5 (NIR), 4 (Red), 3 (Green)) of the Devon Ice Cap (DIC). Our chosen sites to  
625 study ice cap hydrology are (b) western and (c) southern sections of the DIC, shown in two Sentinel-2 images (also acquired 28 July 2016, RGB:  
626 bands 8 (NIR), 4 (Red), 3 (Green)). The dark dust zone is enclosed by the yellow line.  
627



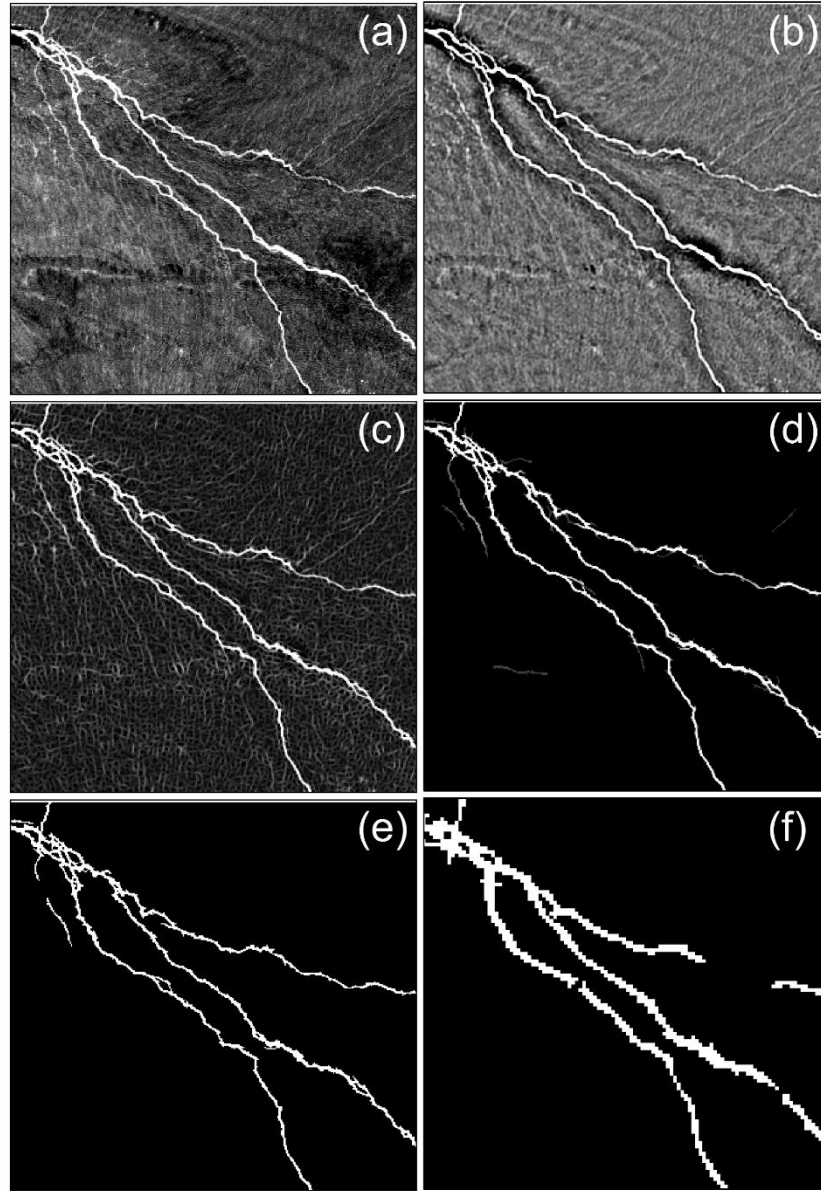
629 **Figure 4.** (a) Landsat-8 image (acquired on 9 August 2016, RGB: bands 5 (NIR), 4 (Red), 3 (Green)) of the Barnes Ice Cap (BIC). Our chosen  
630 sites to study ice cap hydrology are (b) western and (c) eastern sections of the BIC, shown in two Sentinel-2 images (acquired on 20 August 2016,  
631 RGB: bands 8 (NIR), 4 (Red), 3 (Green)).



