Relationships between iceberg plumes and sea-ice conditions on northeast Devon Ice Cap, Nunavut, Canada

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ABSTRACT. This study investigates the impact of sea-ice conditions on the production of iceberg plumes from two tidewater glaciers on Devon Ice Cap, Nunavut, Canada. These effects are quantified using a 12 year RADARSAT-1 satellite record from 1997–2008 that contains imagery from approximately every 1–2 weeks in the winter and every 1–4 days in the summer. Iceberg plumes identified in this record are verified against terrestrial time-lapse photography of Belcher Glacier from 2007–08. Results suggest a strong relationship between iceberg plumes and the retreat of sea ice from the glacier termini, with the plumes caused by both the release of previously calved icebergs (ice melange) and new glacier calving. Iceberg plumes are also sometimes observed at other times in the summer and in midwinter (occasionally on both glaciers simultaneously), with these events likely due to new glacier calving alone. Analysis of tides and air temperatures suggests that they provide a minor influence on the timing of iceberg plumes. Instead, it appears that changes in the presence of sea ice are dominant on seasonal timescales, although internal glacier dynamics likely play a significant role for winter plume events that occur when substantial thicknesses of landfast sea ice are present.

1. INTRODUCTION

Arctic sea ice has undergone dramatic changes in the recent past, with end-of-summer area shrinking by an average of 10.7% per decade between 1979 and 2007 (Stroeve and others, 2008), and average thickness decreasing by almost half over this period (Kwok and Rothrock, 2009). Within Canada, sea-ice losses between 1968 and 2008 have occurred at a rate of $2.9 \pm 1.2\%$ per decade in the Canadian Arctic Archipelago and $8.9 \pm 3.1\%$ per decade in Baffin Bay (Tivy and others, 2011). In concert with these changes, terrestrial ice masses in the Arctic have been undergoing substantial changes. For example, there has been widespread acceleration and retreat of outlet glaciers around Greenland (Joughin and others, 2010), and decrease in area and mass of ice caps in the Canadian High Arctic (Abdalati and others, 2004; Burgess and Sharp, 2004; Gardner and others, 2011). Little is currently known about the detailed interactions between sea ice and tidewater glaciers, however, particularly in the Canadian High Arctic. This information is required to properly assess how glaciers may change under a warming climate, and to better understand the controls on glacier dynamics and iceberg production rates. This is of particular importance given that calving can account for a significant proportion of mass loss from High Arctic ice caps and glaciers. For example, Burgess and others (2005) found that glacier calving into the ocean may account for up to 30% of the total volume loss of Devon Ice Cap over the past 40 years, while Williamson and others (2008) argue that calving could account for ~40% of the current combined mass loss from glaciers in the Canadian Arctic, Svalbard and Russian Arctic.

Previous studies of the interactions between Arctic sea ice and glacier calving events have largely focused on Greenland. For example, Reeh and others (2001) found that landfast sea-ice conditions in front of Nioghalvfjerdsfjorden Glacier, northeast Greenland, have an important impact on the stability of its floating margin. Increased sea-ice cover ensures greater stability by protecting the glacier front from wave action and winds. Major calving events did not occur when landfast sea ice was present, but became extensive as the landfast ice broke up. The same series of events was observed on other glaciers in northeast Greenland by Higgins (1989, 1991). There is also strong evidence that variability in glacier calving and terminus position at Jakobshavn Isbræ, Greenland, is related to the presence of sea ice and ice melange (dense mixture of calved icebergs) in the adjacent fiord (Joughin and others, 2008; Amundson and others, 2010), with total summer calving flux more than six times greater than winter calving flux (Sohn and others, 1998). Both seasonal and long-term variations in the surface motion of Jakobshavn Isbræ also appear to be related to the presence of sea ice, ice melange and the associated stability of the terminal ice tongue (Luckman and Murray, 2005; Joughin and others, 2008). Similarly, Howat and others (2010) found that seasonal advance and retreat of the terminus of six marine-terminating glaciers in West Greenland correlates with the presence or absence of an adjacent ice melange.

In the Canadian Arctic, previous research on this topic has primarily investigated the interactions between sea ice and ice-shelf calving events. For example, Copland and others (2007) found that the 2005 loss of the Ayles Ice Shelf occurred during a summer with the lowest sea-ice extent on record and a large open water lead along northern Ellesmere Island. In contrast, the Ayles and other adjacent ice shelves remained largely intact for long periods when they were protected by a fringe of semi-permanent landfast sea ice in the past. In one of the few studies that have looked at iceberg calving rates from glaciers in the Canadian High Arctic, Williamson and others (2008) argued that summer removal of sea ice could facilitate observed increases in seasonal flow rates, but that it was not an essential condition for order-of-magnitude velocity increases that were observed over short periods on some glaciers.

