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'Detachment' of icefield outlet glaciers – catastrophic thinning and retreat of the Columbia Glacier (Canada)

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Key Points

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

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

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

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

Abstract

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

Keywords

Columbia Icefield, Columbia Glacier, Rocky Mountains, outlet glaciers, Glacier stagnation, outlet glacier detachment

1. Introduction – Glacier change of the Columbia Icefield

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

The Columbia Icefield is one of the most important ice bodies in the Canadian Rockies. It is the largest ice mass in North America outside of the Arctic Circle, covering an area of ~337 km^2 (Baumann, 2017), and acts as a significant water resource (Bolch et al., 2010). Notably, it sits on a triple water divide, with meltwater from the icefield draining into three distinct watersheds (the Athabasca, Saskatchewan and Columbia watersheds) which drain into the Arctic, Atlantic and Pacific Oceans respectively (Tennant & Menounos, 2013). The Columbia Icefield is also of substantial economic importance as a major tourist attraction (Parks Canada Agency, 2011). Being able to predict the future state and extent of the Columbia Icefield is therefore important. Tennant and Menounos (2013) identified 25 individual glaciers that drain from different parts of the icefield, but we focus on seven major named outlet glaciers: Stutfield, Kitchener, Dome, Athabasca, Saskatchewan, Castleguard and Columbia Glaciers (Figure 1).

The Columbia Glacier is one of the most dynamic outlets of the Columbia Icefield, terminating in a significant proglacial lake which is currently unnamed (Figures 1 and 2). Hereafter we refer informally to this lake as 'Lake Columbia'. The glacier is, however, little studied. The Columbia Glacier drains from the Columbia Icefield and over a cliff into a relatively narrow and constrained valley, in which its tongue currently resides. It has a dynamic history, with past phases of expansion and retreat, and various observations of its terminus location providing insight into its fluctuating extent. As a consequence of these historical changes in glacier length, the size of Lake Columbia has also varied. Between 1724 and 1924, the glacier retreated a total of 394 m (Heusser, 1954). Between 1966 and 1977, the glacier advanced by up to 1 km (Baranowski & Henoch, 1978), while from 1966 to 1980 a ~800 m advance filled Lake Columbia (Ommanney, 2002). Ommanney (2002) described the Columbia Glacier as being 8.5 km in length and 16 km^2 in area, and also highlighted a key characteristic – that it has a major icefall that dramatically links the upper icefield-region to the lower glacier tongue. In 2008, the GLIMS (Global Land Ice Measurements from Space) database listed the Columbia Glacier as covering an area of ~29.99 km^2 but gave no details regarding its length (Raup et al. 2007). Based on analysis of data from 1999 and 2009, Tennant and Menounos (2013) suggested that its area was 32.2 km^2, and its length was 5831 m. The differences between these length and area measurements and those of Ommanney (2002) reflect clear differences in exactly where the measurements of length were made, and in precisely how the margins of the glacier were defined. This is particularly so in the upper accumulation area which lies within the icefield itself. Tennant and Menounos (2013) also described how over a period of 90 years between 1919 and 2009, all the glaciers draining from the icefield showed (net) retreat. The glaciers retreated and fluctuated in similar ways, such that the pattern of retreat was correlated with observed changes in both air temperature and precipitation. This strongly suggests a climate-related control (Tennant & Menounos, 2013). Despite the consistent retreat of all Columbia Icefield glaciers, Tennant and Menounos (2013) suggested that the Columbia Glacier had retreated the furthest (3723 (± 34) m between 1919 and 2009, which equates to an average rate of 41.37 m a^{-1}).

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

3. Methodology

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

For all datasets, within GEEDiT, true-colour images were generated by combining bands (3-2-1 for pre-Landsat 8; 4-3-2 for Landsat 8 and 4-3-2 for Sentinel 2). Before the application of GEEDiT, we explored the use of various band-combinations and thresholding techniques to automatically delineate the margins of the icefield and its outlet glaciers (cf. Paul et al., 2016). However, the threshold value required to correctly delineate an ice margin in our data seemed to be somewhat arbitrary, and could vary significantly between image-sets. We therefore preferred the adoption of a manual approach for delineating the ice margins (an approach also adopted by the GEEDiT package), which was deemed more accurate since margins were relatively straightforward to identify visually. It is widely recognised in the literature that complete manual digitisation is sometimes necessary (as applied here) and even when automation is carried out, visual verification and correction are often needed for accurate determination of glacier margins (Paul et al., 2017).

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

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

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

Surface velocity: Annual mean surface velocity data were 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). These data are derived from Landsat 4, 5, 7 and 8 images, and are determined at a 240 m resolution. Full details of the derivation of these datasets can be found at: http://its-live-data.jpl.nasa.gov.s3.amazonaws.com/documentation/ITS_LIVE-Regional-Glacier-and-Ice-Sheet-Surface-Velocities.pdf

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

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

4. Results and analysis

Dynamics and Geometry

Figure 2 shows the result of the determination of a series of Landsat 5 (2009-2011; 30 m resolution), Landsat 7 (2009, 2010, 2012; pan-sharpened 15 m resolution), Landsat 8 (2013-2016 and 2018; pan-sharpened 15 m resolution) and Sentinel-2 (2016-2019; 10 m resolution) images of the Columbia Glacier, which were used to determine terminus locations. The quality of imagery available for analysis is highly variable, and the imagery we were able to use successfully was dictated by season, snow extent, and cloud extent. As a consequence the precise spacing of useable images cannot be controlled. There are thus 7 images from 2009; 5 from 2010; 4 from 2011; 2 from 2012; 4 from 2013; 6 from 2014; 4 from 2015 7 from 2016; 8 from 2017; 8 from 2018 and 1 from 2019. Where there are substantial sets of images from an individual year, apparent minor re-advances and retreats occur that reflect intra-annual variability (i.e. advances in response to mass gains in the winter and retreats due to mass losses in the summer). Figure 3 summarises the changes in the terminus location (and rate of terminus change) of Columbia Glacier in all observation years along a single centre-line (cf. Figure 2). Due to the complexity of the glacier terminus, Figure 4 also displays rates of terminus change of the glacier’s terminus in all observation years (cf. Figure 2). However, this figure shows change at 20m steps along the ice-front. For the most part the figure shows consistent retreat over the observation period with only minor spatial variability. However, in occasional time-steps, greater amounts of retreat take place (darker blue shading) as well as periods of readvance (light green and yellow), as referred to above.

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

In addition to the observed changes in glacier length, and the increased rate of retreat, we also identified a significant geometric modification (described below) of the glacier in the icefall zone that links the upper icefield to the Columbia Glacier tongue (Figure 5). By comparing aerial imagery gathered by the lead author in late May 2017 with imagery from 1969 gathered by Austin Post, it is apparent that this zone of the glacier has narrowed, thinned, and become more fractured since 1969. As a result, the link between the icefield and the glacier tongue has become much narrower than it was in the past. Figure 5 clearly shows this change by comparing the two oblique images. At its narrowest, the contemporary junction between the upper icefield and the outlet is ~150 m wide (±20m – i.e. two Sentinel 2 pixels), but we estimate that this has decreased from a width of ~1000 m wide in the past. Given the ongoing trajectory of continued mass loss, further thinning of the glacier in the vicinity of this junction is likely.