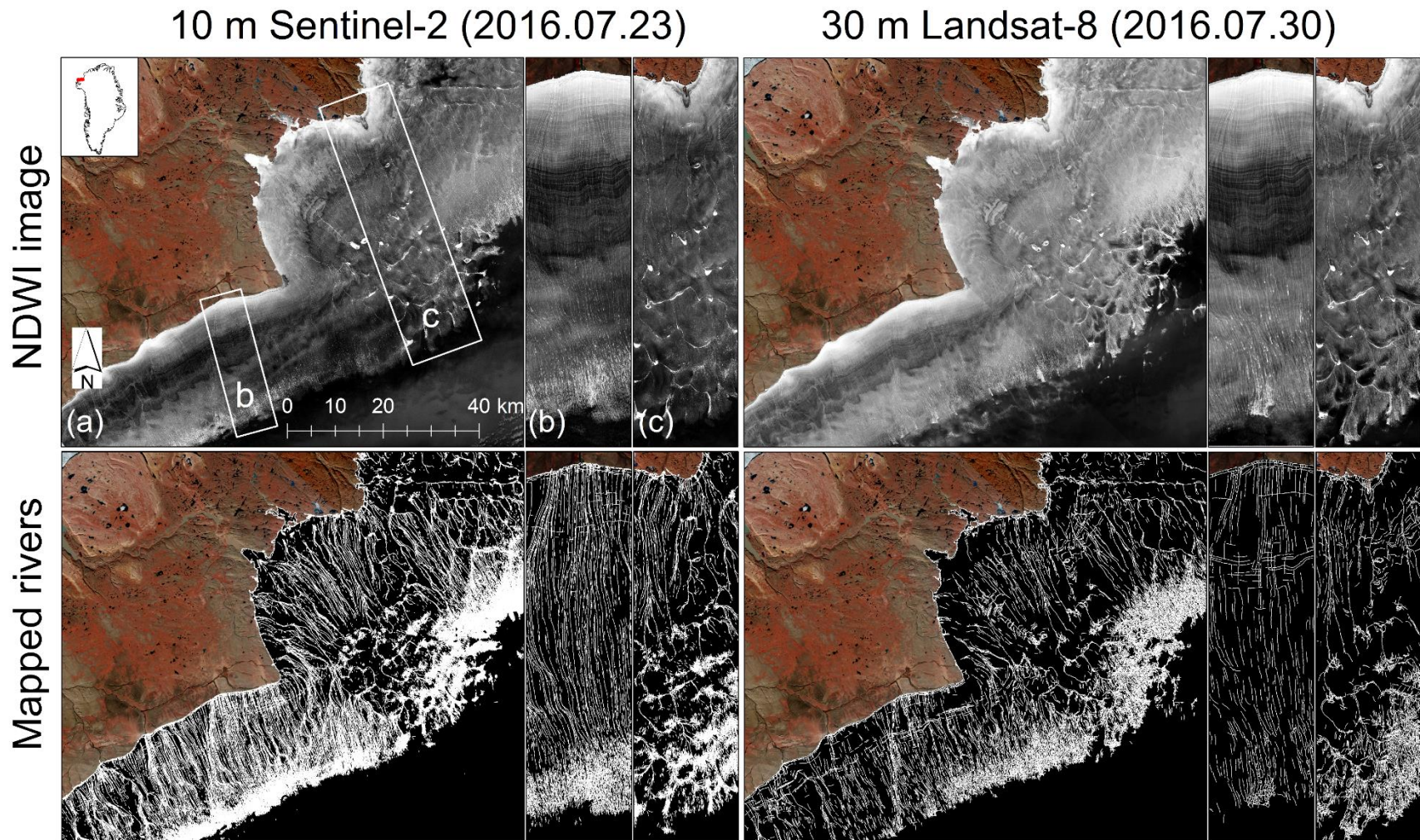
632

633 **Figure 5.** Comparison of supraglacial rivers as detected in (a) 10 m multispectral Sentinel-2 MSI image (acquired on 25 July 2016, RGB: bands 8  
634 (NIR), 4 (Red), 3 (Green)), (b) 30 m multispectral and (c) 15 m panchromatic Landsat-8 OLI imagery (acquired on 26 July 2016). Panels (d) and  
635 (e) show the corresponding normalized difference water index (NDWI) images derived from (a) and (b). Panel (f) shows the inverse gray image  
636 for the panchromatic image in which meltwater is represented as white color.

