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The Cryosphere Discussions

Title: Simultaneous disintegration of outlet glaciers in Porpoise Bay (Wilkes Land), East Antarctica, and the long-term speed-up of Holmes Glacier.

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Abstract: The floating ice shelves and glacier tongues which fringe the Antarctic continent are important because they help buttress ice flow from the ice sheet interior. Dynamic feedbacks associated with glacier calving have the potential to reduce buttressing and subsequently increase ice flow into the ocean. However, there are few high temporal resolution studies on glacier calving, especially in East Antarctica. Here we use remote sensing to investigate monthly glacier terminus change across six marine-terminating outlet glaciers in Porpoise Bay (-76°S, 128°E), Wilkes Land (East Antarctica), between November 2002 and March 2012. This reveals a large simultaneous calving event in January 2007, resulting in a total of ~2,900 km^2 of ice being removed from glacier tongues. Our observations suggest that sea-ice must be removed from glacier termini for any form of calving to take place, and we link this major calving event to a rapid break-up of the multi-year sea-ice which usually occupies Porpoise Bay. Using sea-ice concentrations as a proxy for glacier calving, and by analysing available satellite imagery stretching back to 1963, we reconstruct the long-term calving activity of the largest glacier in Porpoise Bay: Holmes (West) Glacier. This reveals that its present-day velocity (~1450 m a^{-1}) is approximately 50% faster than between 1963 and 1973 (~900 m a^{-1}). We also observed the start of a large calving event in Porpoise Bay in March2016 that is consistent with our reconstructions of the periodicity of major calving events. These results highlight the importance of sea-ice in modulating outlet glacier calving and velocity in East Antarctica.

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1. Introduction

Iceberg calving is an important process that accounts for around 50% of total mass loss to the ocean in Antarctica (Depoorter et al., 2013; Rignot et al., 2013). Moreover, dynamic feedbacks associated with retreat and/or thinning of buttressing ice shelves or floating glacier tongues can result in an increased discharge of ice into the ocean (De Angelis and Skvarca, 2003; Rignot et al., 2004; Wuite et al., 2015). At present, calving dynamics are only partially understood (Benn et al., 2007; Chapuis and Tetzlaff, 2014) and models struggle to replicate observed calving rates (van der Veen, 2002; Astrom et al., 2014). Therefore, improving our understanding of the mechanisms driving glacier calving and how glacier calving cycles have responded to recent changes in the ocean-climate system is important in the context of future ice sheet mass balance and sea level.

Calving is a two-stage process that requires both the initial ice fracture and the subsequent transport of the detached iceberg away from the calving front (Bassis and Jacobs, 2013). In Antarctica, major calving events can be broadly classified into two categories: the discrete detachment of large tabular icebergs (e.g. Mertz glacier tongue: Massom et al., 2015) or the spatially extensive disintegration of floating glacier tongues or ice shelves into numerous smaller icebergs (e.g. Larsen A & B ice shelves (Rott et al., 1996; Scambos et al., 2009). Observations of decadal-scale changes in glacier terminus position in both the Antarctic Peninsula and East Antarctica have suggested that despite some degree of stochasticity, iceberg calving and glacier advance/retreat is likely driven by external climatic forcing (Cook et al., 2005; Miles et al., 2013). However, despite some well-documented ice shelf collapses (Scambos et al., 2003; Banwell et al., 2013) and major individual calving events (Masson et al., 2015) there is a paucity of data on the nature and timing of calving from glaciers in Antarctica (e.g. compared to Greenland: Moon and Joughin, 2008; Carr et al., 2013), and particularly in East Antarctica.

Following recent work that highlighted the potential vulnerability of the East Antarctic Ice Sheet in Wilkes Land to ocean-climate forcing and marine ice sheet instability (Greenbaum et al., 2015; Aitken et al., 2016; Miles et al., 2016), we analyse the recent calving activity of six outlet glaciers in the Porpoise Bay region using monthly satellite imagery between November 2002 and March 2012. We then turn our attention to investigating the drivers behind the observed calving dynamics, before examining evidence for any longer term changes in calving using sea ice concentrations and satellite imagery from 1963, 1973, 1991, 1997, 2002 and 2016.