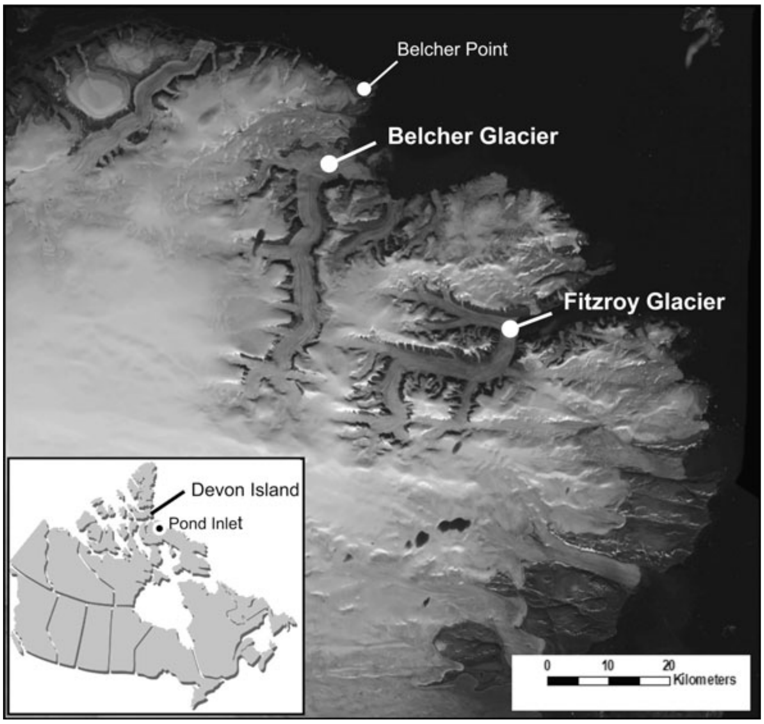

Fig. 1. Study locations on Devon Ice Cap (base image: 2000 Landsat Enhanced Thematic Mapper Plus).

In this study we provide an assessment of the links between sea-ice conditions, glacier calving and the production of iceberg plumes from two large tidewater glaciers flowing from the northeast portion of Devon Ice Cap, Nunavut, Canada. A 12 year record from RADARSAT-1 synthetic aperture radar (SAR) imagery provides information on the frequency, magnitude and temporal variability of iceberg plumes which originate from these glaciers over both summer and winter seasons. This RADARSAT-1 imagery, terrestrial time-lapse photography, climate data and tidal predictions are used to assess the causes of these iceberg plumes and their relationship to sea-ice conditions. This research provides a contribution towards the international GLACIODYN project, which examines the response of Arctic glaciers to climate change. It also provides information required for understanding the causes of spatial and temporal variations in ice motion recorded on Devon Ice Cap (e.g. Van Wychen, 2010).

2. STUDY AREA

Devon Ice Cap is situated on the east side of Devon Island and has a surface area of ~14 000 km^2 (Burgess and Sharp, 2008; Fig. 1). The eastern margin of the ice cap is fringed by extensive tidewater glaciers that exist due to high accumulation rates driven by moisture sources from nearby Baffin Bay (Burgess and others, 2005; Mair and others, 2005). This study focuses on two major outlet glacier fronts of the northeast coast of Devon Ice Cap: Belcher and Fitzroy Glaciers (Fig. 1). Belcher Glacier is a large polythermal glacier that is ~5 km wide at its front, and grounded below sea level at its terminus. Ice thicknesses are ~100–250 m across the northern half of its terminus and ~300–500 m along the southern portion (Dowdeswell and others, 2004). Fitzroy Glacier also appears to be grounded below sea level at its terminus, where it attains a thickness of ~200 m. Belcher Glacier is characterized by motion of >250 m a^{-1} at its ice front, compared to motion of up to ~200 m a^{-1} at the terminus of Fitzroy Glacier (Van Wychen, 2010). Both glaciers are ~35 km long, although Belcher drains a larger area. Burgess and others (2005) calculated that Belcher Glacier is responsible for ~47% of total glacier calving into the ocean from Devon Ice Cap, while the other glaciers along the eastern margin account for ~40%.

3. METHODS

3.1. RADARSAT-1 imagery

Sea-ice conditions and the production of iceberg plumes from Belcher and Fitzroy Glaciers were catalogued using imagery from the Canadian Ice Service (CIS) RADARSAT-1 satellite image archive for the period 1997–2008. RADARSAT-1 provides frequent ScanSAR Wide-B coverage of the Canadian Arctic at 100 m resolution, thus enabling imaging during both the day and night, as well as through clouds. These scenes are used operationally by the CIS to map sea-ice conditions, but have not been used to map iceberg production events before. The archive contains images of northeast Devon Ice Cap approximately every 1–4 days from the end of June to the end of September for the entire 12 year study period, and approximately weekly to fortnightly coverage when landfast sea ice is present in the winter months (October–June).

Detection and classification of iceberg plumes was completed via visual analysis of changes in backscatter between RADARSAT-1 images. SAR backscatter is sensitive to both surface roughness and moisture content, so that smooth and/or wet surfaces typically appear dark, while rough and/or dry surfaces typically appear bright. Freshly calved glacier ice appears bright due to its high surface roughness, no matter in what season the event occurs. Iceberg production also occurs over much shorter time

