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1 **‘Detachment’ of icefield outlet glaciers – catastrophic**  
2 **thinning and retreat of the Columbia Glacier (Canada)**

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22 **Key Points**

23 *1. Rapid retreat of the Columbia Glacier is (in part) attributed to the detachment of this*  
24 *outlet glacier from the Columbia Icefield.*

25 *2. Such 'detachment' has occurred previously on other outlet glaciers of the Columbia*  
26 *Icefield and looks set to take place on more.*

27 *3. We identify this process of 'detachment' (whereby outlet glaciers lose contact with*  
28 *the upper icefield) as an important mechanism by which icefields may decay.*

29 *4. Outlet glacier 'detachment' results in an isolated 'perched' icefield, accelerated*  
30 *glacier retreat and snout-stagnation.*

31 **Abstract**

32 We present an investigation of changes taking place on the Columbia Glacier – a lake-  
33 terminating outlet of the Columbia Icefield in the Canadian Rockies. The Columbia  
34 Icefield is the largest, and one of the most important, ice bodies in the Canadian  
35 Rockies. Like other ice masses, it stores water as snow and ice during the winter and  
36 releases it during warmer summer months, sustaining river flows and the ecosystems  
37 that rely on them. However, the Columbia Glacier and Icefield is shrinking. We use  
38 Landsat and Sentinel-2 imagery to show that the Columbia Glacier has retreated  
39 increasingly rapidly in recent years, and suggest that this looks set to continue.  
40 Importantly, we identify a previously undocumented process that appears to be playing  
41 an important role in the retreat of this glacier. This process involves the '*detachment*'  
42 of the glacier tongue from its accumulation area in the Columbia Icefield. This process  
43 is important because the tongue is cut off from the accumulation area and there is no  
44 replenishment of ice that melts in the glacier's ablation area by flow from upglacier. As  
45 a consequence, for a given rate of ablation, the ice in the tongue will disappear much  
46 faster than it would if the local mass loss by melting/calving was partly offset by mass  
47 input by glacier flow. Such a change would alter the relationship between rates of  
48 surface melting and rates of glacier frontal retreat. We provide evidence that  
49 *detachment* has already occurred elsewhere on the Columbia Icefield and that it is  
50 likely to affect other outlet glaciers in the future. Modelling studies forecast this  
51 detachment activity, which ultimately results in a smaller 'perched' icefield without  
52 active outlets.

53

54 **Keywords**

- 55 Columbia Icefield, Columbia Glacier, Rocky Mountains, outlet glaciers, Glacier
- 56 stagnation, outlet glacier detachment

## 57 **1. Introduction – Glacier change of the Columbia Icefield**

58 In mountainous regions of the world, meltwater from glaciers makes a significant  
59 contribution to streamflow, sustaining water flows for a range of needs (Zappa & Kan,  
60 2007; Moore et al., 2009; Jost et al., 2012). As climate warms and glaciers shrink and  
61 retreat, it is predicted that there will eventually be a decrease in the glacial contribution  
62 to streamflow (e.g. Gurtz et al., 2003). In Canada, glaciers have been melting rapidly  
63 since the end of the Little Ice Age (~150 years ago; Canadian Cryospheric Information  
64 Network, 2015), and there is mounting evidence that, in the Canadian Rockies,  
65 continuing climate change will result in reductions in glacier volume of up to 80-90%  
66 over the coming decades (Marshall et al., 2011) with few glaciers remaining by 2100  
67 (Clarke et al., 2015). The possibility that complete loss of these glaciers could occur  
68 by the end of the century is of great concern because they represent a significant water  
69 resource, with meltwater helping to supplement summer flow levels and regulate  
70 stream temperatures, both of which are important for a range of services, including  
71 irrigation, hydro-electric power generation, and industrial usage, as well as for  
72 downstream ecosystems (e.g. Henoch, 1971; Barry, 2006; Granshaw & Fountain,  
73 2006; Stahl & Moore, 2006; Moore et al., 2009).

74 The Columbia Icefield is one of the most important ice bodies in the Canadian Rockies.  
75 It is the largest ice mass in North America outside of the Arctic Circle, covering an area  
76 of ~337 km<sup>2</sup> (Baumann, 2017), and acts as a significant water resource (Bolch et al.,  
77 2010). Notably, it sits on a triple water divide, with meltwater from the icefield draining  
78 into three distinct watersheds (the Athabasca, Saskatchewan and Columbia  
79 watersheds) which drain into the Arctic, Atlantic and Pacific Oceans respectively  
80 (Tennant & Menounos, 2013). The Columbia Icefield is also of substantial economic  
81 importance as a major tourist attraction (Parks Canada Agency, 2011). Being able to

82 predict the future state and extent of the Columbia Icefield is therefore important.  
83 Tennant and Menounos (2013) identified 25 individual glaciers that drain from different  
84 parts of the icefield, but we focus on seven major named outlet glaciers: Stutfield,  
85 Kitchener, Dome, Athabasca, Saskatchewan, Castleguard and Columbia Glaciers  
86 (Figure 1).

87 The Columbia Glacier is one of the most dynamic outlets of the Columbia Icefield,  
88 terminating in a significant proglacial lake which is currently unnamed (Figures 1 and  
89 2). Hereafter we refer informally to this lake as 'Lake Columbia'. The glacier is,  
90 however, little studied. The Columbia Glacier drains from the Columbia Icefield and  
91 over a cliff into a relatively narrow and constrained valley, in which its tongue currently  
92 resides. It has a dynamic history, with past phases of expansion and retreat, and  
93 various observations of its terminus location providing insight into its fluctuating extent.  
94 As a consequence of these historical changes in glacier length, the size of Lake  
95 Columbia has also varied. Between 1724 and 1924, the glacier retreated a total of 394  
96 m (Heusser, 1954). Between 1966 and 1977, the glacier advanced by up to 1 km  
97 (Baranowski & Henoch, 1978), while from 1966 to 1980 a ~800 m advance filled Lake  
98 Columbia (Ommanney, 2002). Ommanney (2002) described the Columbia Glacier as  
99 being 8.5 km in length and 16 km<sup>2</sup> in area, and also highlighted a key characteristic –  
100 that it has a major icefall that dramatically links the upper icefield-region to the lower  
101 glacier tongue. In 2008, the GLIMS (Global Land Ice Measurements from Space)  
102 database listed the Columbia Glacier as covering an area of ~29.99 km<sup>2</sup> but gave no  
103 details regarding its length (Raup et al. 2007). Based on analysis of data from 1999  
104 and 2009, Tennant and Menounos (2013) suggested that its area was 32.2 km<sup>2</sup>, and  
105 its length was 5831 m. The differences between these length and area measurements  
106 and those of Ommanney (2002) reflect clear differences in exactly where the

107 measurements of length were made, and in precisely how the margins of the glacier  
108 were defined. This is particularly so in the upper accumulation area which lies within  
109 the icefield itself. Tennant and Menounos (2013) also described how over a period of  
110 90 years between 1919 and 2009, all the glaciers draining from the icefield showed  
111 (net) retreat. The glaciers retreated and fluctuated in similar ways, such that the  
112 pattern of retreat was correlated with observed changes in both air temperature and  
113 precipitation. This strongly suggests a climate-related control (Tennant & Menounos,  
114 2013). Despite the consistent retreat of all Columbia Icefield glaciers, Tennant and  
115 Menounos (2013) suggested that the Columbia Glacier had retreated the furthest  
116 (3723 ( $\pm$  34) m between 1919 and 2009, which equates to an average rate of 41.37 m  
117 a<sup>-1</sup>).

118 Since the work of Tennant and Menounos (2013) there has been no further study of  
119 this glacier. In summer 2017, we undertook survey flights over the Columbia Icefield  
120 and observed some unusual changes in the geometry of the Columbia Glacier (when  
121 compared to historical imagery), which we hypothesize are linked to the ongoing mass  
122 balance changes in the region. These observations form the basis of this paper, and  
123 provide the motivation to further study this glacier. Here, we present an up-to-date  
124 assessment of the recent changes that have taken place on the Columbia Glacier, as  
125 an indication of the glacier's health. We also explore temporal changes in dynamic  
126 behaviour thanks to a newly-available dataset of mean annual velocities. Most  
127 importantly however, we explore changes in the geometry of the glacier and propose  
128 a distinctive mechanism of change for glaciers draining from plateau icefields.

129

### 130 **3. Methodology**



131 ***Long-term changes in glacier length:*** In order to document the changes taking place  
132 on the Columbia Glacier, we used freely available optical satellite imagery from  
133 Landsat-5, Landsat-7, Landsat-8 (via USGS Earth Explorer) and Sentinel-2 (via ESA  
134 Copernicus). Our investigations of glacier margin change were carried out using the  
135 Google Earth Engine Digitisation Tool (GEEDiT), developed by Lea (2018), to explore  
136 all optical imagery for the period between July 2009 and June 2019. The approach is  
137 particularly advantageous since it allows all imagery to be viewed virtually  
138 instantaneously and then either rejected or (where the margin is clearly visible) used  
139 in assessing glacier change. This approach is useful because it enables rapid  
140 searching of the image archive, regardless of cloud-cover, and for image usefulness  
141 to be determined on a case-by-case basis. We began our search in 2009 – the year  
142 in which Tennant and Menounos’s (2013) analysis ended. Our search provided 79  
143 sets of images acquired in the months of July to September between 2009 and 2019.  
144 This dataset was subsequently temporally filtered so as to explore images separated  
145 by at least 7-day gaps (and maximum of 400 days). This reduced the image selection  
146 to 56 sets, but improved visualisation of the data by only exploring change over  
147 timescales of greater interest than day-to-day (Lea, 2018).