In the absence of any well-defined information on the location of the equilibrium line, we explored the location of the end-of-summer snowline from a series of Landsat and Sentinel-2 images gathered in the month of September between 2000 and 2018 (Figure 2). Although snowline variability is inevitable, the mean snowline elevation over a period of 18 years can be seen as an approximate proxy for the ELA. As such, this can be defined as ~2353 m a.s.l., which is well above the junction between the glacier tongue and the upper icefield. The entirety of the glacier tongue (and a small portion of the icefield plateau) is therefore considered to be undergoing net mass loss. If this thinning continues to the point where the lower tongue becomes completely detached from the upper icefield, we anticipate important impacts on the dynamic properties of the tongue. With the loss of the link between the icefield (much of which is the accumulation zone) and the glacier tongue (the ablation zone), the glacier tongue will no longer be fed by ice flow from above – an important development when considering the health of the glacier tongue. However, the icefall geometry shown in Figure 5c suggests that much of the ice flux from the icefield to the tongue is, at least for now, occurring by ice avalanching rather than by coherent ice flow, whereas in the past when the ice was thicker, coherent flow was more likely. Contributions via this mechanism to the ablation zone may help the tongue to persist, although it is hard to envisage that such a mechanism for nourishing the tongue will do so as efficiently as flow from a fully-connected accumulation zone. Furthermore, such avalanching may result in a rougher ice surface at certain length-scales than occurs when flow is the dominant ice transfer mechanism, and exposes a significantly greater surface area to ablation than would be the case if ice flow dominated transfer to the tongue.

With regards to the dynamic behaviour of the Columbia Glacier, Figure 6 shows annual mean surface ice velocities of the Columbia Glacier and surrounding region 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 is a summary-plot showing how surface velocities vary at 12 locations along a glacier centreline over the ten-year observation period. The key observation from Figures 6 and 7 is that there is (on average) a glacier-wide increase in overall surface velocity from ~15-25 m a^{-1} to ~67 m a^{-1} by 2012, with highest velocities in the upper portion of the Columbia Glacier (Figures 6 and 7). After this, there is a drop-off in average velocities although they remain consistently high (~62-83 m a^{-1}) in the upper reaches, towards the zone of detachment. Although these observations are focussed on the Columbia Glacier alone, the ITS_LIVE mission (Gardner et al., 2019) reveals similar behaviour across the entirety of the Columbia Icefield (Figure 8), whereby the (active) outlet glaciers increased in velocity in the early parts of the current decade, and these velocity increases have generally been sustained since then.

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

Model output

Figure 9 is similar to Figure S32 of Clarke et al. (2015) but is focused on the Columbia Glacier alone. It shows how their model evolves when forced by different RCPs at a series of time-steps between the present day and 2100. The inclusion of 2018 model output is a useful way to verify the accuracy of the model, particularly since the background image for each sub-plot of Figure 9 is a Sentinel-2 image from 2018. Figure 9 shows that in all runs based on AR5 emission scenarios there is close agreement with the observed extent of the Columbia Glacier. Slight differences and discrepancies are to be expected given the 200m resolution of the model and the occurrence of shorter-term fluctuations in the extent of the Columbia Glacier (as evidenced in Figures 2, 3 and 4). All scenarios tend to overestimate slightly the extent of adjacent areas of the icefield, indicating the presence of ice in some limited regions where, in fact, no ice is present. Again, such minor discrepancies are not surprising given the model resolution and other limitations. All emissions scenarios for 2050 indicate similar (and marked) retreat of the Columbia Glacier, but by 2075, there is little left of the Columbia Glacier. In simulations based on RCP 2.6 and RCP 4.5, the glacier retreats to the location of the lower-limits of the icefall, whereas the retreat is greater in simulations driven by RCP 6.0 and RCP 8.5, in which the glacier terminus is located further back in the upper icefield. By 2100, under all emissions scenarios, the Columbia Glacier, as an outlet glacier, has disappeared entirely and retreat continues high up in the icefield itself. Indeed, as Figure 10 shows, by 2075, all the key outlet glaciers of the Columbia Icefield have disappeared, and the Columbia Icefield exists as a ‘perched icefield’. By 2100 (Figure 10b) simulations based on the higher emission scenarios (particularly RCP 8.5) yield an icefield that has broken up into smaller, discrete ice masses and is on the verge of complete disappearance, with only a small number of isolated regions of ice cover remaining. Under all other scenarios for 2100 (and all scenarios for 2075) the icefield persists in its perched form but is much-reduced in size, and has no discernible outlet glaciers.

5. Discussion

Our observations and measurements reveal that the Columbia Glacier is a glacier in retreat. Our work was initially motivated by observations of the slowdown of flow in the tongue of the Columbia Glacier and the ongoing separation of the tongue from the glacier's accumulation zone in the Columbia Icefield. These observations lead us to consider that, in time, the Columbia Glacier may become fully-detached from the Columbia Icefield. Although this suggestion is speculative, modelling of the future evolution of the Columbia Icefield by Clarke et al. (2015) does simulate the occurrence of a process whereby the icefield ultimately breaks up into a number of isolated parts, with no discernible outlet glaciers. Although the rate and speed with which this happens in model simulations depends on the future emissions scenario used to force the glacier model, by 2075, under all scenarios, the icefield is no longer drained by significant outlets in the form of valley glaciers that we see today. What the Clarke et al. (2015) modelling does not reveal is whether the detachment of outlet glaciers from the icefield occurs before they fully disintegrate – i.e. it is not clear whether there is a period during which the outlet glacier tongues still exist, but are no longer supplied at all with ice from the parent icefield. Although the model resolution is too coarse to reveal this, on the basis of the observations we have made here, we suggest that such detachment may well occur as a precursor to loss of the outlet glacier tongues, and that this might, in fact, increase the rate at which the tongues are lost. If and when complete detachment occurs, the isolated glacier tongue will no longer be supplied with ice from the icefield accumulation area and, as a consequence, the tongue will likely stagnate and shrink faster. We propose the term ‘detachment’ of outlet glaciers to describe this process, by which inflow to a glacier tongue from upglacier sources is progressively reduced over time as a result of thinning of ice in the icefall transition zone between the accumulation area and the glacier tongue.

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

Such ‘detachment’ is important for two reasons. Firstly, as suggested above, it results in the tongue being cut off from the accumulation area and as a result there is no replenishment by ice-flow from upglacier. Consequently, for a given rate of surface melting, ice in the tongue will disappear much faster without inflow than it would if the local mass loss by melting were partly offset by mass input by flow from upglacier. This process has the potential to change the relationship between rates of surface melting and rates of glacier frontal retreat. As a result, the outlet glaciers (and the Columbia Glacier in this specific case) will retreat more quickly. Indeed, there is some evidence to suggest that this is already occurring. Tennant and Menounos (2013) suggested that the Columbia Glacier has retreated more than any of the other Columbia Icefield outlets, and we hypothesise that this rapid retreat may (in part) be a consequence of the detachment process, and a lack of nourishment from within the icefield. Further evidence for this diminishing nourishment is provided by our observation of a doubling in the rate of retreat over our observation period, when compared with that reported by Tennant and Menounos (2013; ~80.1 m a^{-1} as compared with 41.37 m a^{-1}).