637



639 **Figure 6.** Workflow for delineating a supraglacial river network from 10 m multispectral Sentinel-2 MSI imagery, following the method of Yang  
640 et al. (2017): (a) input NDWI image; (b) NDWI image after band-pass DFT filtering; (c) Gabor filtering of (b); (d) enhancement of (c) using a path  
641 opening algorithm; (e) final supraglacial river detection results. For comparison, panel (f) shows detection using a contemporary 30 m  
642 multispectral Landsat-8 OLI image.

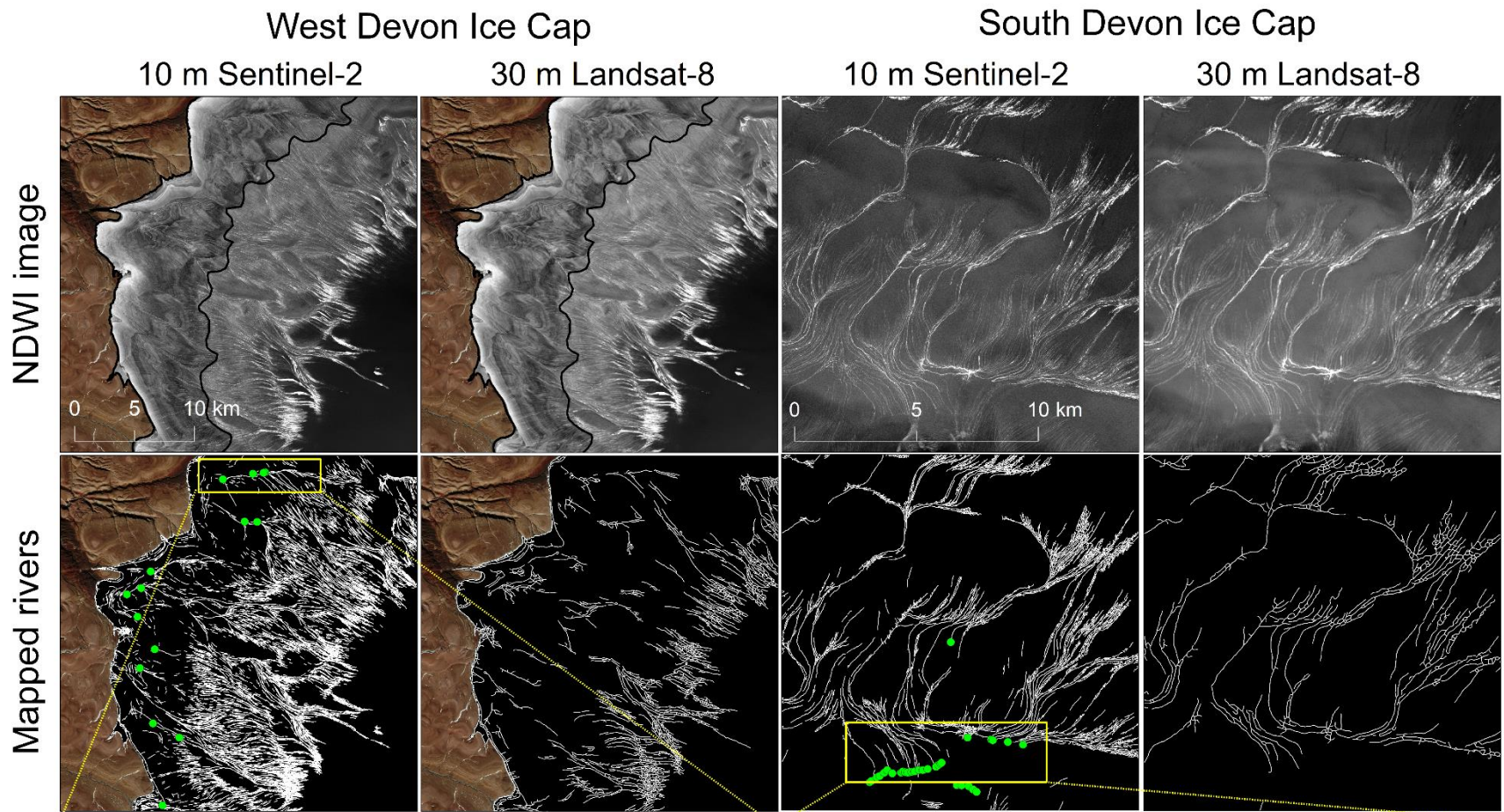


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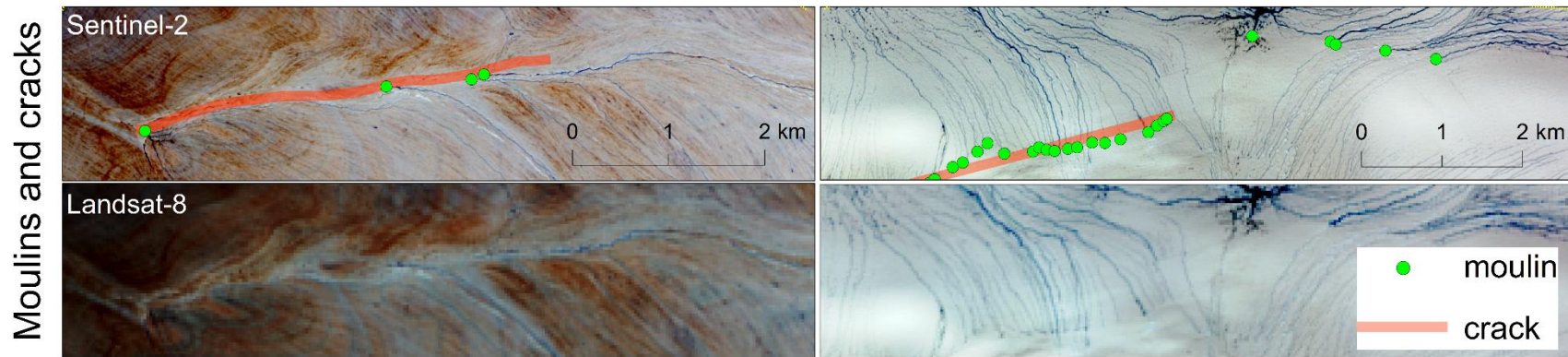
644 **Figure 7.** Supraglacial river networks on the northwest Greenland Ice Sheet near Inglefield Land mapped from two 10 m Sentinel-2 images

645 (acquired on 23 July 2016) and two 30 m Landsat-8 satellite images (acquired on 30 July 2016). Insets reveal (b) long, subparallel supraglacial

646 rivers flowing ~30 km over the ice to the proglacial zone; and (c) supraglacial rivers interconnecting and draining supraglacial lakes to the  
647 proglacial zone.



648