148 For all datasets, within GEEDiT, true-colour images were generated by combining  
149 bands (3-2-1 for pre-Landsat 8; 4-3-2 for Landsat 8 and 4-3-2 for Sentinel 2). Before  
150 the application of GEEDiT, we explored the use of various band-combinations and  
151 thresholding techniques to automatically delineate the margins of the icefield and its  
152 outlet glaciers (cf. Paul et al., 2016). However, the threshold value required to correctly  
153 delineate an ice margin in our data seemed to be somewhat arbitrary, and could vary  
154 significantly between image-sets. We therefore preferred the adoption of a manual  
155 approach for delineating the ice margins (an approach also adopted by the GEEDiT

156 package), which was deemed more accurate since margins were relatively  
157 straightforward to identify visually. It is widely recognised in the literature that complete  
158 manual digitisation is sometimes necessary (as applied here) and even when  
159 automation is carried out, visual verification and correction are often needed for  
160 accurate determination of glacier margins (Paul et al., 2017).

161 Changes in glacier extent were quantified using both a single centreline and a multi-  
162 centreline method (Lea, 2018). This is an development of the more traditional single  
163 centreline approach, developed by Lea (2018), here generating 42 centrelines,  
164 separated by gaps of 10 m, across the glacier tongue, parallel to the centreline shown  
165 in Figure 2. The approach offers significant new insights because, by facilitating many  
166 one-dimensional measurements of terminus change, spatial variability in the glacier  
167 margin position is easily determined. This is important when a glacier margin is  
168 complex and where they may be variations in the rate of response along a terminus.

169 In order to account for the subjective nature of manual margin delineation, the glacier  
170 terminus was digitised on three separate occasions for each image. This provided  
171 some assessment of the uncertainty inherent in the mapping process.

172 ***Geometric changes:*** The key motivation for this work was an observation made by  
173 the lead-author during a survey-flight over the Columbia Icefield during the summer of  
174 2017. These flights were carried out in order to gather optical imagery for Structure  
175 from Motion (SfM) processing and subsequent building of high resolution digital  
176 elevation models (DEMs) and orthomosaics (OMs; not presented here). However,  
177 observations of the Columbia Icefield and Columbia Glacier were made during this  
178 flight, and further oblique photographs of the region of interest were collected (see

179 below). Our interpretations of these observations and images form the basis for the  
180 hypothesis presented here.

181 **Surface velocity:** Annual mean surface velocity data were generated using auto-RIFT  
182 (Gardner et al., 2018) and provided by the NASA MEaSUREs (Making Earth System  
183 Data Records for Use in Research Environments) ITS\_LIVE (Inter-Mission Time  
184 Series of Land Ice Velocity and Elevation) project (Gardner et al., 2019). These data  
185 are derived from Landsat 4, 5, 7 and 8 images, and are determined at a 240 m  
186 resolution. Full details of the derivation of these datasets can be found at: [http://its-  
187 live-data.jpl.nasa.gov.s3.amazonaws.com/documentation/ITS\\_LIVE-Regional-  
188 Glacier-and-Ice-Sheet-Surface-Velocities.pdf](http://its-live-data.jpl.nasa.gov.s3.amazonaws.com/documentation/ITS_LIVE-Regional-Glacier-and-Ice-Sheet-Surface-Velocities.pdf)

189 **Model comparison:** In 2015, Clarke et al. published an extensive modelling study of  
190 likely future changes in the glaciers and icefields of Western Canada. They drove their  
191 model with output from six atmospheric General Circulation Models (GCMs) forced by  
192 the four IPCC AR5 emissions scenarios, which represent different levels of increase  
193 in the radiative forcing on the climate system by 2100, relative to values from the pre-  
194 industrial period. Full details of this work are not repeated here, but can be found in  
195 Clarke et al. (2015). Here we use results from runs forced by output from the MIROC-  
196 ESM (Japan Agency for Marine-Earth Science and Technology, Atmosphere and  
197 Ocean Research Institute (University of Tokyo) and the National Institute for  
198 Environmental Studies (Japan)) GCM. Clarke et al. (2015) consider that these results  
199 best represent the median of outputs from the GCM models that they explored, and  
200 used them in their detailed exploration of future ice mass change. Here, we first  
201 compare the model's predicted extent of the Columbia Icefield in 2018 with Sentinel-  
202 2 imagery also from 2018, and then explore the model's predictions of future ice extent.  
203 While Clarke et al. (2015) show the projected deglaciation of the entirety of the

204 Columbia Icefield (their Figure S32), we focus on how the projected retreat of the  
205 Columbia Glacier itself compares with that of the Columbia Icefield as a whole. Our  
206 intention is to determine whether the model results reproduce the patterns of  
207 geometric change that we infer from the analysis of recent imagery.

208

## 209 **4. Results and analysis**

### 210 ***Dynamics and Geometry***

211 Figure 2 shows the result of the determination of a series of Landsat 5 (2009-2011; 30  
212 m resolution), Landsat 7 (2009, 2010, 2012; pan-sharpened 15 m resolution), Landsat  
213 8 (2013-2016 and 2018; pan-sharpened 15 m resolution) and Sentinel-2 (2016-2019;  
214 10 m resolution) images of the Columbia Glacier, which were used to determine  
215 terminus locations. The quality of imagery available for analysis is highly variable, and  
216 the imagery we were able to use successfully was dictated by season, snow extent,  
217 and cloud extent. As a consequence the precise spacing of useable images cannot be  
218 controlled. There are thus 7 images from 2009; 5 from 2010; 4 from 2011; 2 from 2012;  
219 4 from 2013; 6 from 2014; 4 from 2015 7 from 2016; 8 from 2017; 8 from 2018 and 1  
220 from 2019. Where there are substantial sets of images from an individual year,  
221 apparent minor re-advances and retreats occur that reflect intra-annual variability (i.e.  
222 advances in response to mass gains in the winter and retreats due to mass losses in  
223 the summer). Figure 3 summarises the changes in the terminus location (and rate of  
224 terminus change) of Columbia Glacier in all observation years along a single centre-  
225 line (cf. Figure 2). Due to the complexity of the glacier terminus, Figure 4 also displays  
226 rates of terminus change of the glacier's terminus in all observation years (cf. Figure  
227 2). However, this figure shows change at 20m steps along the ice-front. For the most

228 part the figure shows consistent retreat over the observation period with only minor  
229 spatial variability. However, in occasional time-steps, greater amounts of retreat take  
230 place (darker blue shading) as well as periods of readvance (light green and yellow),  
231 as referred to above.

232 Tennant and Menounos (2013) suggested that of all the Columbia Icefield outlets, the  
233 Columbia Glacier had retreated the most, with a measured retreat of  $3723 (\pm 34)$  m  
234 between 1919 and 2009. This magnitude is more than three times the mean of all the  
235 Columbia Icefield outlets ( $1150 \pm 34$  m). For the Columbia Glacier, this equates to an  
236 average rate of retreat of  $41.37 \text{ m a}^{-1}$ , as compared to a mean rate of all Columbia  
237 Icefield glaciers of  $12.8 \pm 0.4 \text{ m a}^{-1}$ . Our analysis reveals that between 2009 and 2019,  
238 the Columbia Glacier showed a total retreat of  $\sim 802$  m, equivalent to a mean annual  
239 retreat rate of the glacier terminus of  $\sim 80.1 \pm 2.6 \text{ m a}^{-1}$ . We calculate errors by  
240 considering an uncertainty of 1 pixel either side of a measurement in the first (Landsat  
241 5 image;  $\pm 30$  m) and last (Sentinel-2 image;  $\pm 10$  m) and incorporate all possible  
242 combinations of these uncertainties into our three separate terminus measurements  
243 to arrive at an error margin based on the standard deviation of all these possible  
244 measurements. In addition however, there is also significant variability within each  
245 year in terms of the magnitude of change, even with periods of advance also occurring  
246 (Figures 3b and 4). Figure 3b also indicates that the degree of variability has increased  
247 in recent years, with periods of much greater retreat as well as some periods of  
248 advance. On average, our work indicates that the retreat rate of the Columbia Glacier  
249 has doubled in the past ten years as compared to rates identified by Tennant and  
250 Menounos (2013).

251 In addition to the observed changes in glacier length, and the increased rate of retreat,  
252 we also identified a significant geometric modification (described below) of the glacier

253 in the icefall zone that links the upper icefield to the Columbia Glacier tongue (Figure  
254 5). By comparing aerial imagery gathered by the lead author in late May 2017 with  
255 imagery from 1969 gathered by Austin Post, it is apparent that this zone of the glacier  
256 has narrowed, thinned, and become more fractured since 1969. As a result, the link  
257 between the icefield and the glacier tongue has become much narrower than it was in  
258 the past. Figure 5 clearly shows this change by comparing the two oblique images. At  
259 its narrowest, the contemporary junction between the upper icefield and the outlet is  
260 ~150 m wide ( $\pm 20\text{m}$  – i.e. two Sentinel 2 pixels), but we estimate that this has  
261 decreased from a width of ~1000 m wide in the past. Given the ongoing trajectory of  
262 continued mass loss, further thinning of the glacier in the vicinity of this junction is  
263 likely.

264 In the absence of any well-defined information on the location of the equilibrium line,  
265 we explored the location of the end-of-summer snowline from a series of Landsat and  
266 Sentinel-2 images gathered in the month of September between 2000 and 2018  
267 (Figure 2). Although snowline variability is inevitable, the mean snowline elevation over  
268 a period of 18 years can be seen as an approximate proxy for the ELA. As such, this  
269 can be defined as ~2353 m a.s.l., which is well above the junction between the glacier  
270 tongue and the upper icefield. The entirety of the glacier tongue (and a small portion  
271 of the icefield plateau) is therefore considered to be undergoing net mass loss. If this  
272 thinning continues to the point where the lower tongue becomes completely detached  
273 from the upper icefield, we anticipate important impacts on the dynamic properties of  
274 the tongue. With the loss of the link between the icefield (much of which is the  
275 accumulation zone) and the glacier tongue (the ablation zone), the glacier tongue will  
276 no longer be fed by ice flow from above – an important development when considering  
277 the health of the glacier tongue. However, the icefall geometry shown in Figure 5c

278 suggests that much of the ice flux from the icefield to the tongue is, at least for now,  
279 occurring by ice avalanching rather than by coherent ice flow, whereas in the past  
280 when the ice was thicker, coherent flow was more likely. Contributions via this  
281 mechanism to the ablation zone may help the tongue to persist, although it is hard to  
282 envisage that such a mechanism for nourishing the tongue will do so as efficiently as  
283 flow from a fully-connected accumulation zone. Furthermore, such avalanching may  
284 result in a rougher ice surface at certain length-scales than occurs when flow is the  
285 dominant ice transfer mechanism, and exposes a significantly greater surface area to  
286 ablation than would be the case if ice flow dominated transfer to the tongue.