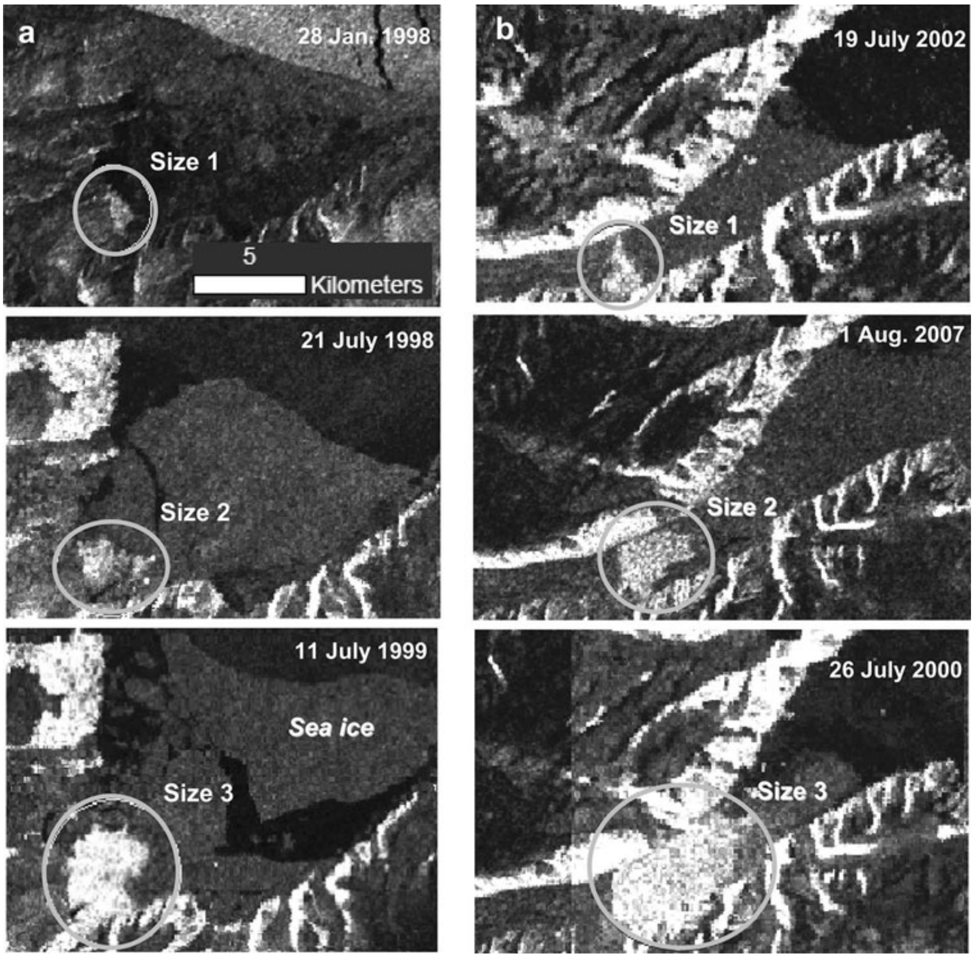

Fig. 2. Examples of size 1–3 (small, medium, large) iceberg plumes in RADARSAT-1 imagery from (a) Belcher Glacier and (b) Fitzroy Glacier. (RADARSAT imagery © Canadian Space Agency.)

periods than changes in surface wetness, so comparison of changes between RADARSAT-1 scenes enables clear identification of events (Fig. 2).

The dates of annual landfast sea-ice break-up and freeze-up were determined from both the RADARSAT-1 imagery and weekly ice charts from the CIS Digital Archive (Tivy and others, 2011). Break-up dates were determined to the nearest 1–2 days, while freeze-up dates could only be determined to the nearest week due to the reduced availability of RADARSAT-1 imagery in the fall. Note that care was taken to ensure that only new iceberg plumes were identified; brash ice, consisting of accumulations of floating sea ice and iceberg fragments, often gets blown back into the glacier bays after landfast sea-ice break-up and could be mistaken for freshly released glacier ice. However, it appears greyer in RADARSAT-1 imagery than freshly calved glacier ice, making it distinguishable from the iceberg plumes studied.

The resolution of the ScanSAR Wide-B imagery made it difficult to precisely define the size of iceberg plumes, so all detected events were classified into one of three categories based on order-of-magnitude changes in glacier area (Fig. 2). Size 1 indicates a small event (area loss on the order of tens of m^2), size 2 indicates a medium-sized event (area loss on the order of hundreds of m^2) and size 3 indicates a large event (area loss on the order of thousands of m^2). Where available, these changes were verified against the time-lapse photography and occasional RADARSAT-1 fine beam images (~8 m resolution).

3.2. Time-lapse photography

Oblique photography from the Belcher Glacier Time-Lapse Camera Project of the University of Alberta was compared with the RADARSAT-1 scenes for the summers of 2007 and 2008. This camera was placed on a ridge overlooking the terminus of Belcher Glacier, and photographed the southern half of the glacier front at 3 hour intervals in 2007 and 1 hour intervals in 2008. These photographs were used to verify interpretations made using the RADARSAT-1 scenes, and to assess both the relative size of iceberg plumes in the SAR imagery and the smallest identifiable events. They also enabled a more detailed assessment of the relative importance of new glacier calving events versus the release of existing ice melange in causing the observed iceberg plumes. Although the time-lapse photos were only available for the last two summers of the study period, validation of the satellite imagery against these photos increases confidence in the robustness of the RADARSAT-1 image interpretations over the entire 12 year record.