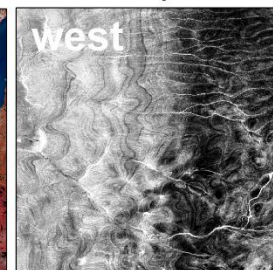
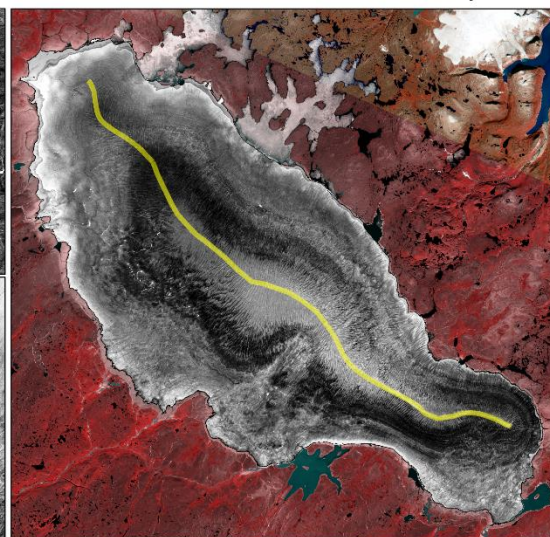
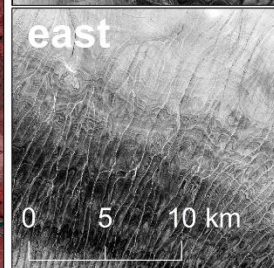
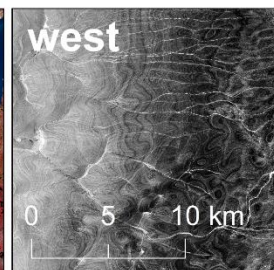
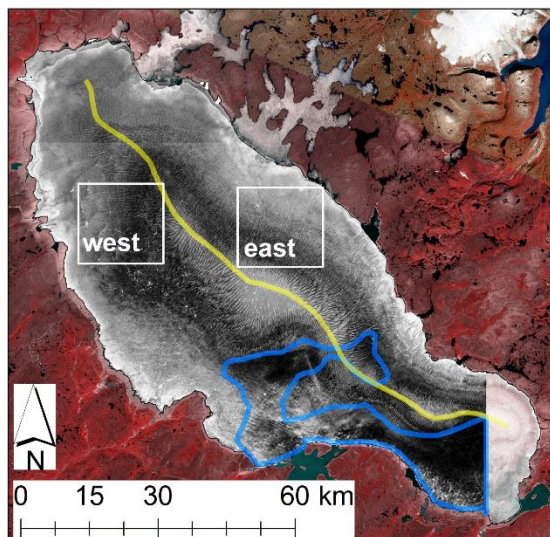
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650 **Figure 8.** Supraglacial river networks on the western (Figure 2b) and the southern (Figure 2c) sections of the Devon Ice Cap (DIC) mapped from  
 651 concurrent 10 m Sentinel-2 and 30 m Landsat-8 satellite images (captured on 28 July 2016). Moulins (abrupt terminations of supraglacial river  
 652 networks) can be reliably identified from the Sentinel-2 images. On the western section of the DIC, straight supraglacial rivers flow continuously  
 653 toward the ice margin, become more sinuous at low elevations, and are captured by 16 moulins; on the southern section of the DIC, supraglacial  
 654 rivers are very sinuous and often turn at right angles, indicating strong controls of surface topography. A ~3 km long west-east orientated linear  
 655 crevasse abruptly terminate supraglacial rivers and form 18 moulins in this small area.