287 With regards to the dynamic behaviour of the Columbia Glacier, Figure 6 shows annual  
288 mean surface ice velocities of the Columbia Glacier and surrounding region generated  
289 using auto-RIFT (Gardner et al., 2018) and provided by the NASA MEaSUREs  
290 (Making Earth System Data Records for Use in Research Environments) ITS\_LIVE  
291 (Inter-Mission Time Series of Land Ice Velocity and Elevation) project (Gardner et al.,  
292 2019). Figure 7 is a summary-plot showing how surface velocities vary at 12 locations  
293 along a glacier centreline over the ten-year observation period. The key observation  
294 from Figures 6 and 7 is that there is (on average) a glacier-wide increase in overall  
295 surface velocity from  $\sim 15\text{-}25\text{ m a}^{-1}$  to  $\sim 67\text{ m a}^{-1}$  by 2012, with highest velocities in the  
296 upper portion of the Columbia Glacier (Figures 6 and 7). After this, there is a drop-off  
297 in average velocities although they remain consistently high ( $\sim 62\text{-}83\text{ m a}^{-1}$ ) in the  
298 upper reaches, towards the zone of detachment. Although these observations are  
299 focussed on the Columbia Glacier alone, the ITS\_LIVE mission (Gardner et al., 2019)  
300 reveals similar behaviour across the entirety of the Columbia Icefield (Figure 8),  
301 whereby the (active) outlet glaciers increased in velocity in the early parts of the current  
302 decade, and these velocity increases have generally been sustained since then.

303 A velocity increase associated with glacier retreat and mass loss, as we outline here,  
304 is consistent with significant dynamically-controlled ice recession (cf. Sakakibara &  
305 Sugiyama, 2014). Increased ice flow coupled to a loss of direct inputs of ice from  
306 upglacier, as we propose is occurring here, indicates an increased likelihood that the  
307 remnant glacier snout will rapidly thin and recede in the coming years.

### 308 ***Model output***

309 Figure 9 is similar to Figure S32 of Clarke et al. (2015) but is focused on the Columbia  
310 Glacier alone. It shows how their model evolves when forced by different RCPs at a  
311 series of time-steps between the present day and 2100. The inclusion of 2018 model  
312 output is a useful way to verify the accuracy of the model, particularly since the  
313 background image for each sub-plot of Figure 9 is a Sentinel-2 image from 2018.  
314 Figure 9 shows that in all runs based on AR5 emission scenarios there is close  
315 agreement with the observed extent of the Columbia Glacier. Slight differences and  
316 discrepancies are to be expected given the 200m resolution of the model and the  
317 occurrence of shorter-term fluctuations in the extent of the Columbia Glacier (as  
318 evidenced in Figures 2, 3 and 4). All scenarios tend to overestimate slightly the extent  
319 of adjacent areas of the icefield, indicating the presence of ice in some limited regions  
320 where, in fact, no ice is present. Again, such minor discrepancies are not surprising  
321 given the model resolution and other limitations. All emissions scenarios for 2050  
322 indicate similar (and marked) retreat of the Columbia Glacier, but by 2075, there is  
323 little left of the Columbia Glacier. In simulations based on RCP 2.6 and RCP 4.5, the  
324 glacier retreats to the location of the lower-limits of the icefall, whereas the retreat is  
325 greater in simulations driven by RCP 6.0 and RCP 8.5, in which the glacier terminus  
326 is located further back in the upper icefield. By 2100, under all emissions scenarios,  
327 the Columbia Glacier, as an outlet glacier, has disappeared entirely and retreat



328 continues high up in the icefield itself. Indeed, as Figure 10 shows, by 2075, all the  
329 key outlet glaciers of the Columbia Icefield have disappeared, and the Columbia  
330 Icefield exists as a 'perched icefield'. By 2100 (Figure 10b) simulations based on the  
331 higher emission scenarios (particularly RCP 8.5) yield an icefield that has broken up  
332 into smaller, discrete ice masses and is on the verge of complete disappearance, with  
333 only a small number of isolated regions of ice cover remaining. Under all other  
334 scenarios for 2100 (and all scenarios for 2075) the icefield persists in its perched form  
335 but is much-reduced in size, and has no discernible outlet glaciers.

336

## 337 **5. Discussion**

338 Our observations and measurements reveal that the Columbia Glacier is a glacier in  
339 retreat. Our work was initially motivated by observations of the slowdown of flow in the  
340 tongue of the Columbia Glacier and the ongoing separation of the tongue from the  
341 glacier's accumulation zone in the Columbia Icefield. These observations lead us to  
342 consider that, in time, the Columbia Glacier may become fully-detached from the  
343 Columbia Icefield. Although this suggestion is speculative, modelling of the future  
344 evolution of the Columbia Icefield by Clarke et al. (2015) does simulate the occurrence  
345 of a process whereby the icefield ultimately breaks up into a number of isolated parts,  
346 with no discernible outlet glaciers. Although the rate and speed with which this  
347 happens in model simulations depends on the future emissions scenario used to force  
348 the glacier model, by 2075, under all scenarios, the icefield is no longer drained by  
349 significant outlets in the form of valley glaciers that we see today. What the Clarke et  
350 al. (2015) modelling does not reveal is whether the detachment of outlet glaciers from  
351 the icefield occurs before they fully disintegrate – i.e. it is not clear whether there is a

352 period during which the outlet glacier tongues still exist, but are no longer supplied at  
353 all with ice from the parent icefield. Although the model resolution is too coarse to  
354 reveal this, on the basis of the observations we have made here, we suggest that such  
355 detachment may well occur as a precursor to loss of the outlet glacier tongues, and  
356 that this might, in fact, increase the rate at which the tongues are lost. If and when  
357 complete detachment occurs, the isolated glacier tongue will no longer be supplied  
358 with ice from the icefield accumulation area and, as a consequence, the tongue will  
359 likely stagnate and shrink faster. We propose the term 'detachment' of outlet glaciers  
360 to describe this process, by which inflow to a glacier tongue from upglacier sources is  
361 progressively reduced over time as a result of thinning of ice in the icefall transition  
362 zone between the accumulation area and the glacier tongue.

363 There is substantial evidence that this process is also underway on the Saskatchewan,  
364 the Athabasca, and the Castleguard glaciers (Figures 11 and 12), whereas it has  
365 already largely taken place on the Dome, Kitchener and Stutfield glaciers, which  
366 extend north-eastwards away from the icefield (Figures 11 and 12). Our own  
367 observations based on aerial imagery indicate that these glaciers have become almost  
368 entirely detached from the icefield. Dome, Kitchener and Stutfield glaciers are also  
369 heavily debris-covered and have very low surface velocities (Figure 8). We suggest  
370 that they have effectively stagnated.

371 Such 'detachment' is important for two reasons. Firstly, as suggested above, it results  
372 in the tongue being cut off from the accumulation area and as a result there is no  
373 replenishment by ice-flow from upglacier. Consequently, for a given rate of surface  
374 melting, ice in the tongue will disappear much faster without inflow than it would if the  
375 local mass loss by melting were partly offset by mass input by flow from upglacier.  
376 This process has the potential to change the relationship between rates of surface

377 melting and rates of glacier frontal retreat. As a result, the outlet glaciers (and the  
378 Columbia Glacier in this specific case) will retreat more quickly. Indeed, there is some  
379 evidence to suggest that this is already occurring. Tennant and Menounos (2013)  
380 suggested that the Columbia Glacier has retreated more than any of the other  
381 Columbia Icefield outlets, and we hypothesise that this rapid retreat may (in part) be a  
382 consequence of the detachment process, and a lack of nourishment from within the  
383 icefield. Further evidence for this diminishing nourishment is provided by our  
384 observation of a doubling in the rate of retreat over our observation period, when  
385 compared with that reported by Tennant and Menounos (2013;  $\sim 80.1 \text{ m a}^{-1}$  as  
386 compared with  $41.37 \text{ m a}^{-1}$ ).

387 A recent report by Environment Canada (2016) states that the rate of climate warming  
388 in Canada as a whole from 1948 to 2013 has been greater than double the global  
389 mean, while winter precipitation in Alberta and British Columbia has been decreasing.  
390 While climate change across Canada is predicted to be non-uniform, the World  
391 Climate Research Programme (WCRP) and their Coupled Model Inter-comparison  
392 Project (CMIP; as used in the IPCC 5<sup>th</sup> Assessment Report (IPCC, 2013)) project  
393 mean summer air temperature changes in Alberta and British Columbia of the order  
394 of at least  $1^{\circ}\text{C}$  between 2016 and 2035 (relative to a 1986-2005 reference period).  
395 There is, of course, some uncertainty related to the choice of the emissions scenario  
396 used to drive the model simulations (IPCC, 2013), and predicted precipitation changes  
397 are also spatially variable and uncertain. Despite this uncertainty, continued warming  
398 in the Rocky Mountains seems inevitable and there is no foreseeable mechanism by  
399 which the ongoing detachment of outlet glaciers from the Columbia Icefield can be  
400 prevented. Mass loss in this way may also impact on the discharge of river systems to  
401 which the Columbia Glacier (and indeed the wider icefield) contribute.