3.3. Climate and tidal data

The relationship between sea-ice conditions, production of iceberg plumes and air temperature was studied using climate data from a permanent Environment Canada meteorological station at Pond Inlet, Nunavut, ~300 km south of the study site (Fig. 1). The station at Grise Fiord, Nunavut, is closer to Devon Ice Cap, but data from there are

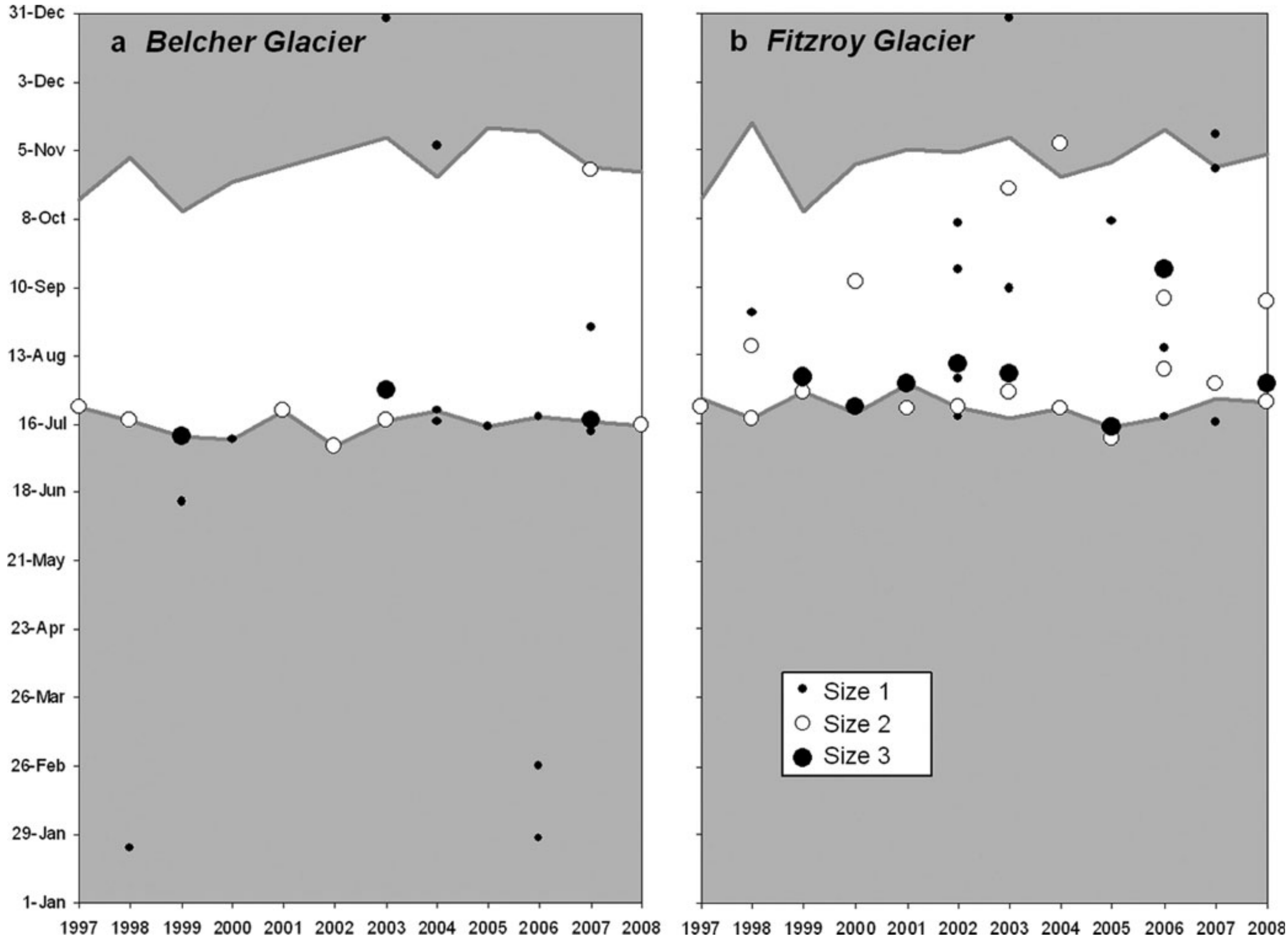

Fig. 3. Temporal variability in the presence (grey area) and absence (white area) of landfast sea ice, together with the timing and size of iceberg plumes from (a) Belcher Glacier and (b) Fitzroy Glacier, 1997–2008.

incomplete as they are recorded manually during working hours only. It is assumed that Pond Inlet experiences weather comparable to Belcher and Fitzroy Glaciers since it is open to Baffin Bay in a similar way to these ice masses. At the same time, it is acknowledged that only general interpretations are possible using these data given the distance between the station and the study site.

Tidal data from WXTide32 prediction software were used to understand the effect of tides on iceberg plume events. Tides were calculated for Belcher Point, ~5 km from the northern margin of Belcher Glacier (Fig. 1), between 1997 and 2008. These are assumed to be representative of tidal conditions around northeast Devon Ice Cap, and compare well against sea-level measurements made at the terminus of Belcher Glacier in summer 2008 (personal communication from L. Tarasov, 2008)

4. RESULTS

Analysis of the 1997–2008 RADARSAT-1 imagery and CIS charts indicates that annual landfast sea-ice retreat from the bays in front of Belcher and Fitzroy Glaciers generally occurs in the second or third week of July (Fig. 3). The start date of sea-ice break-up ranges between 7 and 23 July for Belcher Glacier, and between 15 July and 1 August for Fitzroy Glacier. Sea-ice retreat from Fitzroy Glacier typically occurs later in the summer than for Belcher Glacier, although sea-ice retreat from both glacier fronts occurred simultaneously from 2003 to 2006. The dates of annual sea-ice retreat for the 12 year period indicate no significant long-term trend, similar to the findings of Tivy and others (2011) for northwest Baffin Bay. In terms of sea-ice formation, this occurs between mid-October and mid-November, with the embayment in front of Fitzroy Glacier typically freezing up a week or two later than that in front of Belcher Glacier (Fig. 3). It appears that freeze-up occurred later near the end of our study period than at the start, although the spatial and temporal resolutions of our record do not allow determination of whether this is a significant long-term trend.