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

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

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

Finally, as well as the glaciological and geomorphological implications of the loss of the Columbia Icefield in its current form, there are potentially significant implications of such a loss for the local economy and tourism. In 2008/09 visitors to Canadian National parks spent $4.4 billion (Outspan Group, 2009; Swartman, 2015), while Parks Canada (2010) indicate that ~2 million people visit Jasper National Park (in which the Columbia Icefield resides) and the Athabasca Glacier outlet is the most visited glacier in North America (Parks Canada, 2014; Swartman, 2015). Clearly then, should the Athabasca Glacier become detached from the icefield, and ultimately decay, a very significant tourism income might be lost. Not only are tourist numbers likely to decrease, but there may be significant increased costs of maintaining existing tourist infrastructure (e.g. the travel-time to the glacier as it recedes further will be greater, and access may also become more and more difficult).

6. Conclusions

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

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Figures

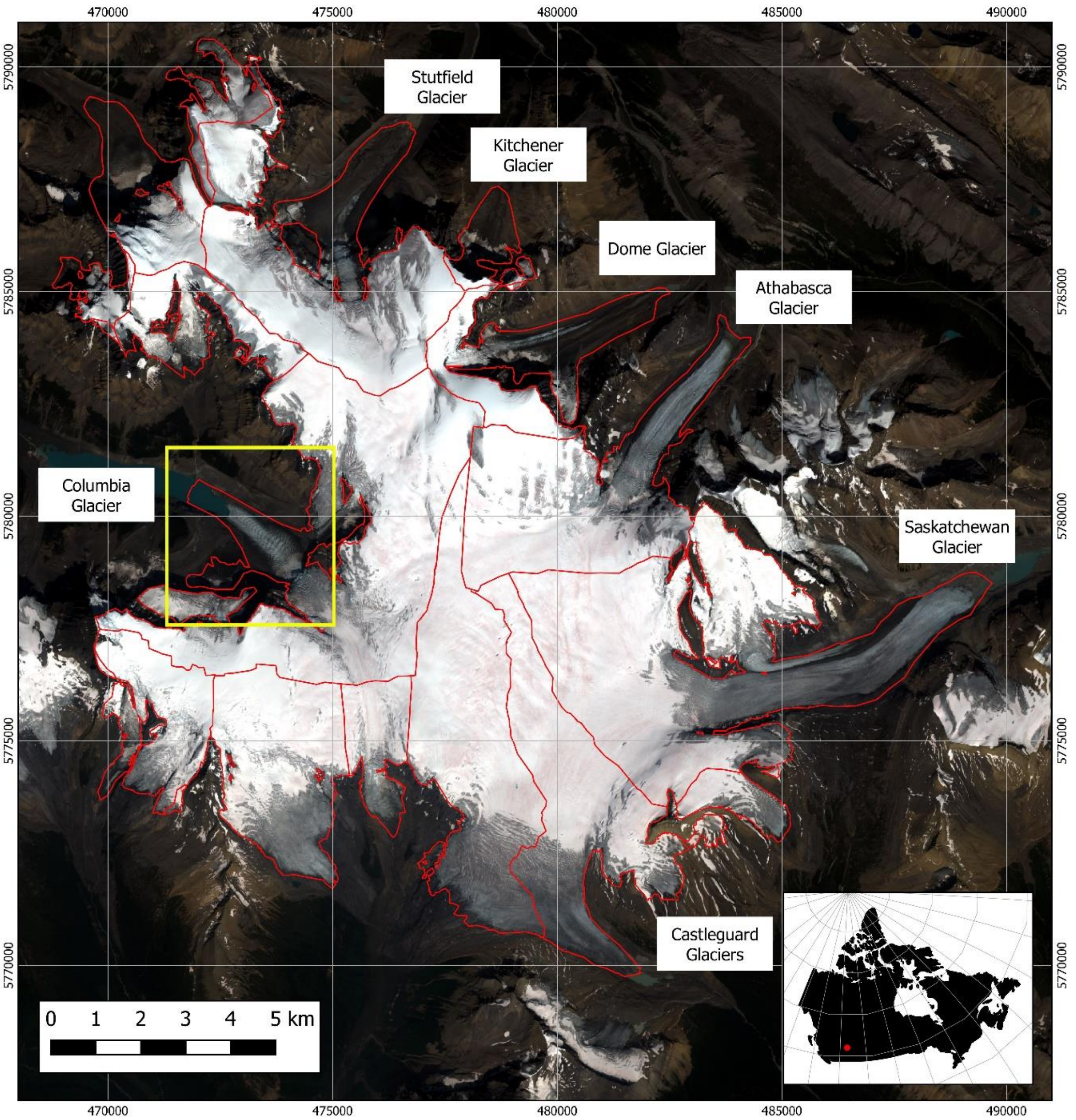

Figure 1: Sentinel-2 image of the Columbia Icefield from August 2018. Glacier outlines (red) from the Randolph Glacier Inventory (6.0; RGI Consortium, 2017) show the delineated extents of each glacier, as well as their contributory basins. All the major outlet glaciers are substantially smaller in this 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