402 Finally, our observations and identification of the detachment process (cf. Figures 5  
403 and 11), coupled with the model outputs of Clarke et al. (2015; cf Figures 9 and 10)  
404 suggest that few glaciers will remain in this region by 2100. The pathway to loss of the  
405 icefield is therefore one which involves initial detachment of outlet glaciers from the  
406 plateau icefield before eventual complete decay of the outlets. We propose that such  
407 a fate awaits all outlets of the Columbia Icefield. However, it is worth noting that as  
408 with the Dome, Kitchener and Stutfield glaciers, initial detachment may well lead to the  
409 Columbia Glacier becoming debris-covered, as a result of the stagnation that seems  
410 likely with the loss of flow of ice from above. Significant additional contributions to this  
411 debris-cover may well arise from the detachment process itself, since this process  
412 would expose rock headwalls in what were the transition zones between the icefield  
413 and the glacier tongue, and weathering of this newly exposed bedrock is likely to  
414 become an important source of debris to the isolated glacier tongues below the  
415 headwalls. The potential importance of the detachment process in the ongoing retreat  
416 of the Columbia Icefield means it clearly warrants ongoing investigation.

417 With regards to the icefield itself, as the modelling of Clarke et al. (2015) shows, the  
418 detachment of all outlet glaciers would ultimately lead to a much smaller 'perched'  
419 Columbia Icefield that lacks true flow outlets which extend for any distance from the  
420 parent icefield.

421 Finally, as well as the glaciological and geomorphological implications of the loss of  
422 the Columbia Icefield in its current form, there are potentially significant implications  
423 of such a loss for the local economy and tourism. In 2008/09 visitors to Canadian  
424 National parks spent \$4.4 billion (Outspan Group, 2009; Swartman, 2015), while Parks  
425 Canada (2010) indicate that ~2 million people visit Jasper National Park (in which the  
426 Columbia Icefield resides) and the Athabasca Glacier outlet is the most visited glacier

427 in North America (Parks Canada, 2014; Swartman, 2015). Clearly then, should the  
428 Athabasca Glacier become detached from the icefield, and ultimately decay, a very  
429 significant tourism income might be lost. Not only are tourist numbers likely to  
430 decrease, but there may be significant increased costs of maintaining existing tourist  
431 infrastructure (e.g. the travel-time to the glacier as it recedes further will be greater,  
432 and access may also become more and more difficult).

433

## 434 **6. Conclusions**

435 We have defined and explored a previously unidentified process of outlet glacier  
436 'detachment' from the Columbia Icefield. This process represents a mechanism for the  
437 geometry of icefield decay whereby outlet glaciers become detached and isolated from  
438 the parent icefield, resulting in a remnant 'perched' icefield with no discernible and  
439 active outlet glaciers. Such a process has significant implications for the way in which  
440 we consider icefield retreat into the future. It may also be important for contributions  
441 of meltwater to proglacial streams, and (in the case of the Canadian Rockies) for  
442 tourism which relies on ease of accessibility to the Athabasca Glacier in particular. Our  
443 work represents an initial identification of this process, and despite the considerations  
444 and discussions presented here, the precise consequences of outlet glacier  
445 detachment, and the timescale over which it occurs remain to be determined. We  
446 suggest that there is a need to consider how significant and widespread this process  
447 might be globally. Overall, we propose that it likely has highly significant  
448 consequences, and will lead to snout-stagnation and markedly accelerated retreat of  
449 outlet glaciers and key changes to the glacial landscapes in this region, as well as  
450 profound implications for the tourism economy.

451

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467

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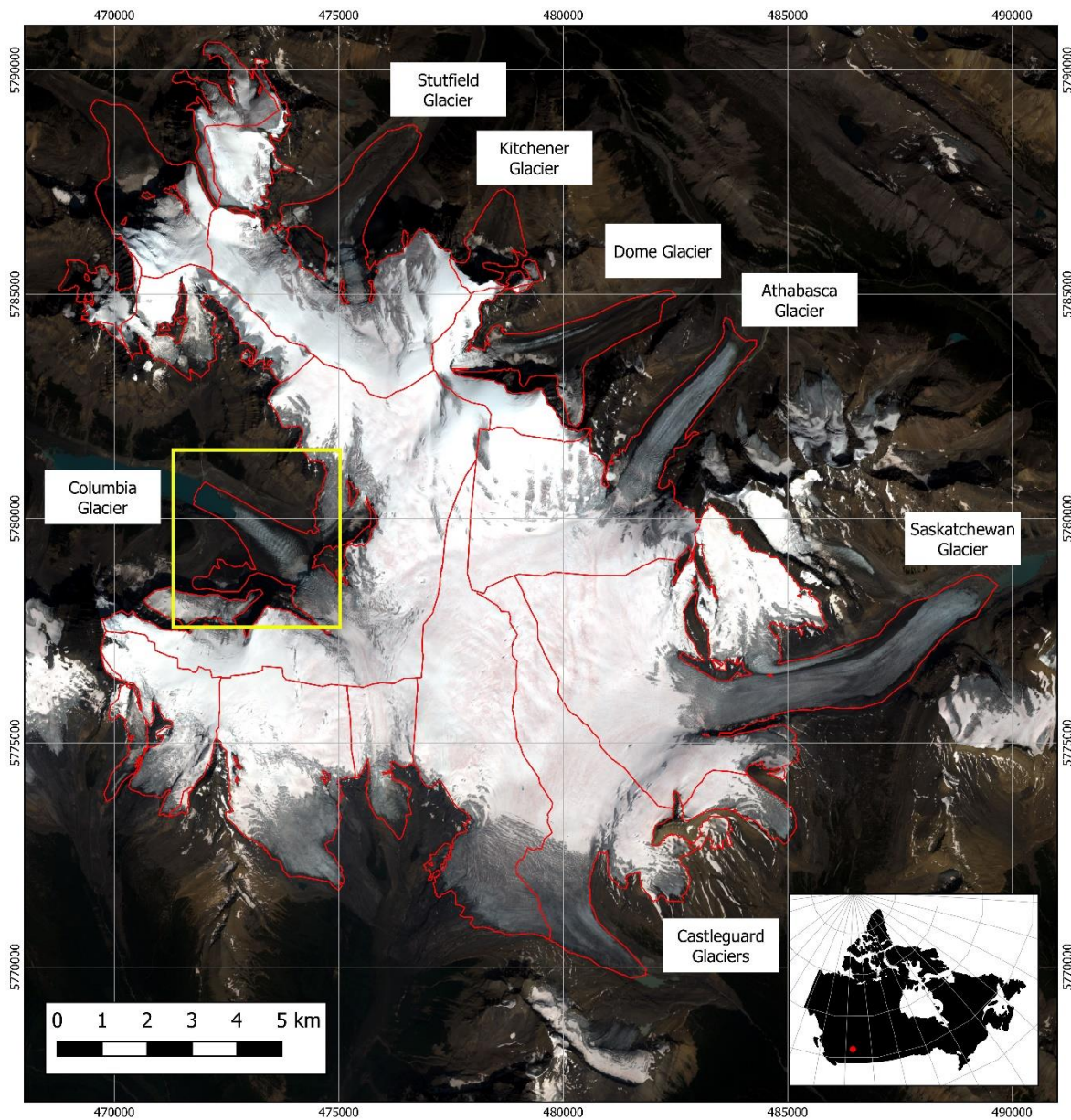


Figure 1: Sentinel-2 image of the Columbia Icefield from August 2018. Glacier outlines (red) from the Randolph Glacier Inventory (6.0; RGI Consortium, 2017) show the delineated extents of each glacier, as well as their contributory basins. All the major outlet glaciers are substantially smaller in this 2016 image than their RGI-delineated margins, but the largest change relates to the Columbia Glacier (bound by the yellow box; cf. Figure 2). Inset shows the location of the Columbia Icefield (red circle) in Canada

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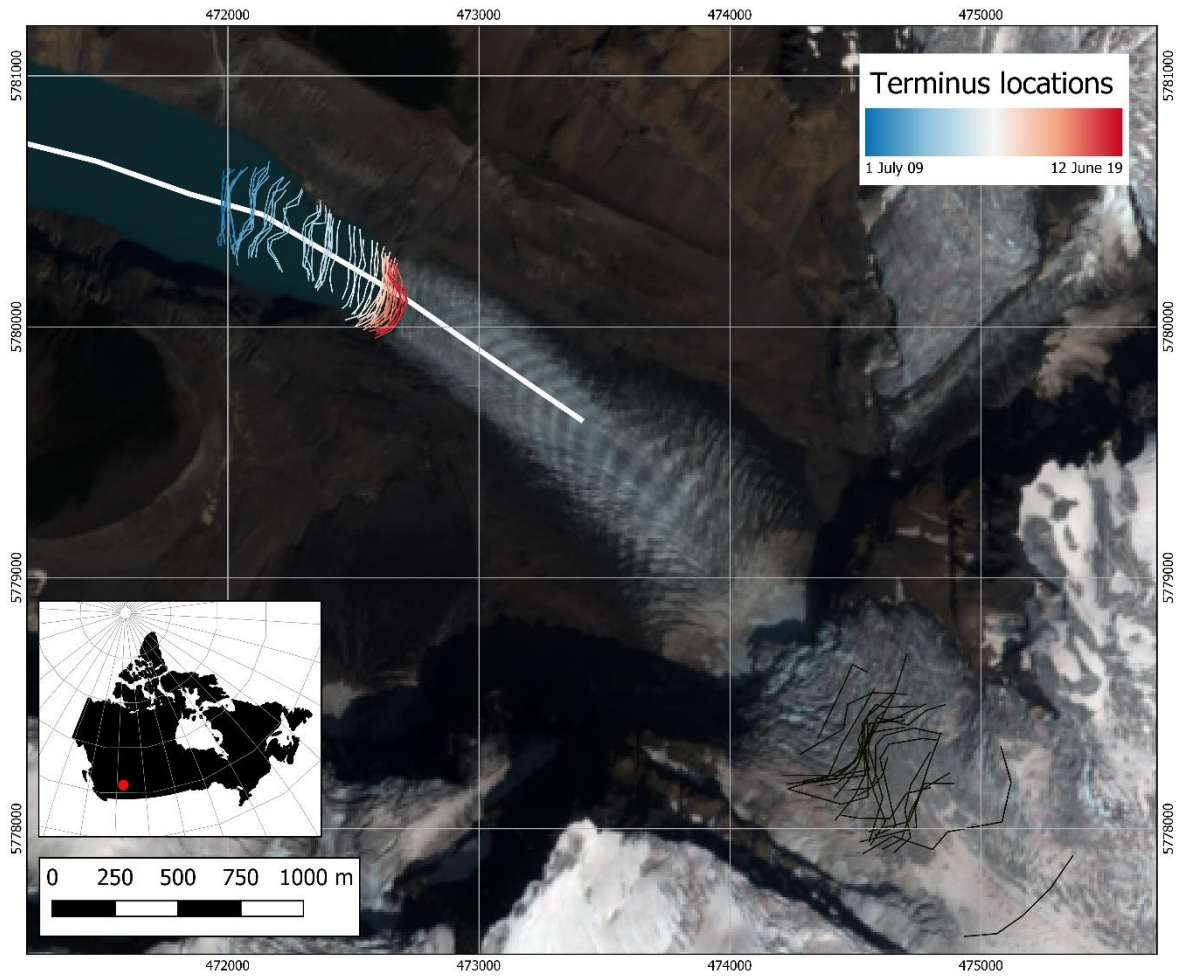