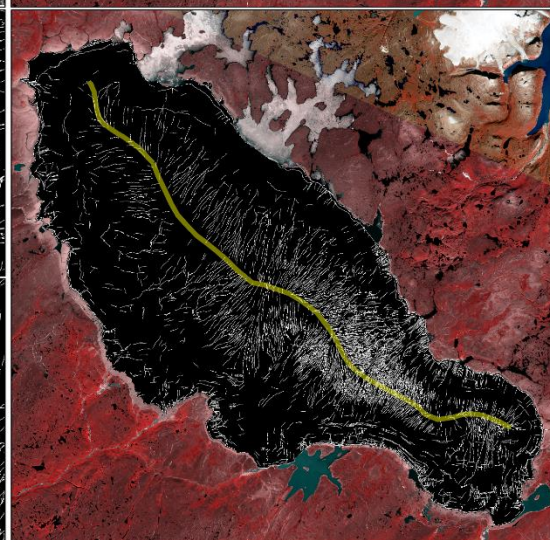
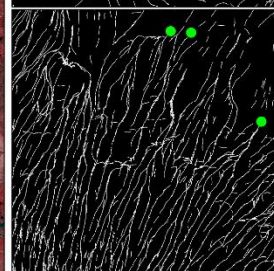
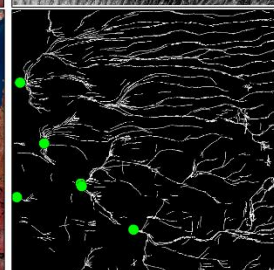
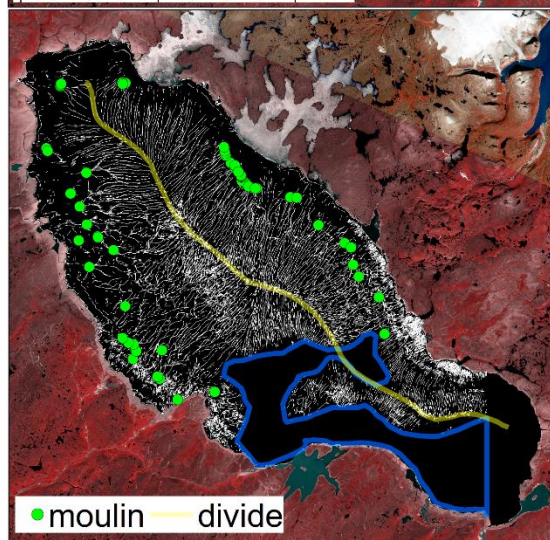
10 m Sentinel-2 (2016.08.20)

30 m Landsat-8 (2016.08.09)