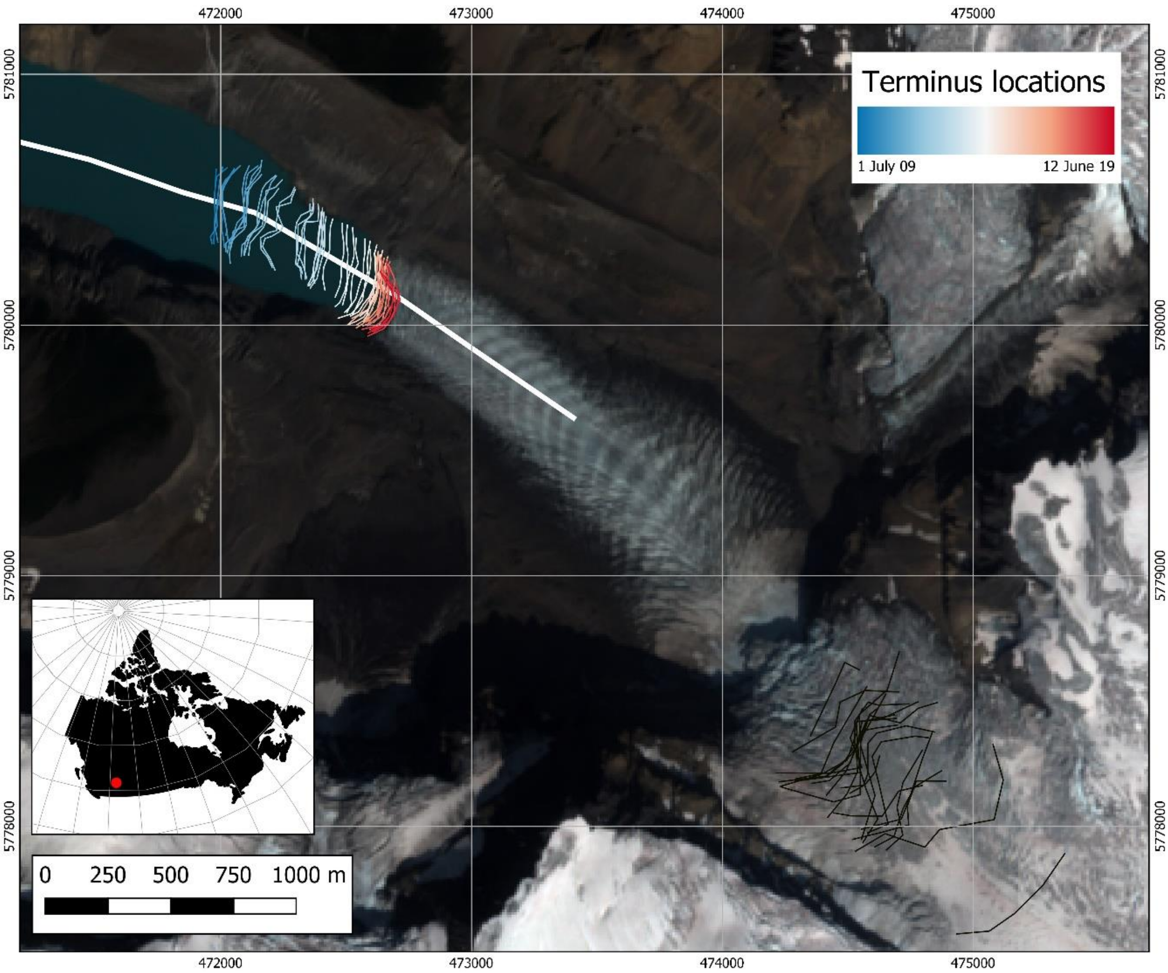

Figure 2: Columbia Glacier terminus locations in all observation years (2009 to 2019) derived from Landsat and Sentinel-2 imagery. Background is a Sentinel-2 image from August 2018. Inset shows the location of the Columbia Icefield in Canada. The white line is an approximate centreline, along which terminus 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

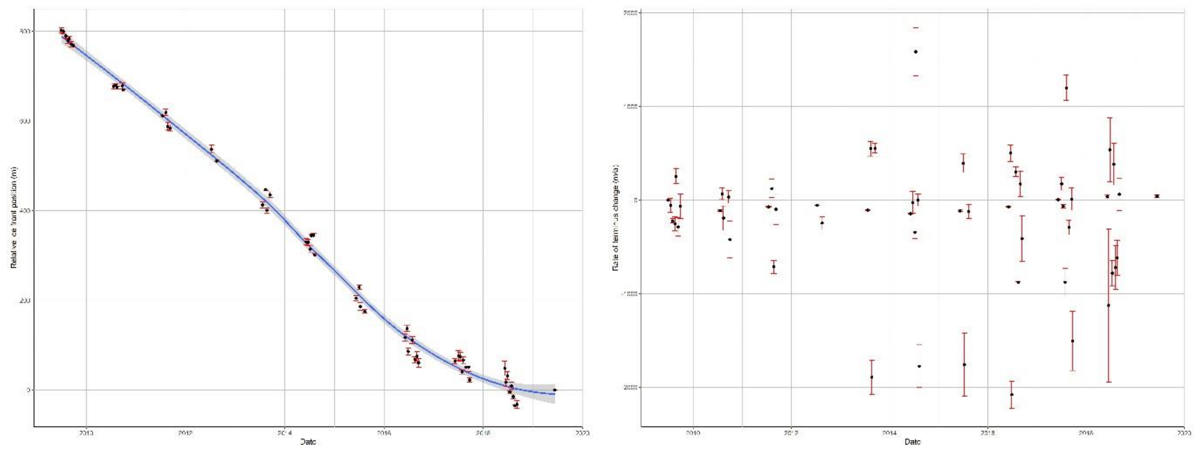

Figure 3: Retreat of the Columbia Glacier terminus along a single centreline, between July 2009 and June 2019, between observations separated by at least 7 days. (a) Terminus positions over this 10-year period, determined by manually digitising the glacier terminus on three separate occasions. The mean 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

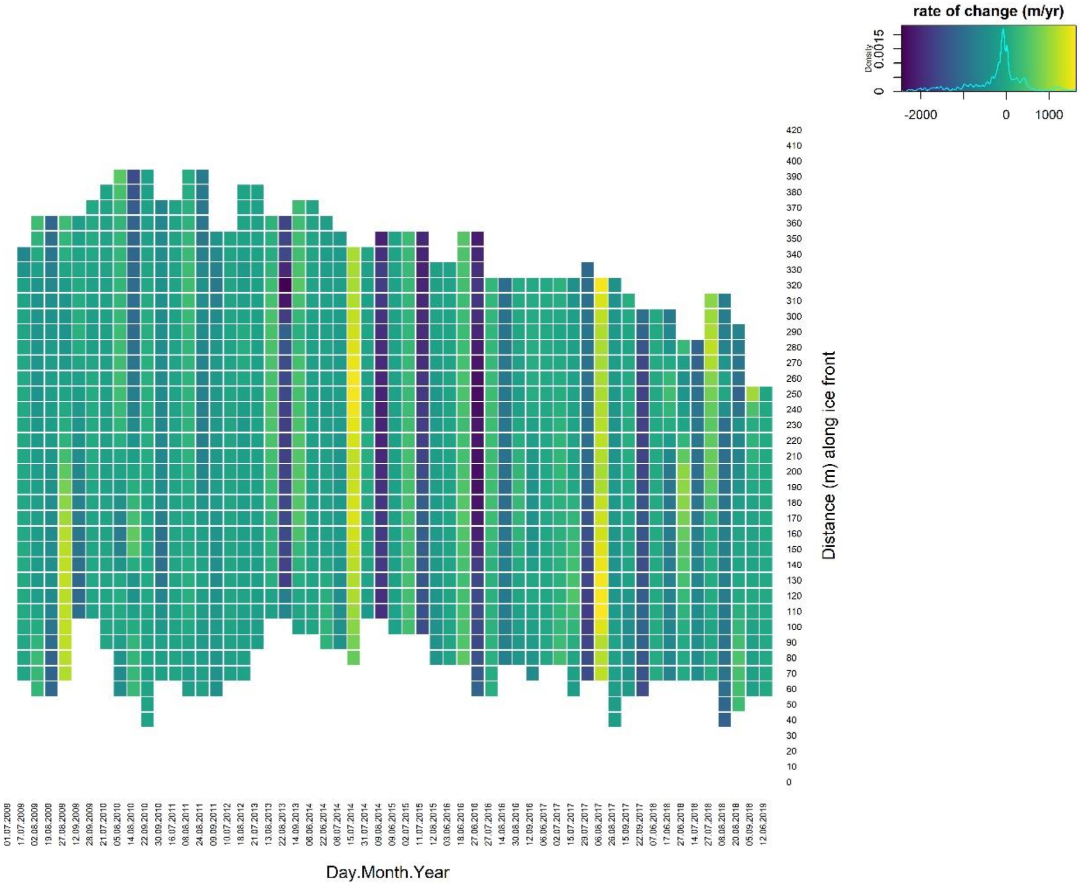

Figure 4: Rates of retreat of the glacier terminus across the whole terminus for observations separated by at least 7 days. For much of the 10 year period, rates of retreat are consistent. Periods of minor readvance are visible where shadings are light green/yellow, and these apparent minor re-advances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