Figure 2: Columbia Glacier terminus locations in all observation years (2009 to 2019) derived from Landsat and Sentinel-2 imagery. Background is a Sentinel-2 image from August 2018. Inset shows the location of the Columbia Icefield in Canada. The white line is an approximate centreline, along which terminus locations are determined. The series of black lines to the bottom-right of the image represent approximate end-of-summer snowlines between 2000 and 2018. The mean altitude of these snowlines is 2353 m a.s.l. and is indicative of the approximate equilibrium line in the absence of any better approximations



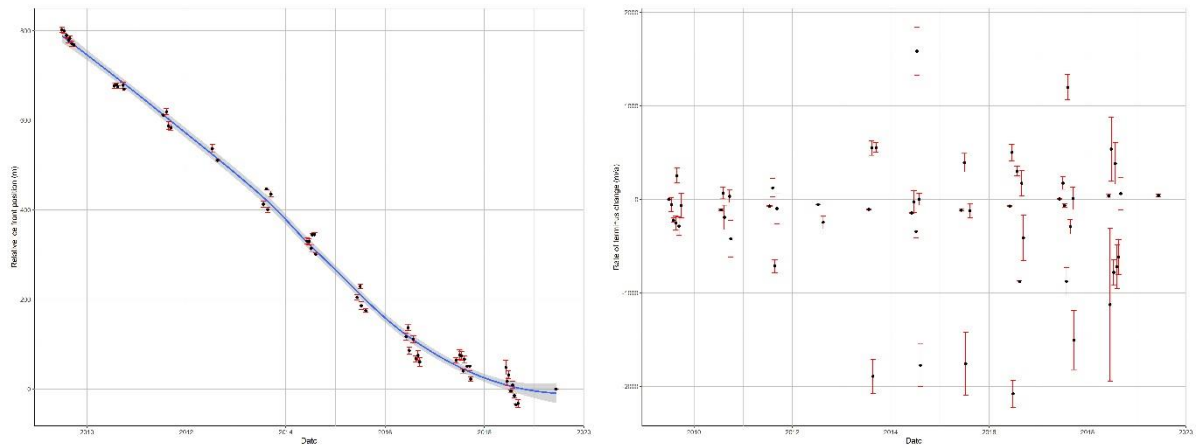


Figure 3: Retreat of the Columbia Glacier terminus along a single centreline, between July 2009 and June 2019, between observations separated by at least 7 days. (a) Terminus positions over this 10-year period, determined by manually digitising the glacier terminus on three separate occasions. The mean of these measurements at each time-step is displayed, along with error bars indicating the standard deviation of these measurements. The blue line represents a smoothed trend through all the data, with the grey shaded area indicating the 95% confidence interval of this model. (b) Rate of terminus change over the 10-year study period. Although there is a substantial degree of variability, rates of change tend to increase nearer to the present day

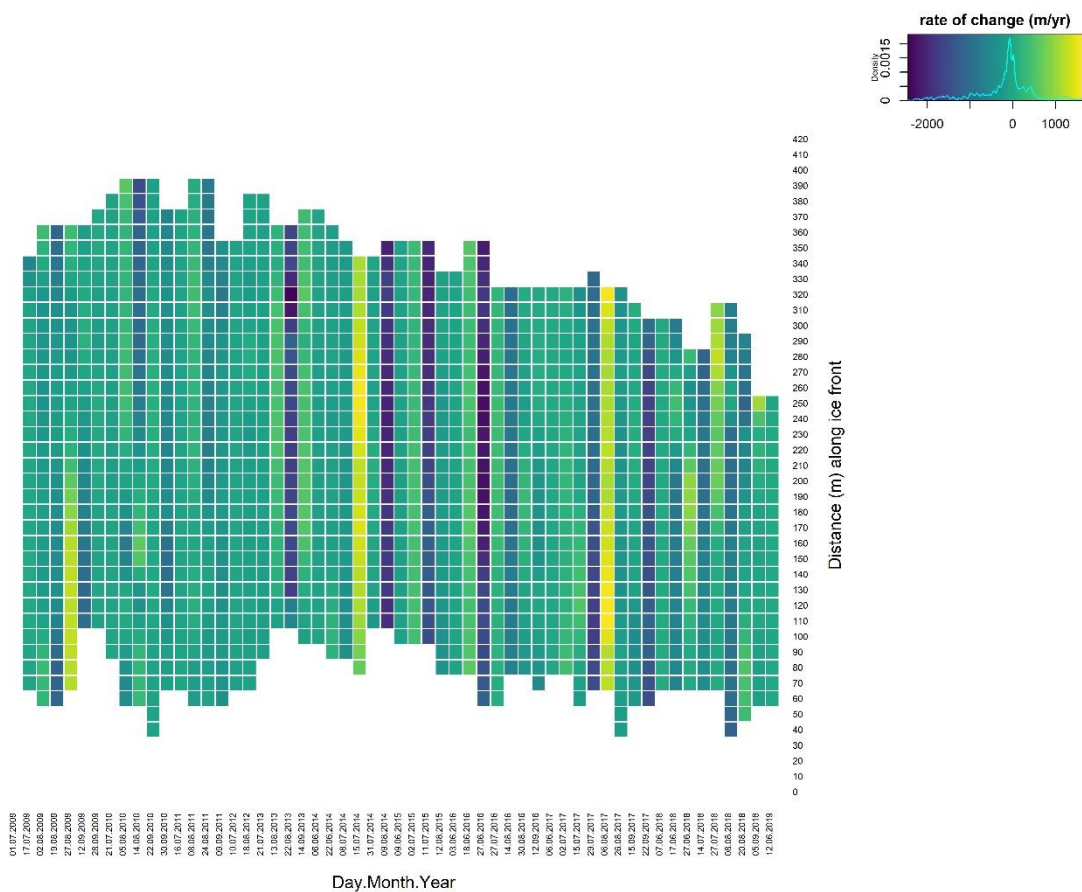


Figure 4: Rates of retreat of the glacier terminus across the whole terminus for observations separated by at least 7 days. For much of the 10 year period, rates of retreat are consistent. Periods of minor readvance are visible where shadings are light green/yellow, and these apparent minor re-advances presumably reflect inter-annual variability in response to mass gains in the winter. Periods of particularly high loss are marked by darker colours