RADARSAT-1 imagery from 1997–2008 indicates that the production of iceberg plumes is strongly related to the retreat of sea ice from the glacier fronts (Fig. 3). Plumes typically appear in front of both glaciers coincident with sea-ice break-up, although occasionally they occur up to a few days prior to the first day of sea-ice retreat (e.g. 2001, 2002, 2005 and 2007 for Fitzroy Glacier; Fig. 3). Comparison of the iceberg plumes observed in the SAR imagery with the 2007–08 time-lapse photography at Belcher Glacier suggests that these events are likely dominated by the release of an ice melange accumulated at the glacier front during the preceding spring and winter, together with some new glacier calving. It is difficult to quantify the relative importance of these sources to the iceberg plumes observed during sea-ice break-up at Fitzroy Glacier and in other years at Belcher

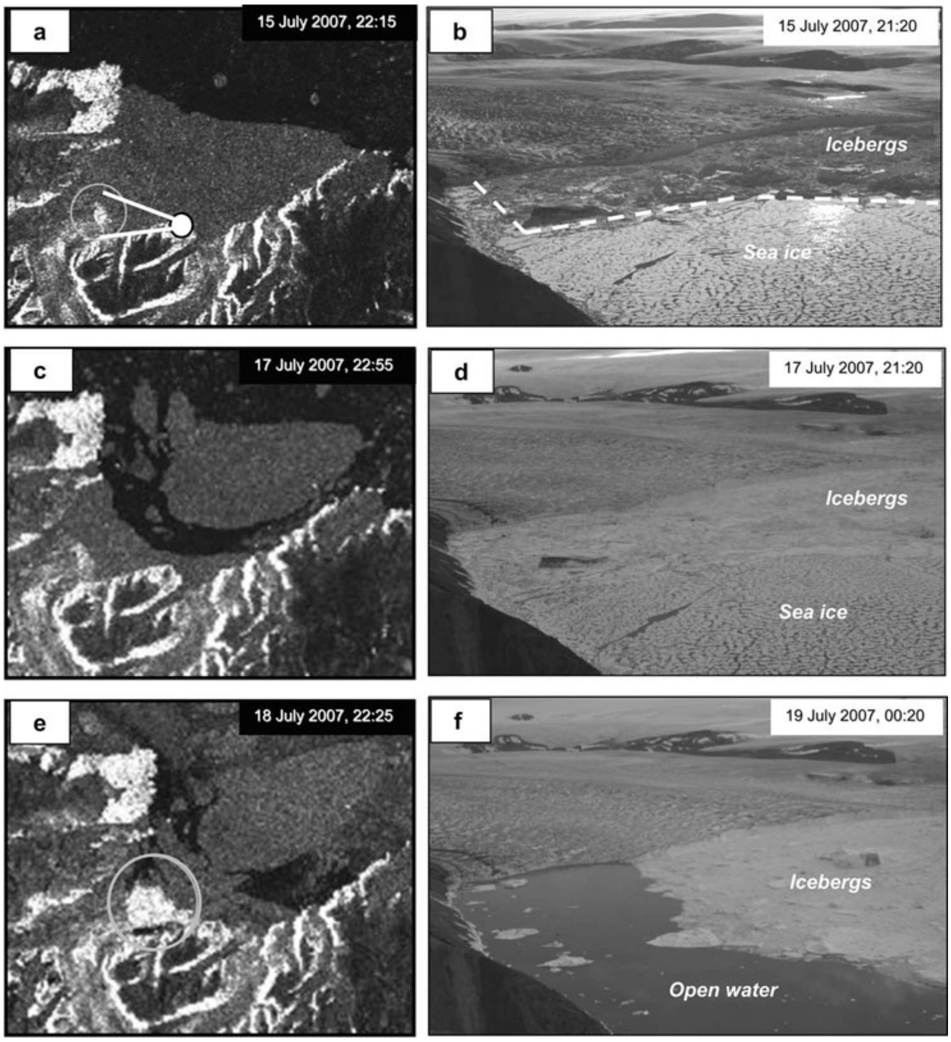

Fig. 4. Sea-ice conditions and iceberg plumes at Belcher Glacier in July 2007 in RADARSAT-1 ScanSAR Wide-B imagery (a, c, e) and near-coincident time-lapse photography (b, d, f). (a, b) A new iceberg plume prior to sea-ice retreat (field of view of time-lapse camera shown by white lines). (c, d) Landfast sea-ice break-up and retreat without any new iceberg plume. (e, f) Major iceberg plume shortly after sea ice retreats from Belcher Bay. Times are in UTC. (RADARSAT imagery © Canadian Space Agency.)

Glacier, but analysis of the SAR imagery suggests that both processes are important. At other times of the year, it appears that new glacier calving provides essentially all of the source for the observed iceberg plumes. The time-lapse photography indicates that both small icebergs and large, full-glacier-thickness icebergs are calved from Belcher Glacier.

Multiple iceberg plumes typically occur annually from both glaciers, although they are more frequent from Fitzroy Glacier than from Belcher Glacier, especially for large (size 3) events (Fig. 3). During the 12 year study period, 24 plumes in total were recorded from Belcher Glacier in the RADARSAT-1 imagery, compared to 38 from Fitzroy Glacier. Some of these events occurred simultaneously on both glaciers, but many did not. Iceberg plumes were typically restricted to an origin from the southern portion of Belcher Glacier (where the ice is thickest), but originated from across the entire terminus of Fitzroy Glacier.