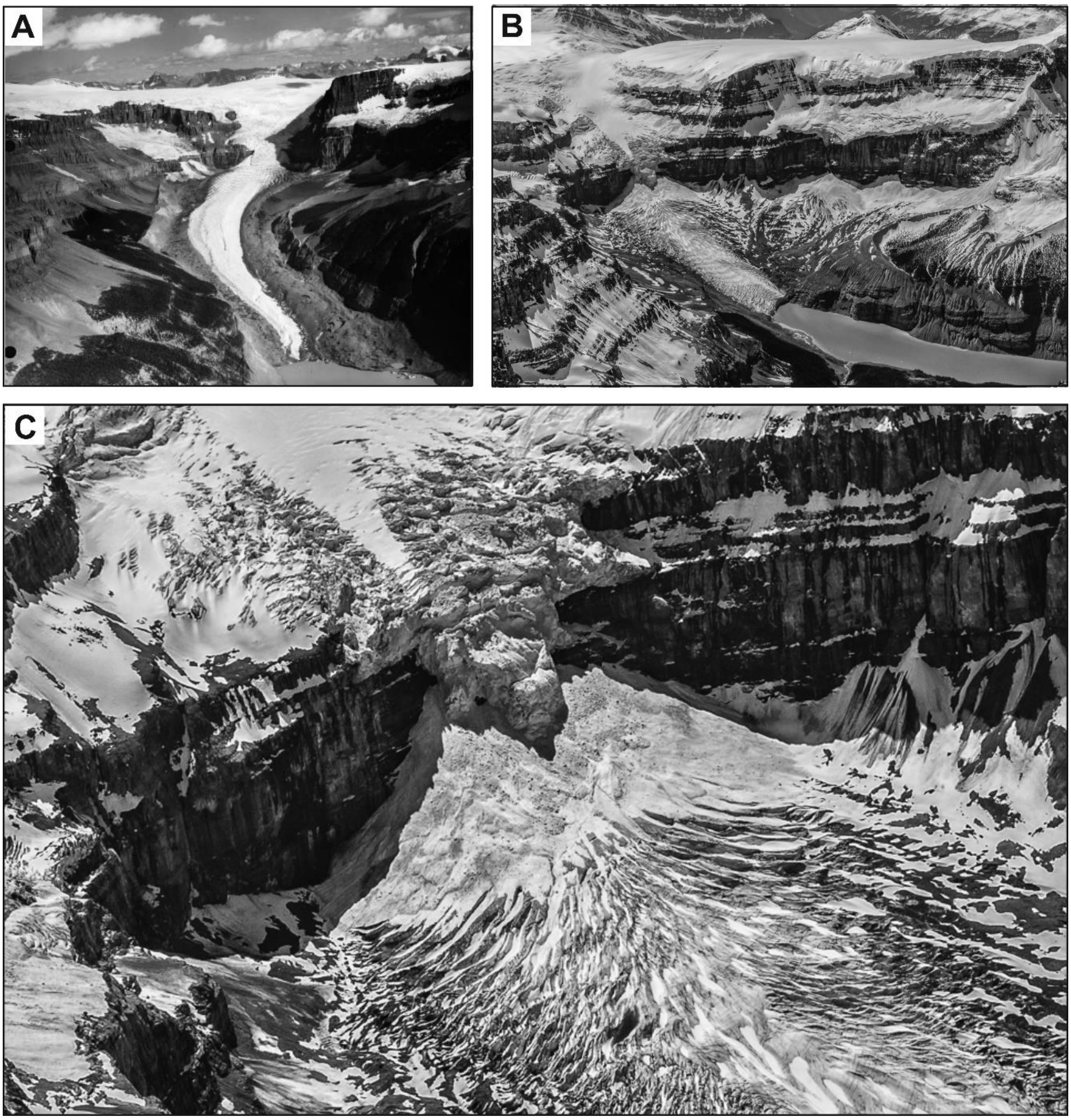

Figure 5: Columbia Glacier in: (A) 1969 (source: Austin Post and US Geological Survey) and in: (B) May 2017. Despite the two images being gathered from slightly different locations, it is clear just how much the glacier has reduced in length and width (see text for detailed discussion). Also marked are 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

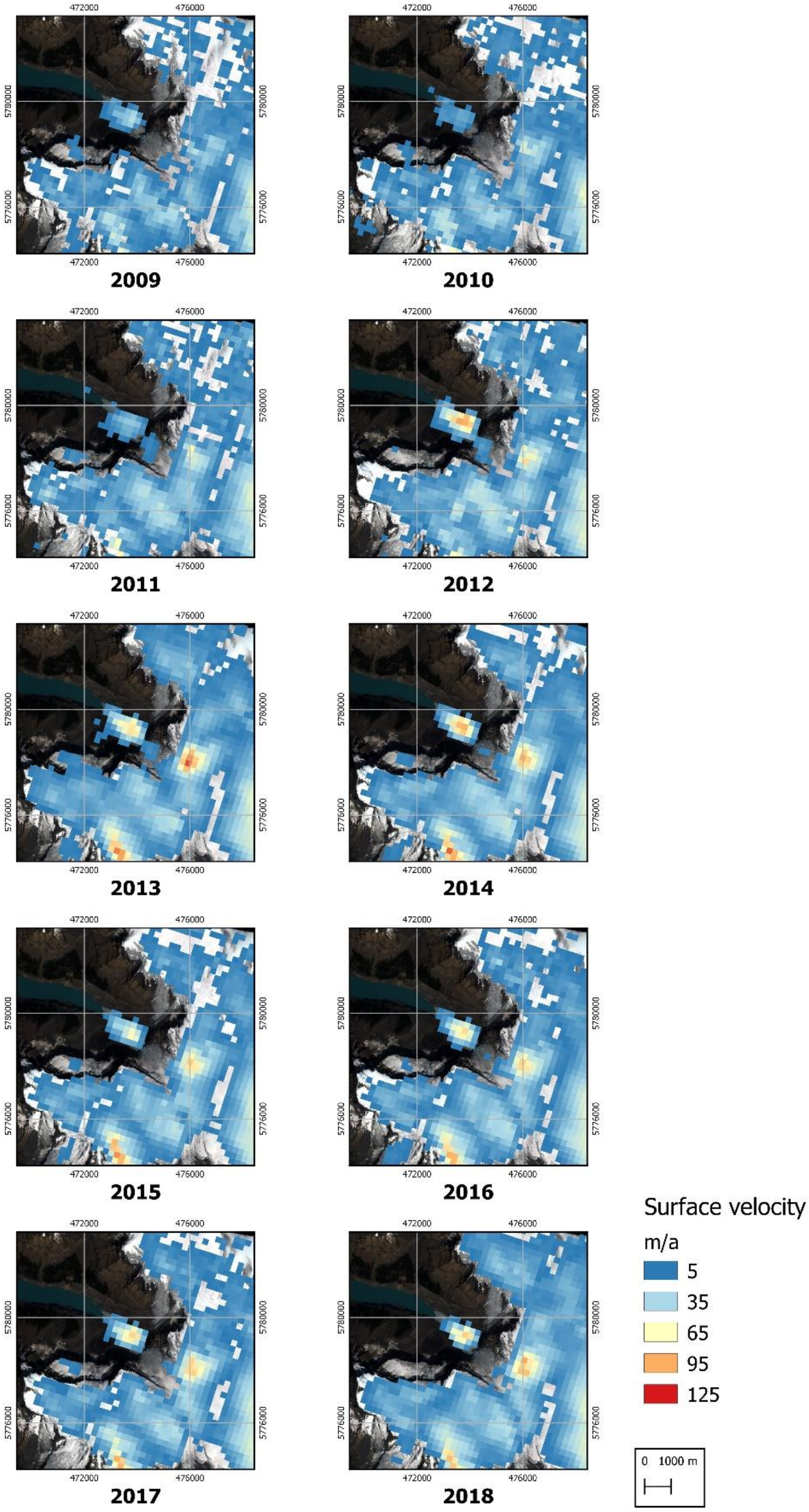

Figure 6: Mean annual surface ice velocities over the Columbia Glacier and surrounding region between 2009 and 2018. Velocities are generated using auto-RIFT (Gardner et al., 2018) and provided by the NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) ITS_LIVE (Inter-Mission 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)