2. Study area

Porpoise Bay (-76°S, 128°E) is situated in Wilkes Land, East Antarctica, approximately 300 km east of Moscow University Ice Shelf and 550 km east of Totten glacier (Fig. 1). This area was selected because it occupies a central position in Wilkes Land, which is thought to have experienced mass loss over the past decade (King et al., 2012; Sasgen et al., 2013; McMillan et al., 2014), and which is the only region of East Antarctica where the majority of marine-terminating outlet glaciers are undergoing retreat (Miles et al., 2016). This is particularly concerning because Wilkes Land overlies the Aurora subglacial basin and, due its reverse bed slope and deep troughs (Young et al., 2011), it may have been susceptible to unstable grounding line retreat in the past (Cook et al., 2014), and could make significant contributions to global sea level in the future (DeConto and Pollard, 2016). However, despite some analysis on glacier terminus position on a decadal timescales (Frezzotti and Polizzi, 2002; Miles et al., 2013; 2016), there has yet to be any studies focusing on inter-annual and sub-annual changes in terminus position and calving activity in the region.

Porpoise Bay is 150 km wide and is typically filled with land-fast multi-year sea-ice (Fraser et al., 2012). In total, six glaciers were analysed, with glacier velocities (from Rignot et al., 2011b) ranging from ~440 m yr^{-1} (Sandford Glacier) to ~2000 m yr^{-1} (Frost Glacier) (Table 1). Recent studies have suggested that the largest (by width) glacier feeding into the bay - Holmes Glacier (both the eastern and western branches) - has been thinning over the past decade (Pritchard et al., 2009; McMillan et al., 2014).

3. Methods

3.1 Satellite imagery and terminus position change

Glacier terminus positions were mapped at approximately monthly intervals between November 2002 and March 2012, using Envisat Advanced Synthetic Aperture Radar (ASAR) Wide Swath Mode (WSM) imagery across six glaciers, which were identified from the Rignot et al. (2011b) ice velocity dataset (Fig.1b). Additional sub-monthly imagery between December 2006 and April 2007 were used to gain a higher temporal resolution following the identification of a major calving event around that time. Glacier terminus positions were also mapped on satellite imagery from 1963, 1973, 1990, 1997, 2002, and 2016 (Table 2).

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Approximately 65% of all glacier frontal measurements were made using an automated mapping method that classified glacier tongues and sea-ice into polygons based on their raw pixel value, with the boundary between the two taken as the terminus position. In images where automated classification was unsuccessful, terminus positon was delineated manually. The majority of manual measurements were undertaken in the austral summer (December – February) when automated classification was problematic due to the high variability in backscatter on glacier tongues as a result of surface melt. Following the mapping of the glacier termini, length changes were calculated using the box method (Moon and Joughin, 2008). This method calculates the glacier area change between each time step divided by the width of the glacier, to give an estimation of glacier length change. The width of glacier was obtained by a reference box which approximately delineates the sides of the glacier.

Given the nature of the heavily fractured glacier fronts and the moderate resolution of Envisat ASAR WSM imagery (80 m) it was sometimes difficult to establish if individual or blocks of icebergs were attached to the glacier tongue. As a result, there are relatively large errors in precisely determining terminus change on a monthly time-scale (~± 500 m). However, because our focus is on major calving events, absolute terminus position is less important than the identification of major episodes of calving activity. Indeed, because estimations of terminus position were made at approximately monthly intervals, calving events were easily distinguished because the following month's estimation of terminus positon would clearly show the glacier terminus in a retreated position. In addition, each image was also checked visually to make sure no small calving events were missed (i.e. as indicated by the presence of icebergs proximal to the glacier tongue).

3.2 Sea-ice

The long term record of sea-ice concentrations in Porpoise Bay were calculated using mean monthly Bootstrap sea-ice concentrations derived from the Nimbus-7 satellite and the Defence Meteorological Satellite Program (DMSP) satellites which offers near complete coverage between October 1978 and December 2014 (Comiso, 2014; http://nsidc.org/data/nsidc-0079). To extend the sea-ice record, we also use mean monthly Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR) derived sea-ice concentrations (Parkinson et al., 2004; https://nsidc.org/data/docs/daac/nsidc0009_esmr_seaice.gd.html), which offer coverage between December 1972 and March 1977. However,

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from March to May 1973, August 1973, April 1974 and June to August 1975, mean monthly sea-ice concentrations were not available.

Sea-ice concentrations were extracted from 18 grid cells that extended across Porpoise Bay, but not into the open water that extended beyond the limits of the bay (Fig. 1b). Grid cells which were considered likely to be filled with glacial ice were excluded. Both datasets have a spatial resolution of 25 km and monthly sea-ice concentration anomalies were calculated from the 1972-2014 monthly mean.