The largest iceberg plumes from Belcher Glacier often occur within a 24 hour period of most of the landfast sea ice breaking up and retreating (Fig. 3). For example, in 2007 a small iceberg plume (size 1) was first detected in the RADARSAT-1 imagery on 15 July (Fig. 4a). The sea ice then began to break up in front of Belcher Glacier on 17 July (Fig. 4c), followed by the release of a large plume of icebergs (size 3) the next day after most of the sea ice had retreated from the glacier front (Fig. 4e). Some of these icebergs originated from the release of the existing iceberg melange, but it appears that there was also new glacier calving shortly after the loss of the landfast sea ice. This sequence of events was confirmed by the time-lapse photography (Fig. 4b, d and f), which indicates that glaciers can calve icebergs even when landfast ice is present, but that large calving events typically only occur once the landfast ice has gone.

On Fitzroy Glacier the largest iceberg plumes (size 3) typically occur in late July or early August, between a few days and a couple of weeks after landfast sea-ice retreat (Figs 3 and 5). Small and medium iceberg plumes typically occur simultaneously with the initial loss of sea ice, but large size 3 events are not so common at this time.

Winter iceberg plumes were occasionally detected in the SAR imagery when landfast sea ice was present, although these events are less frequent and generally smaller than summer events (Fig. 3). Over the 12 year study period, a total of six iceberg plumes from Belcher Glacier and five from Fitzroy Glacier were recorded more than a week before break-up or a week after freeze-up. Winter events occur on

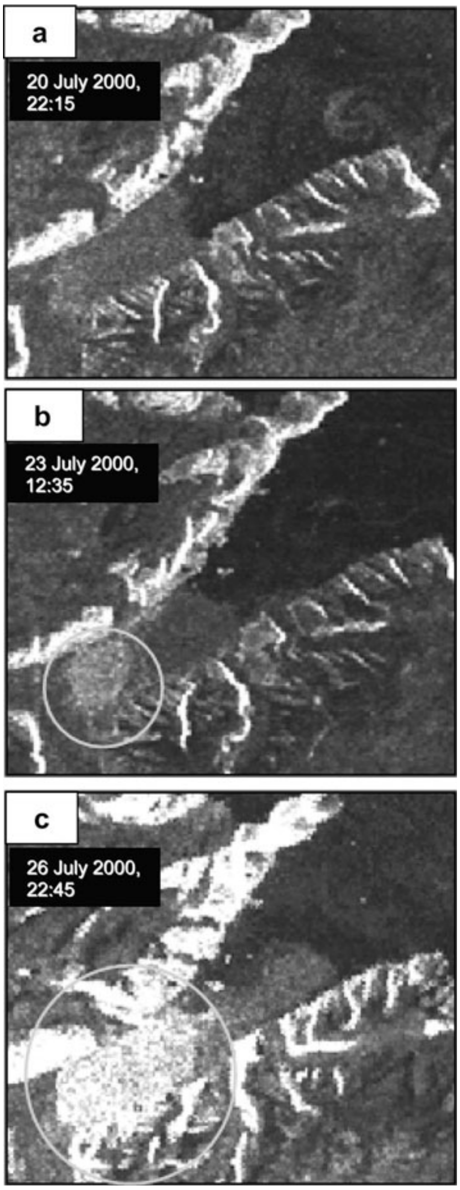

Fig. 5. Progression of sea-ice break-up and production of iceberg plumes from Fitzroy Glacier in RADARSAT-1 ScanSAR Wide-B imagery from summer 2000. (a) Fitzroy Glacier front with landfast sea-ice cover. (b) Beginning of landfast ice break-up with a small iceberg plume. (c) Large (size 3) iceberg plume when no sea ice present. Times are in UTC. (RADARSAT imagery © Canadian Space Agency.)

both glaciers simultaneously in some years, but appear isolated in other years. For example, an iceberg plume occurred on 27–28 January 2006 from Belcher Glacier, when no plume was observed from Fitzroy Glacier. However, iceberg plumes occurred simultaneously from both glaciers on 28–30 December 2003.

An important issue when assessing events observed in the satellite record is whether the RADARSAT-1 imagery captures all the iceberg production events that occur from Belcher and Fitzroy Glaciers. To test this, all of the Belcher time-lapse photography was compared with the satellite image record for both summers 2007 and 2008. This comparison indicated that small glacier calving events prior to landfast sea-ice retreat are not always reliably identified using RADARSAT-1 scenes with 100 m resolution. However, events that occurred when sea ice was no longer present were easier to identify due to their typically greater size and the high backscatter contrast between rough calved ice and open water. Another issue is that small, short-lived events are captured with time-lapse imagery collected at hourly intervals (Fig. 6a), but may be missed with satellite imagery collected at daily or longer intervals (Fig. 6b and c). The long-term record presented here (Fig. 3) should therefore be treated as a minimum estimate of iceberg production events from northeast Devon Ice Cap, especially for small, short-lived events. However, we have high confidence that medium and large events are well recorded by the satellite imagery, which accounts for the bulk of ice lost by calving in this region.