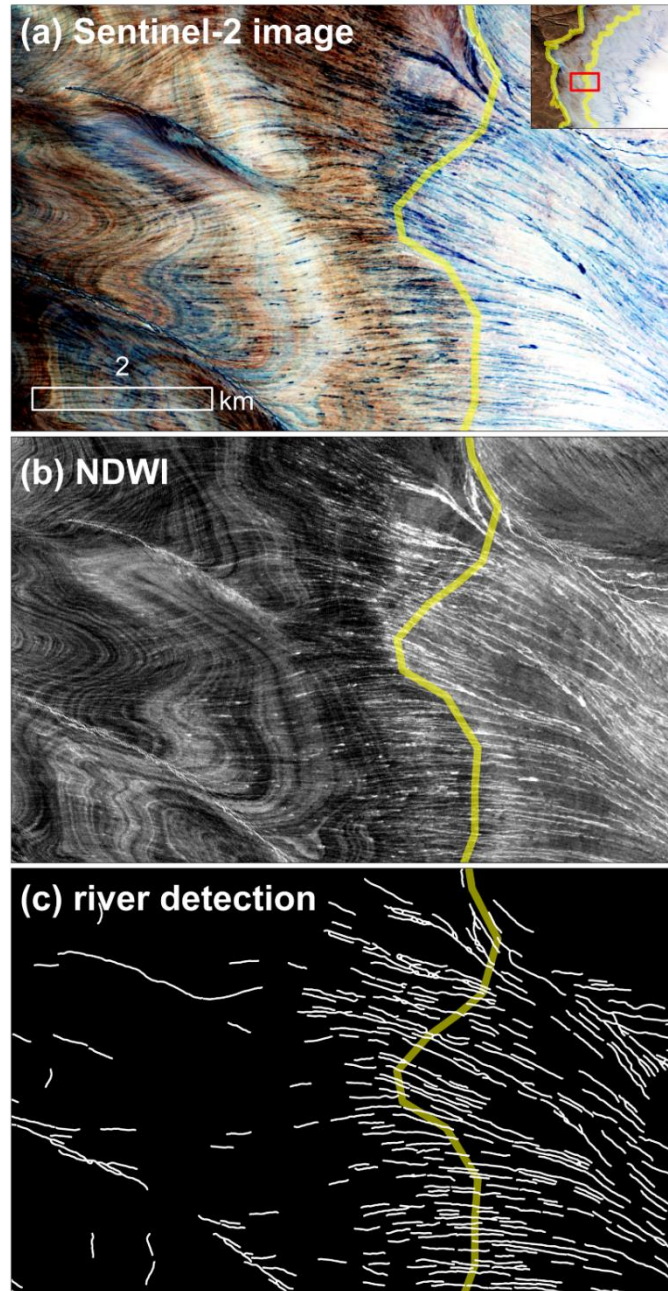
NDWI image



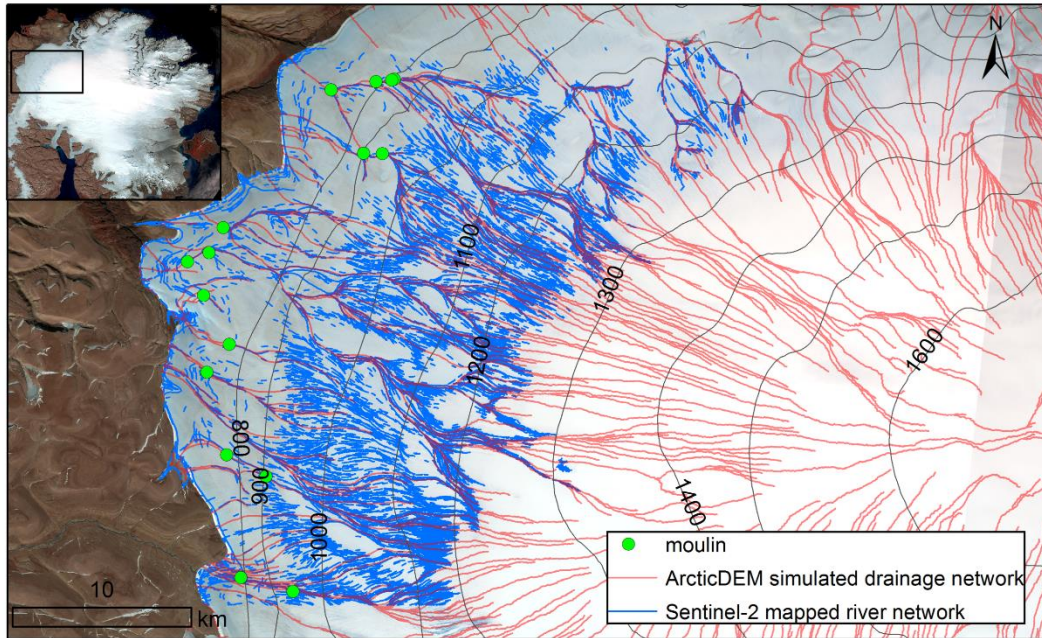
Mapped rivers



657 **Figure 9.** Supraglacial river networks on the Barnes Ice Cap (BIC) mapped from two 10 m Sentinel-2 (captured on 20 August 2016) images and  
658 one 30 m Landsat-8 image (captured on 9 August 2016). Two study sites are selected from the western and the eastern sections of the BIC and  
659 their corresponding river mapping results are showed in detail. Supraglacial rivers are relatively straight and subparallel on the eastern side, while  
660 they are more dendritic on the western side. The yellow line encloses the ice divide and the blue line encloses the area covered by clouds.



661  
 662 Figure 10. A close-up view of the western section of the Devon Ice Cap (Figure 3b) using (a) Sentinel-2  
 663 imagery, (b) derived NDWI image, and (c) meltwater channel detection results, showing “vanishing” of  
 664 numerous supraglacial rivers after flowing into the dark dust zone. The dark dust zone is enclosed by the  
 665 yellow line and the inset red outline shows the study area location in the western section of the Devon Ice  
 666 Cap.



667

668 Figure 11. Comparison of ArcticDEM simulated drainage network with Sentinel-2 mapped supraglacial  
 669 river network for western section of Devon Ice Cap. ArcticDEM simulated drainage networks are more  
 670 continuous than Sentinel-2 river networks but cannot actual distribution of supraglacial river networks  
 671 (overestimating high-elevation rivers, underestimating low-elevation rivers, and failing to identify  