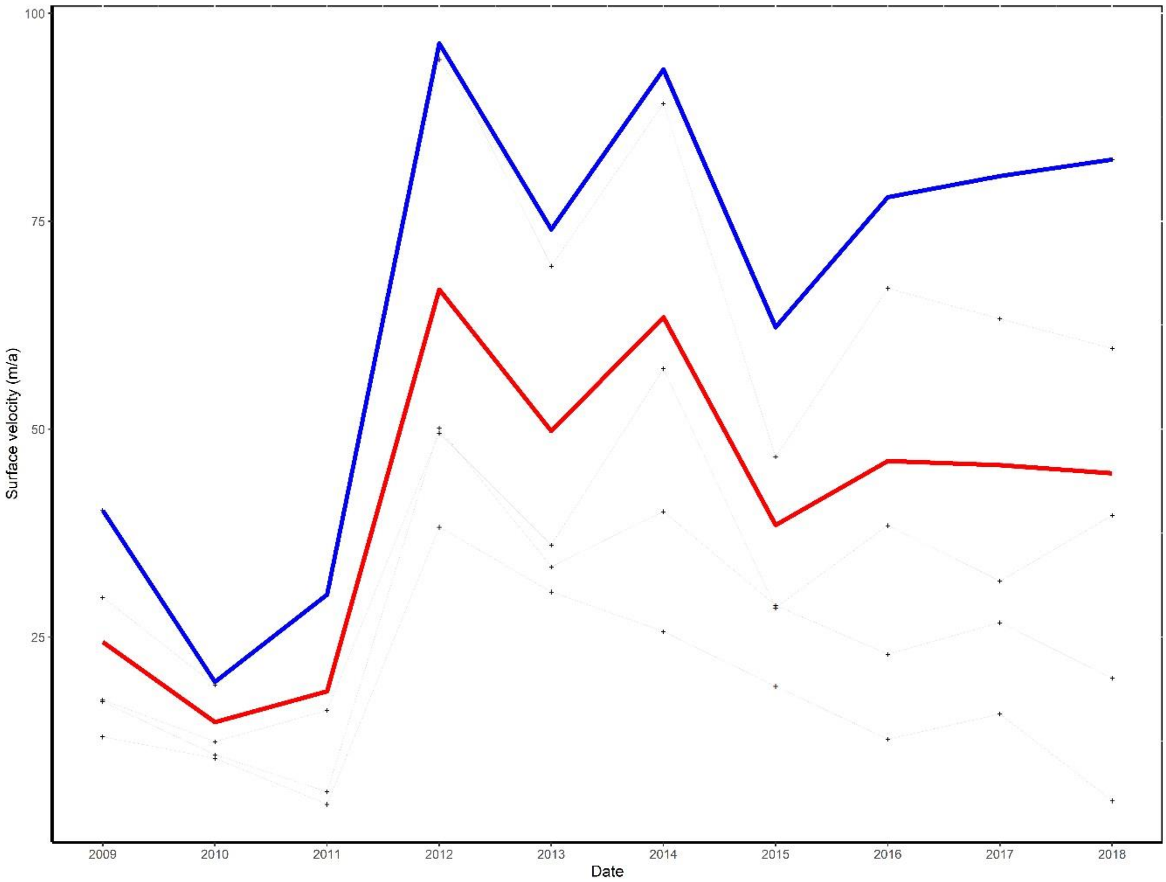

Figure 7: Mean (red) and maximum (blue) surface velocities derived from 12 discrete locations separated by 100 m steps along a centreline through the Columbia Glacier in each year between 2009 and 2018. The fine grey lines represent velocity changes associated with the 12 sample points contributing to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

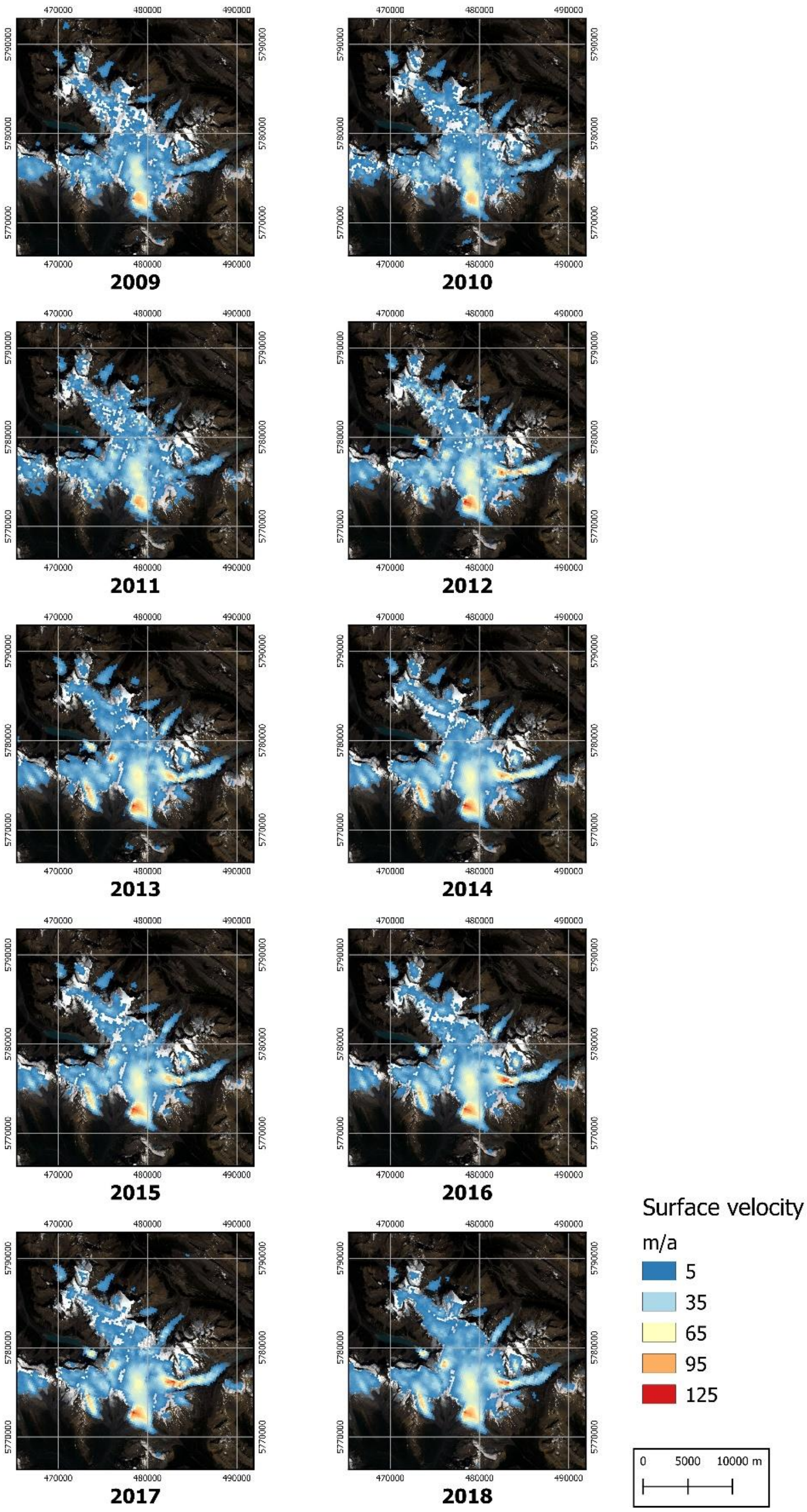

Figure 8: Mean annual surface ice velocities over the entirety of the Columbia Icefield between 2009 and 2018. Velocities are from the NASA MEaSUREs ITS_LIVE project (Gardner et al., 2019). See caption to Figure 6 for full details