4.1. Climate, tides and production of iceberg plumes

The climate data were used to establish the positive degree-day (PDD) sum for each year from 1998 to 2007 (1997 and 2008 data were incomplete). This information indicated that the minimum number of PDDs needed to trigger annual landfast sea-ice loss was ~150 for both glaciers, although the sea ice was not lost until there had been >350 PDD in some years (Fig. 7). In general, more PDDs were required before the sea ice broke up in front of Fitzroy Glacier compared to Belcher Glacier, which reflects the later seasonal loss of sea ice from this more enclosed embayment (Fig. 3).

Analysis of air temperatures both prior to and during the release of iceberg plumes over the 12 year study period did not reveal any particular relationship between the two. Overall there were many more iceberg plumes when temperatures were above freezing, but events occurred both before and after periods of extreme temperature variability (Fig. 8). Winter iceberg plumes also occurred over a wide range of temperatures. In winter 2006, for example, one event occurred from Belcher Glacier at the end of January after a month of temperatures consistently below –30°C, while an event at the end of February occurred after a period of rapidly rising temperatures (Fig. 8b).

Tide predictions from 1997–2008 indicate no consistent relationship between tidal levels and the production of iceberg plumes from either glacier. Semi-diurnal amplitudes range from >2 m during spring tides to <1 m during neap conditions at Belcher Point. Iceberg plumes from Belcher and Fitzroy Glaciers often occur during or after periods of spring tides, but they also occur during neap and other periods, albeit slightly less frequently. Our record lacks sufficient temporal resolution to indicate whether iceberg plumes occur preferentially on the rising or falling limbs of the tidal cycle.

5. DISCUSSION AND CONCLUSIONS

The results of this study demonstrate a direct relationship between sea-ice conditions and the production of iceberg plumes from Belcher and Fitzroy Glaciers. Small to medium iceberg plumes occur almost simultaneously with the loss of landfast sea ice from the embayments in front of the glaciers, which occurs when PDDs have exceeded ~150 a^{-1}. These events likely represent the release of previously trapped ice melange, together with new glacier calving. The largest iceberg plumes then typically occur within a few days of the loss of the landfast ice, during open-water conditions. These events are likely dominated by new glacier calving. This

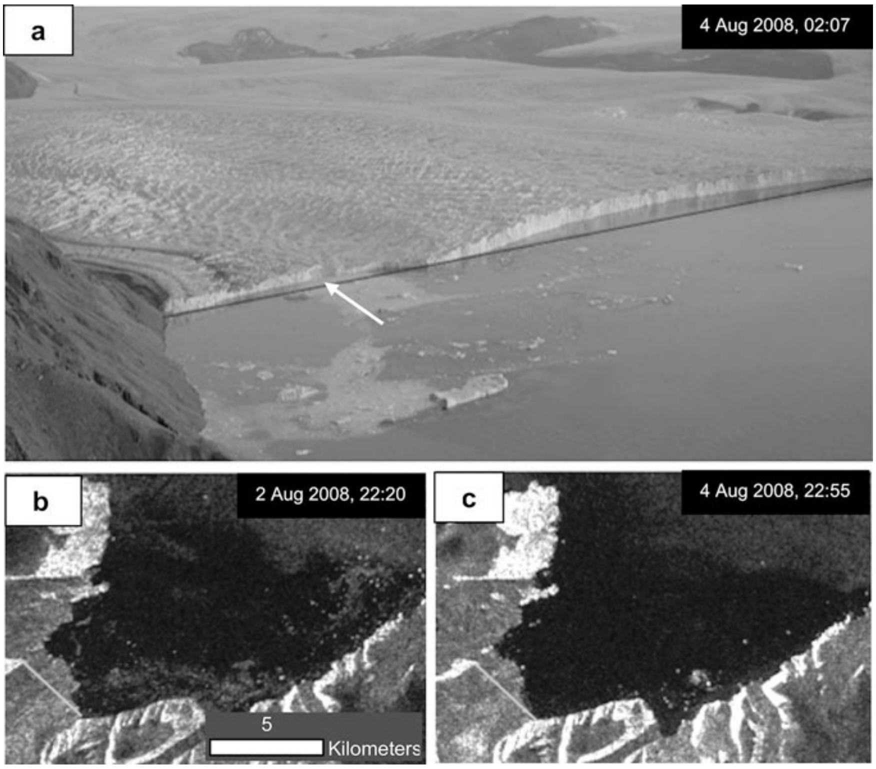

Fig. 6. (a) Photograph of Belcher Glacier from 4 August 2008, showing a very small glacier calving event (white arrow) which had occurred in the previous hour. (b, c) RADARSAT-1 imagery from the closest available times before (b) and after the calving event (c) does not show an iceberg plume, although careful analysis indicates a change in shape of the glacier front over this period. Times are in UTC. (RADARSAT imagery © Canadian Space Agency.)

highlights the importance of sea ice in providing a protective fringe for High Arctic tidewater glaciers, as has previously been found by, for example, Reeh and others (2001) and Howat and others (2010). However, the occurrence of winter iceberg plumes (albeit typically smaller than summer events) when landfast sea ice is present indicates that sea-ice conditions do not provide the only factor controlling iceberg production processes. In addition, it is likely that more small glacier calving events occur than have been identified here due to limitations in detecting them in RADARSAT-1 ScanSAR imagery. Analysis of climate and tidal conditions shows little relationship to the timing of iceberg plumes, which suggests that both winter and summer calving probably also occur as a stochastic process in response to the movement of highly crevassed ice toward the glacier terminus.