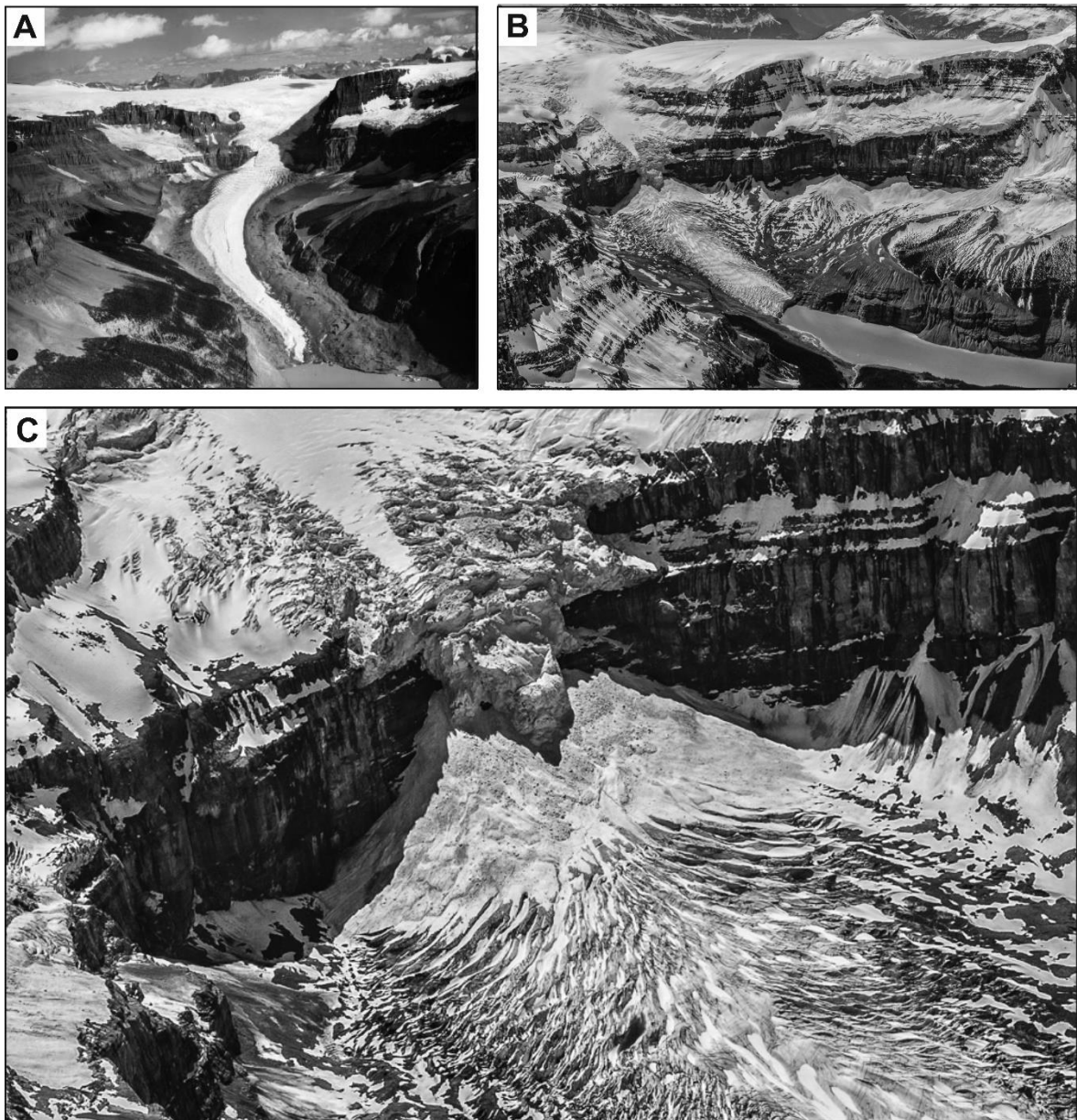


Figure 5: Columbia Glacier in: (A) 1969 (source: Austin Post and US Geological Survey) and in: (B) May 2017. Despite the two images being gathered from slightly different locations, it is clear just how much the glacier has reduced in length and width (see text for detailed discussion). Also marked are the changes in the icefall zone, linking the upper icefield to the lower glacier tongue, and in particular, the width of the icefall is much less in 2017. (C) A close-up of this icefall zone in 2017 where it is clear that the icefall is thin and becoming detached, retaining only a partial link between the icefield and lower tongue



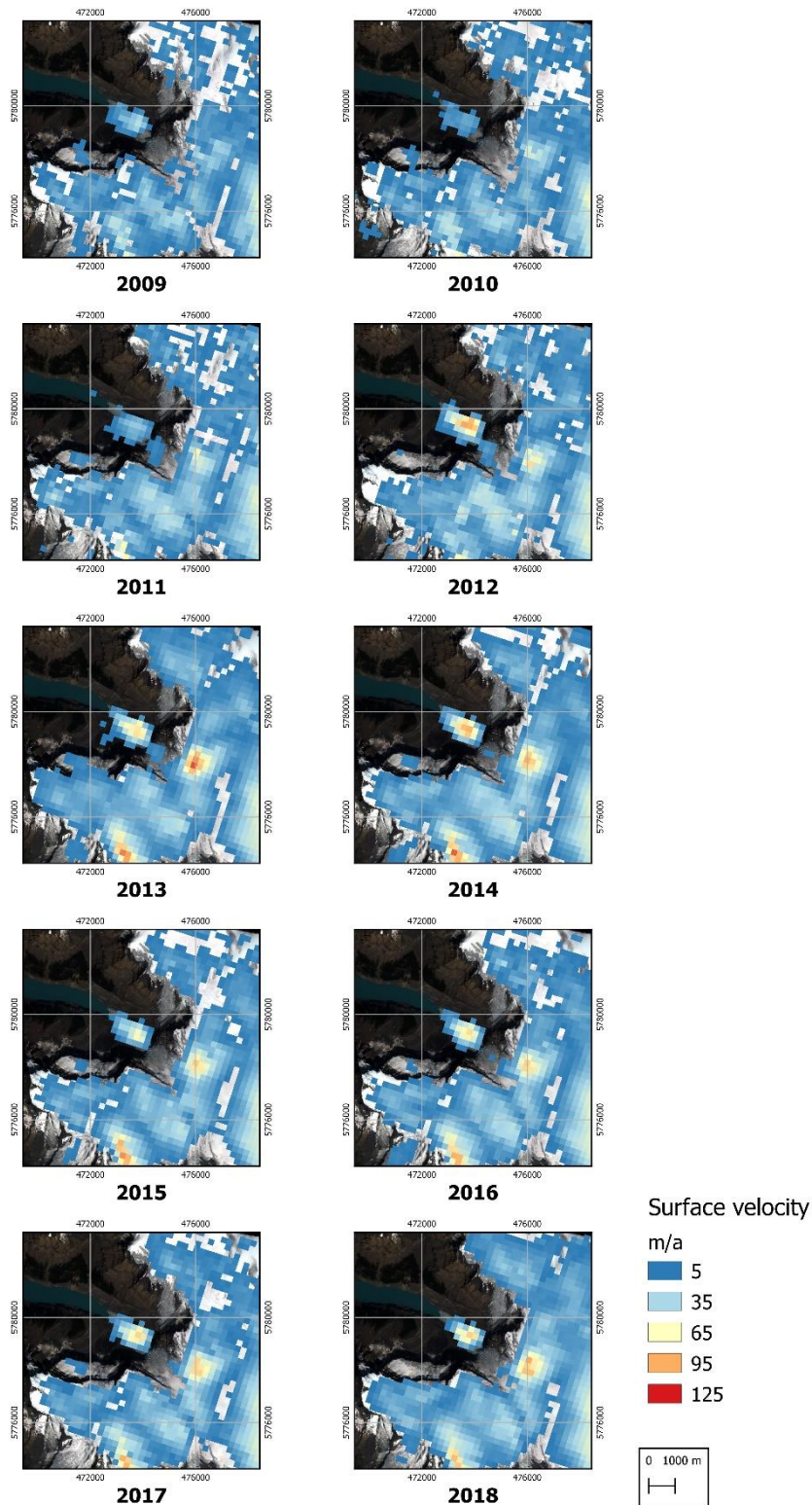


Figure 6: Mean annual surface ice velocities over the Columbia Glacier and surrounding region between 2009 and 2018. Velocities are generated using auto-RIFT (Gardner et al., 2018) and provided by the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) ITS\_LIVE (Inter-Mission Time Series of Land Ice Velocity and Elevation) project (Gardner et al., 2019). The Columbia Glacier itself appears in the middle of each image and is marked by a discrete zone of colouration indicating the surface velocity – the prominent feature of its proglacial lake is visible to the top-left of each image. The background is a Sentinel-2 image from 2018. Velocities are generated using auto-RIFT (Gardner et al., 2018) and provided by the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) ITS\_LIVE (Inter-Mission Time Series of Land Ice Velocity and Elevation) project (Gardner et al., 2019)

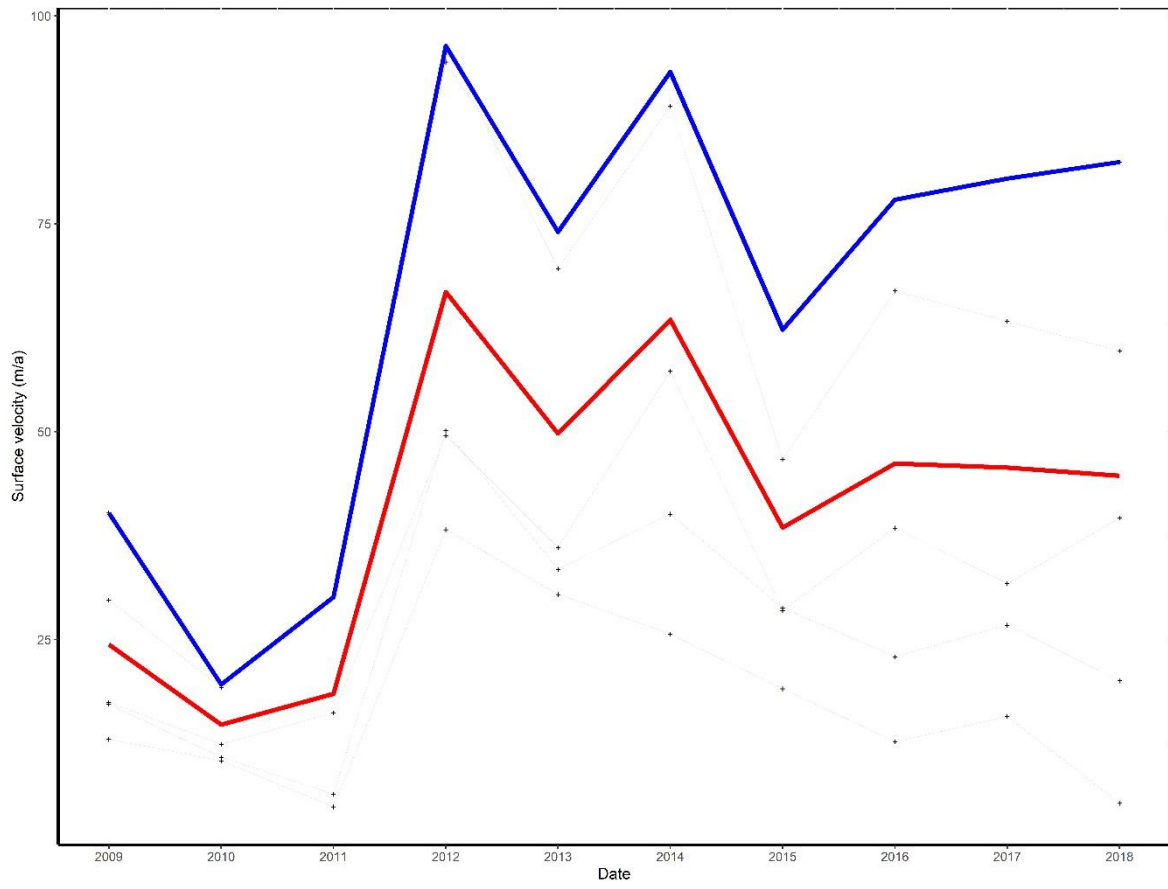


Figure 7: Mean (red) and maximum (blue) surface velocities derived from 12 discrete locations separated by 100 m steps along a centreline through the Columbia Glacier in each year between 2009 and 2018. The fine grey lines represent velocity changes associated with the 12 sample points contributing to these summary data