 672 moulins).

673

**Table 1.** Sentinel-2 (S2A) and Landsat-8 (LC8) satellite images used in this study.

<b>Study area</b>	<b>Image ID</b>	<b>Acquisition Date</b>
<b>Northwest Greenland Ice Sheet</b>	S2A_OPER_MSI_L1C_TL_SGS__20160723T212906_A005672_T19XEH	2016.07.30
	S2A_OPER_MSI_L1C_TL_SGS__20160723T212906_A005672_T19XDG	2016.07.30
	LC80350032016212LGN00	2016.07.23
	LC80350042016212LGN00	2016.07.23
<b>Devon Ice Cap</b>	S2A_OPER_MSI_L1C_TL_SGS__20160728T220647_A005744_T16XEJ	2016.07.28
	S2A_20160728T220647_A005744_T17XMD	2016.07.28
	LC80370072016210LGN00	2016.07.28
<b>Barnes Ice Cap</b>	S2A_OPER_MSI_L1C_TL_MTI__20160820T221251_A006072_T18WWC	2016.08.20
	S2A_OPER_MSI_L1C_TL_MTI__20160820T221251_A006072_T18WWD	2016.08.20
	LC80250112015222LGN00	2016.08.09

676 **Table 2.** Statistics of supraglacial rivers mapped from Sentinel-2 and Landsat-8 images for the northwest  
 677 Greenland Ice Sheet (GrIS), the Devon Ice Cap, and the Barnes Ice Cap.

Study area		Area (km <sup>2</sup> )	Total river length (km)		Drainage density (km <sup>-1</sup> )	
			Sentinel-2	Landsat-8	Sentinel-2	Landsat-8
<b>Northwest GrIS</b>		4281.4	24010.0	11440.2	5.6	2.7
<b>Devon Ice Cap</b>	<b>West</b>	561.7	2866.5	951.2	5.1	1.7
	<b>South</b>	200.1	661.5	292.6	3.3	1.5
<b>Barnes Ice Cap</b>		4660.3*	11653	7282.8	2.5	1.3

678 \*The total area of the Barnes Ice Cap is 5736.2 km<sup>2</sup>. The Sentinel-2 images miss a small east portion  
 679 (280.8 km<sup>2</sup>) and clouds cover an area of 795.2 km<sup>2</sup> (see blue line in Figure 9), both of which are excluded  
 680 from the actual mapped area.