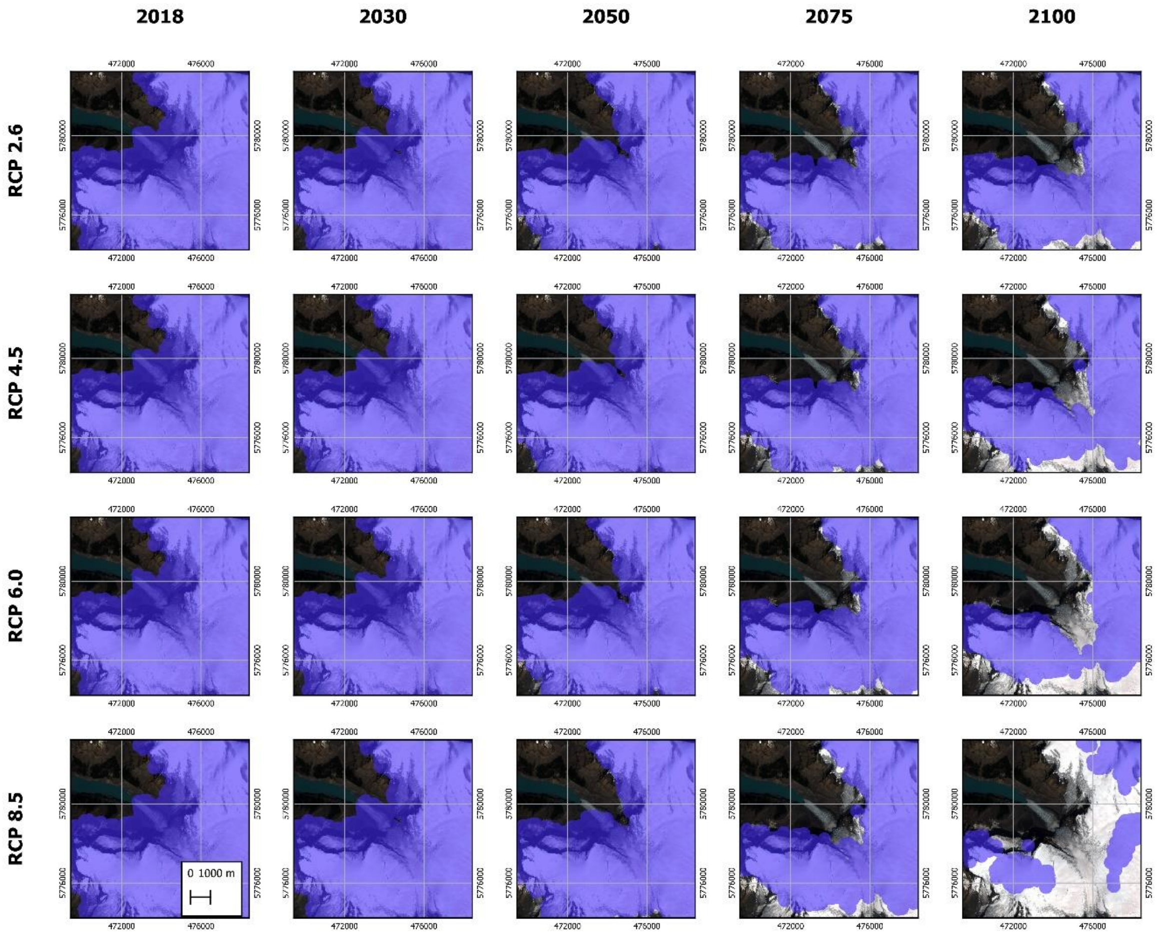

Figure 9: Model outputs following the work of Clarke et al. (2015). The output here is based on modelled extents of the Columbia Glacier based on the MIROC-ESM (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo) and National Institute for 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)

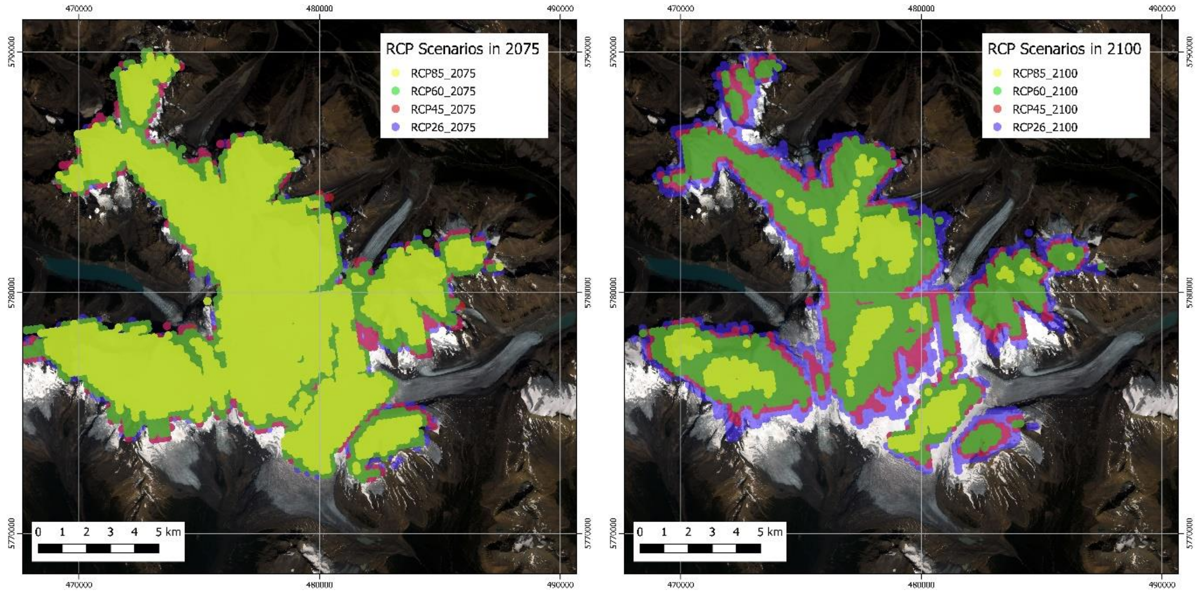

Figure 10: Model outputs following the work of Clarke et al. (2015). The output here is based on modelled extents of the entire Columbia Icefield based on the MIROC-ESM (Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo) and National Institute 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