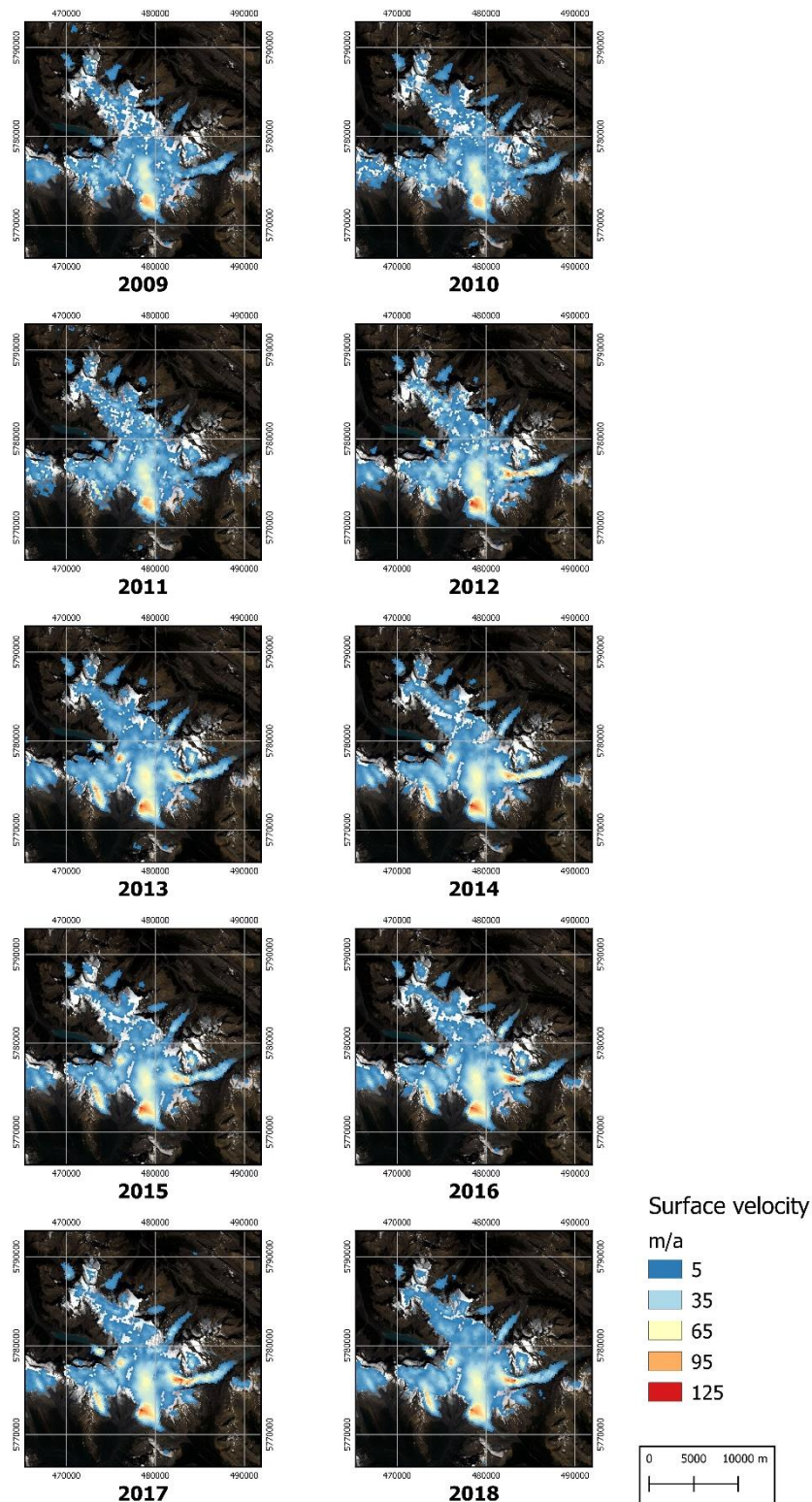


Figure 8: Mean annual surface ice velocities over the entirety of the Columbia Icefield between 2009 and 2018. Velocities are from the NASA MEaSUREs ITS\_LIVE project (Gardner et al., 2019). See caption to Figure 6 for full details



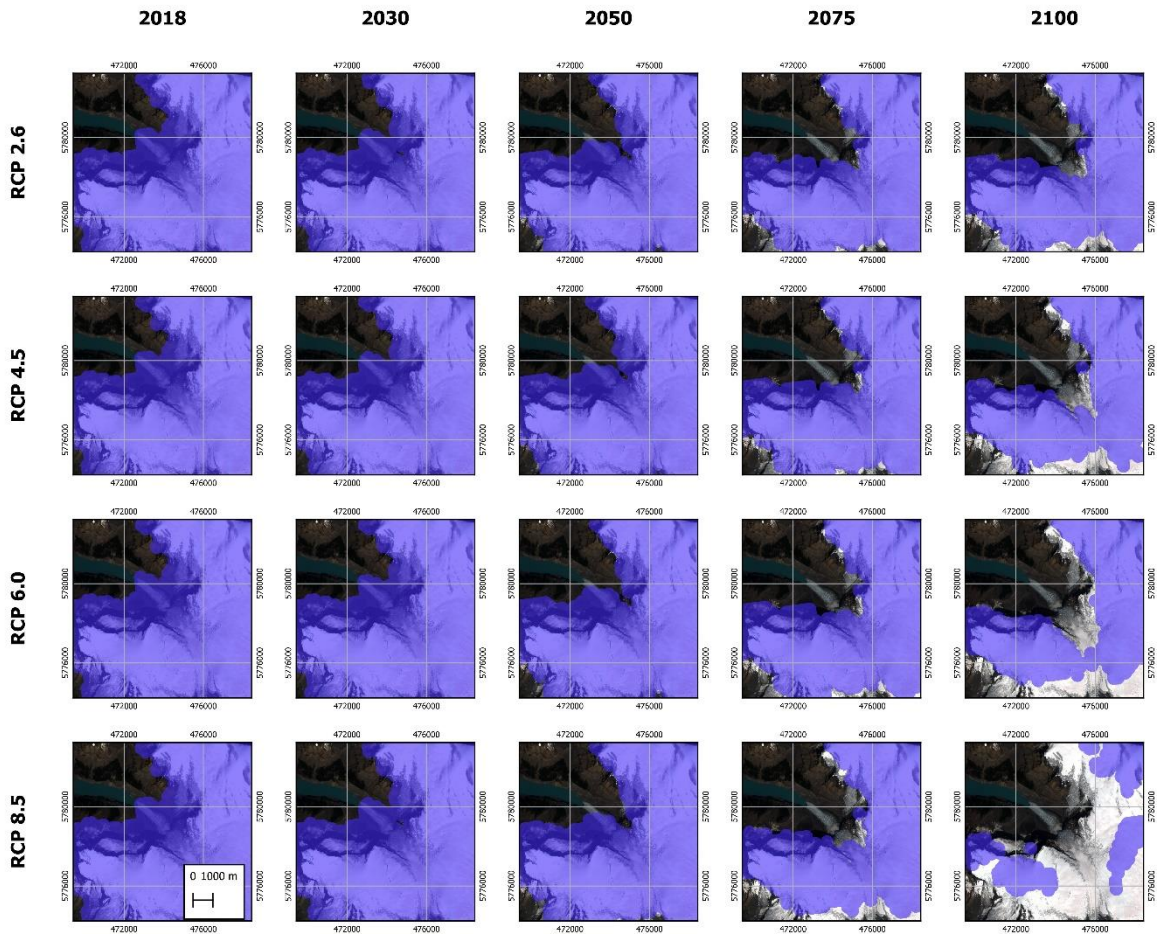


Figure 9: Model outputs following the work of Clarke et al. (2015). The output here is based on modelled extents of the Columbia Glacier based on the MIROC-ESM (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo) and National Institute for Environmental Studies (Japan)) GCM which Clarke et al. (2015) describe as best representing the median of the GCM models they explored. Each horizontal row of images represents forcing by four different AR5 scenarios. Each vertical column represents the modelled ice extent in 2018, 2030, 2050, 2075 and 2100. The background image in all 20 sub-images is a Sentinel-2 image from August 2018, and the blue shading represent the presence of ice in a grid-cell in the model prediction (and thus the extent of the glacier and icefield)

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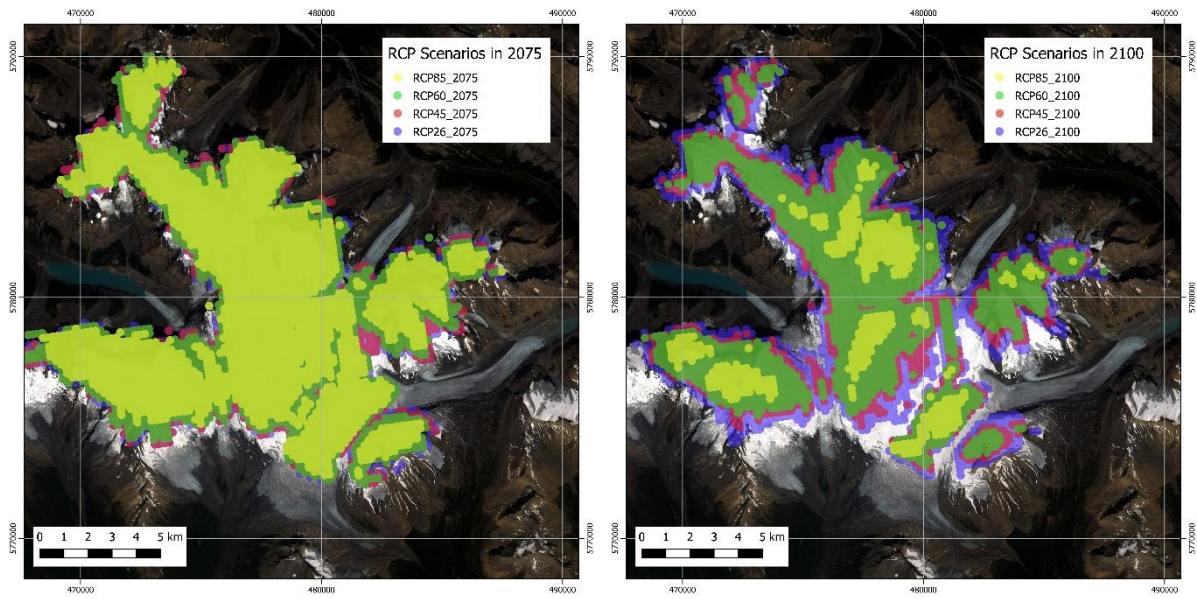