Over the study period, we observed fewer iceberg plumes originating from Belcher Glacier than from Fitzroy Glacier, although there is no evidence of significant terminus retreat of either glacier over the period 1997–2008. The iceberg plumes discussed here thus reflect the normal loss of mass from the terminus of these glaciers as part of the ablation process. Previous studies have mainly focused on glacier dynamics and water depth at the terminus as the primary

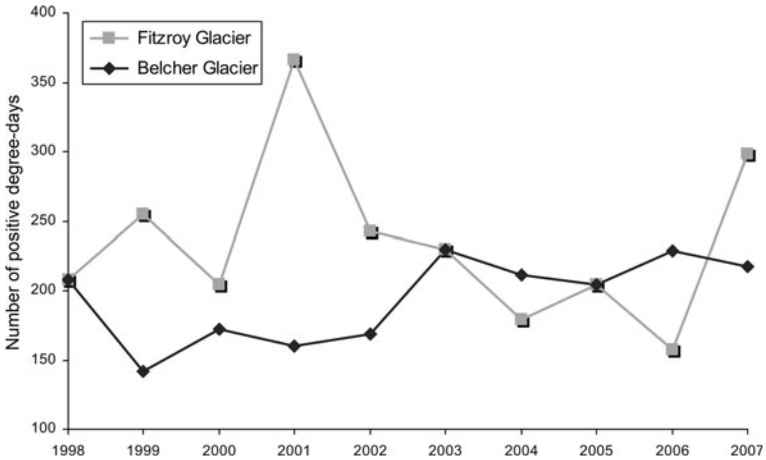

Fig. 7. Number of accumulated PDDs (recorded at Pond Inlet) prior to annual break-up of landfast sea ice in front of Fitzroy and Belcher Glaciers, 1998–2007.

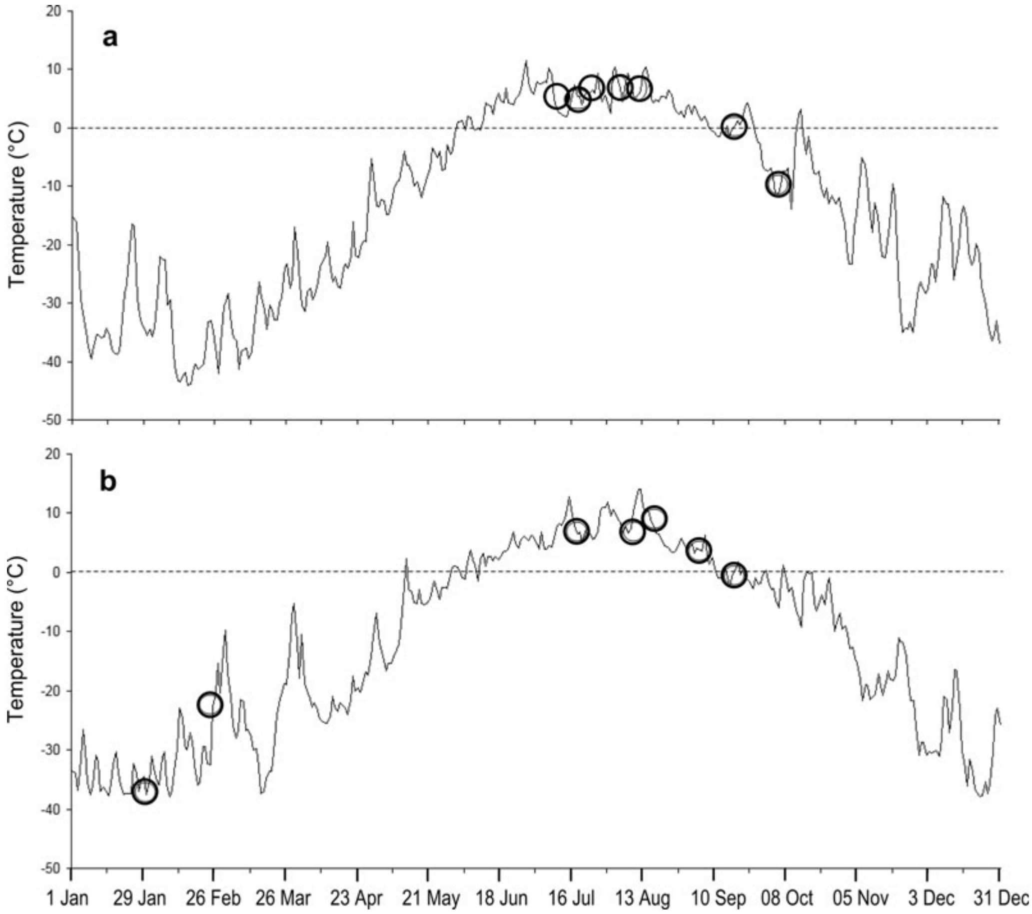

Fig. 8. Mean daily temperatures at Pond Inlet compared to dates of iceberg plumes from Belcher and Fitzroy Glaciers (circles) for two representative years: (a) 2002 and (b) 2006.

factors influencing calving rates on tidewater glaciers (e.g. Van der Veen, 2002), but the results here indicate that adjacent sea-ice conditions should also be considered. This is important for determining the long-term evolution of tidewater glaciers in the Canadian Arctic, as previous studies in West Greenland suggest that sustained glacier retreat may be triggered by declines in sea-ice concentrations (Joughin and others, 2008; Howat and others, 2010; Vieli and Nick, 2011).

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