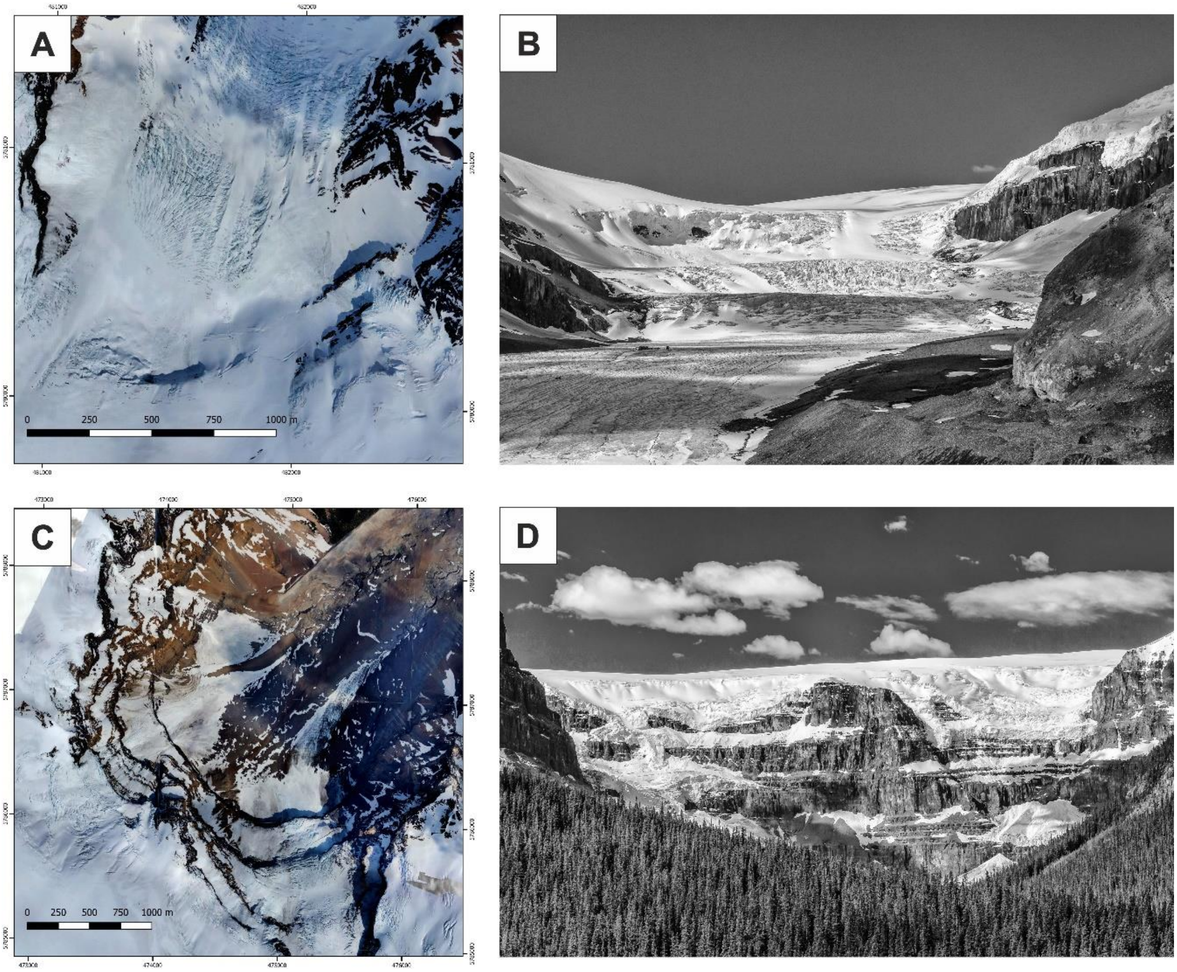

Figure 11: Ortho-mosaics (A and C) and oblique images (B and D) of the icefall zones of the Athabasca (A and B) and Stutfield (C and D) Glaciers – both outlets of the Columbia Icefield. In A and B, there is still a clear physical link between the ice in the upper icefield and the tongue of the Athabasca 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

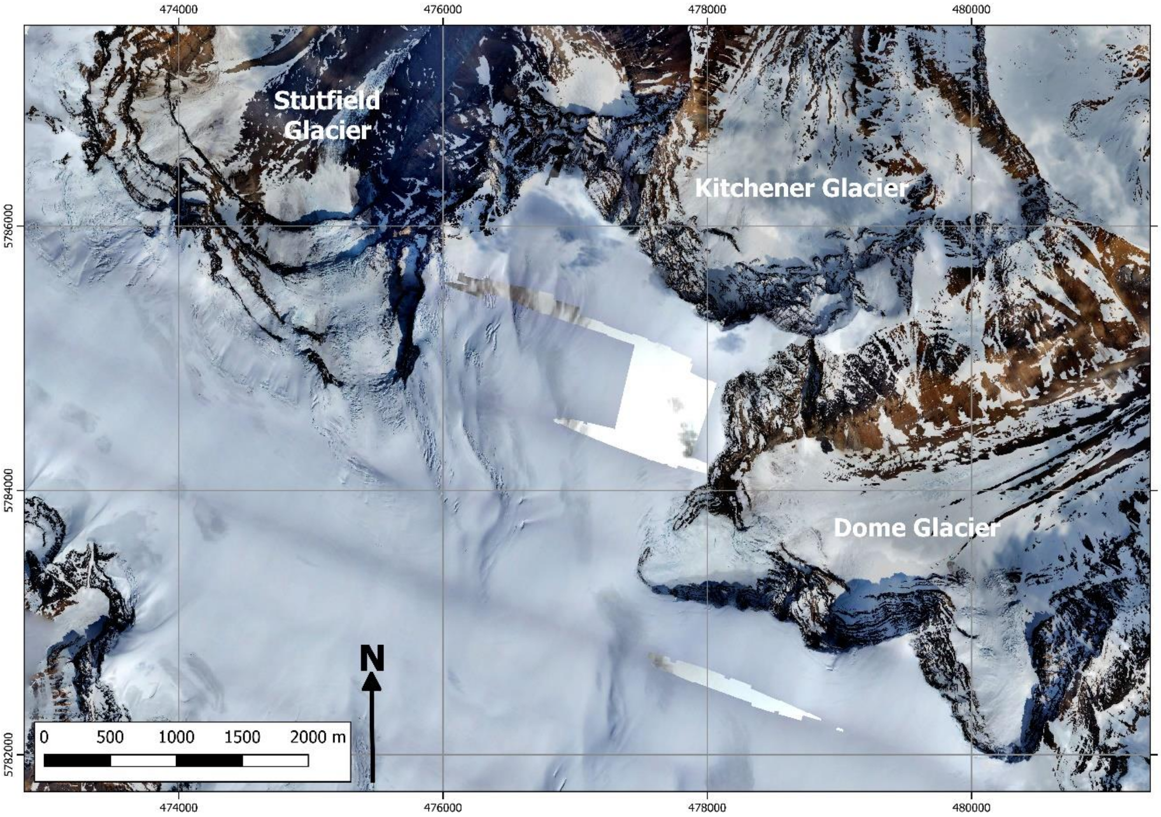

Figure 12: Orthomosaic of the upper reaches of Dome, Kitchener and Stutfield glaciers. The orthomosaics were generated by the authors using imagery gathered in May 2017. It is apparent that aside from a small and isolated location on Stutfield and Dome glaciers, these glaciers retain no direct linkage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