Figure 10: Model outputs following the work of Clarke et al. (2015). The output here is based on modelled extents of the entire Columbia Icefield based on the MIROC-ESM (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo) and National Institute for Environmental Studies (Japan)) GCM which Clarke et al. (2015) describe as best representing the median of the GCM models they explored. Part A shows the extent of the Columbia Icefield in 2075 based on each of four different AR5 scenarios (see key for colour-coding). Part B shows the same but for 2100. The background image is a Sentinel-2 image from August 2018

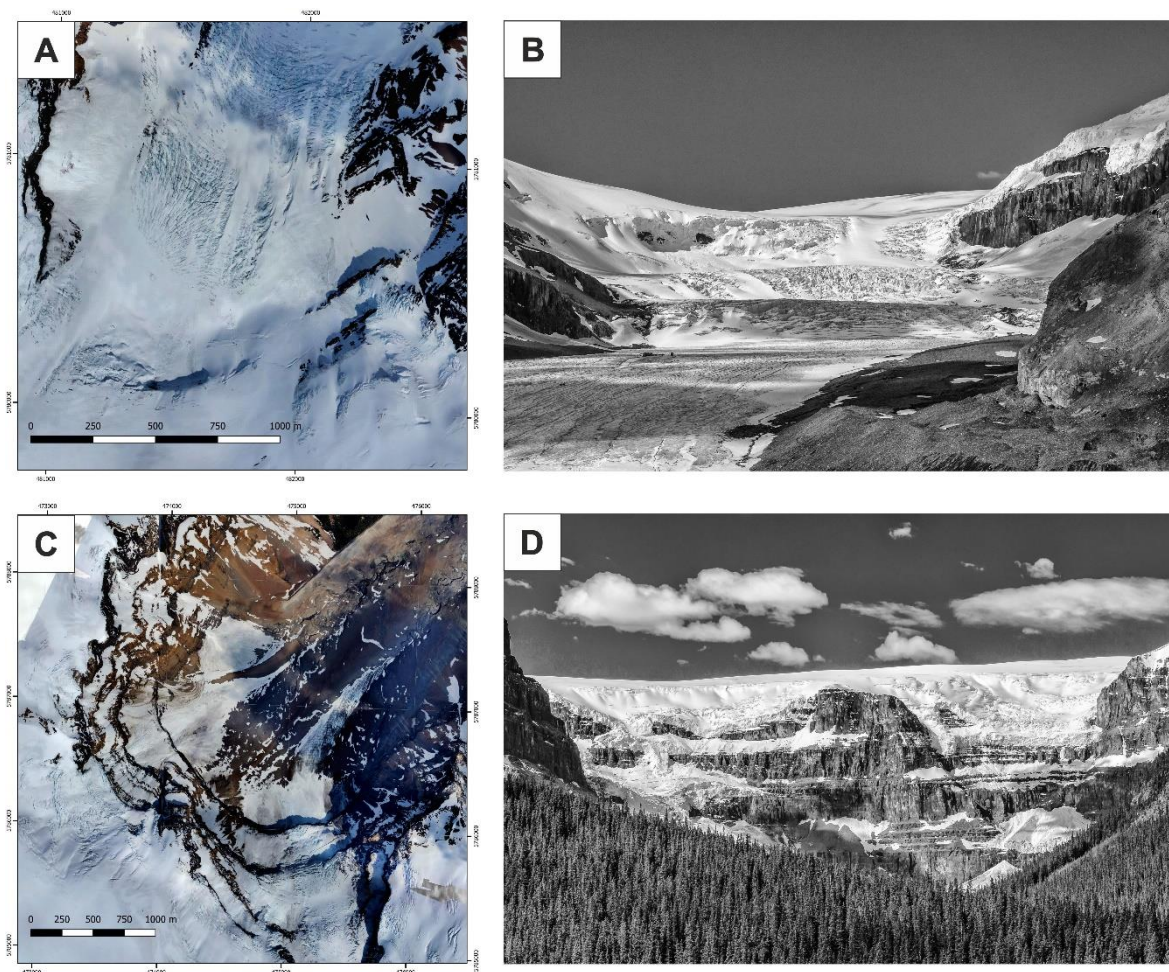


Figure 11: Ortho-mosaics (A and C) and oblique images (B and D) of the icefall zones of the Athabasca (A and B) and Stutfield (C and D) Glaciers – both outlets of the Columbia Icefield. In A and B, there is still a clear physical link between the ice in the upper icefield and the tongue of the Athabasca Glacier, although there is evidence of thinning and underlying rock beginning to become exposed. Flow in (A) is to the top of the image, while in (B) it is towards the bottom of the image. In (C) and (D) there is a partially-severed link – the ice has thinned to such an extent that the upper icefield no longer maintains a physical link with the tongue of the Stutfield Glacier for much of this zone and consequently, there are large expanses of exposed rock. In (C) flow is towards the top-right, while in (D) it is towards the bottom of the image. The hypothesis proposed here is that the Columbia Glacier was once linked to the upper icefield over a larger area (similar to the Athabasca Glacier) but it is now becoming detached, moving in time towards a situation represented by the Stutfield Glacier. Ortho-mosaics were constructed using Structure from Motion techniques by the authors using imagery gathered in May 2017. Oblique images were captured by the authors in June 2017



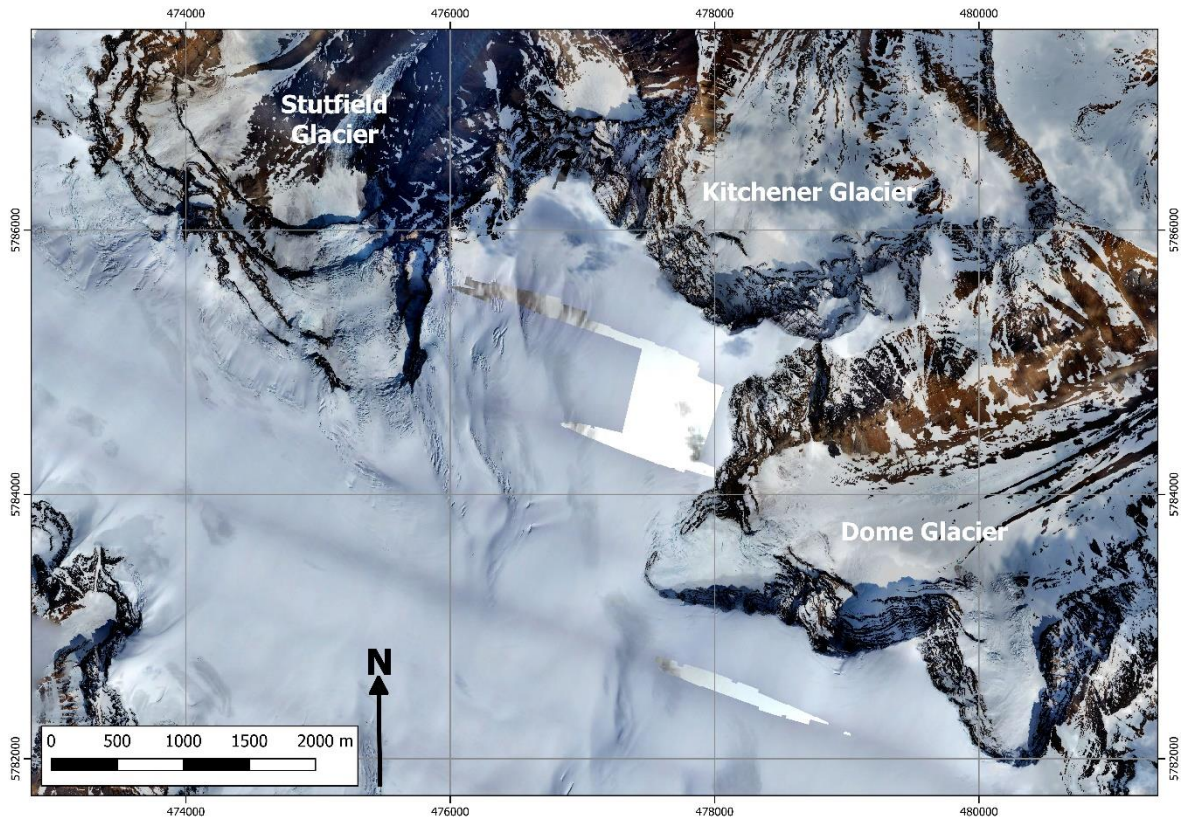


Figure 12: Orthomosaic of the upper reaches of Dome, Kitchener and Stutfield glaciers. The orthomosaics were generated by the authors using imagery gathered in May 2017. It is apparent that aside from a small and isolated location on Stutfield and Dome glaciers, these glaciers retain no direct linkage with the Upper Columbia Icefield, and are thus, effectively, already detached from the icefield