Daily sea-ice concentrations derived from the ASI algorithm from Advanced Microwave Scanning Radiometer- EOS (AMSR-E) data (Spreen et al., 2008) were used to calculate daily sea-ice concentration anomalies during the January 2007 sea-ice break-up (http://icdc.zmaw.de/1/daten/cryosphere/seaiceconcentration-asi-amsre.html). This dataset was used because it provides a higher spatial resolution (6.25 km) compared to those available using Bootstrap derived concentrations (25 km). This is important because it provides a more accurate representation of when sea-ice break-up was initiated and, due to its much higher spatial resolution, it provides data from much closer to the glacier termini.

3.3 RACMO

We used the Regional Atmospheric Climate Model (RACMO) V2.3 (van Wessem et al., 2014) to simulate daily surface melt fluxes in the study area between 1979 and 2015 at a 27 km spatial resolution. The melt values were extracted from floating glacier tongues in Porpoise Bay because the model masks out sea-ice. The actual surface melt values are likely to be different on glacial ice, compared to the sea-ice, but the relative magnitude of melt is likely to be similar temporally.

4. Results

4.1 Terminus position change

Analysis of glacier terminus position change of six glaciers in Porpoise Bay between November 2002 and March 2012 reveals three broad patterns of glacier change (Fig. 2). The first pattern is shown by Holmes (West) glacier, which advances a total of ~13 km throughout the observation period, with no evidence of any major iceberg calving that resulted in substantial retreat of the terminus beyond the measurement error (+/- 500 m). The second is shown by Sandford Glacier tongue, which advanced ~1.5 km into the ocean between

November 2002 and April 2006, before its floating tongue broke away in May 2006. A further smaller calving event was observed in January 2009 and, by the end of the study period, its terminus had retreated around 1 km from its position at the start of the measurement period in 2002. The third pattern is shown by Frost Glacier, Glacier 1, Glacier 2 and Holmes (East) glaciers, which all advanced between November 2002 and January 2007, albeit with a small calving event in Frost glacier in May 2006. However, between January and April 2007, Frost Glacier, Glacier 1, Glacier 2 and Holmes (East) glaciers all underwent a large simultaneous calving event. This lead to 1,300 km^2 of ice being removed from glaciers in Porpoise Bay, although we also note the disintegration of a major tongue from an unnamed glacier further west (see velocity data in Fig. 1b), which contributed a further 1,600 km^2. Thus, in a little over three months a total of 2,900 km^2 of ice was removed from glacier tongues in the study area (Fig. 3). Following this calving event, the fronts of these glaciers stabilised and began advancing at a steady rate until the end of the study period (March, 2012) (Fig. 2), with the exception of Frost glacier which underwent a small calving event in April 2010.

4.2 Evolution of the 2007 calving event

A series of eight sub-monthly images between December 11th 2006 and April 8th 2007 show the evolution of the 2007 calving event (Fig. 4). Between December 11th 2006 and January 2nd 2007, the land-fast sea-ice edge retreats past Sandford glacier to the edge of Frost glacier and there is some evidence of sea-ice fracturing in front of the terminus of Glacier 2 (Fig. 4b). From January 2nd to January 9th a small section (~40 km^2) of calved ice broke away from Frost glacier, approximately in line with the retreat edge of land-fast sea-ice (Fig. 4c). By January 25th, significant fracturing in the land-fast sea-ice had developed, and detached icebergs from Frost, Glacier 1, Glacier 2 and Holmes (East) glaciers begin to breakaway (Fig. 4d). This process of rapid sea-ice breakup in the east section of the bay and the disintegration of sections of Frost glacier, Glacier 1, Glacier 2 and Holmes East glaciers continues up to March 10th 2007 (Fig. 4g). In contrast, the west section of Porpoise Bay remains covered in sea-ice in front of Holmes west glacier, which does not calve throughout this event. By April 8th, the calving event had ended with a large number of calved icebergs now occupying the bay (Fig. 4h).

4.3 Link between sea-ice and calving in Porpoise Bay

Analysis of mean monthly sea-ice concentration anomalies in Porpoise Bay between November 2002 and March 2012 (Fig. 5) reveals a major negative sea-ice anomaly occurred between January and June 2007, where monthly sea-ice concentrations were between 35% and

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40% below average. This is the only noticeable (>20%) negative ice anomaly in Porpoise Bay and it coincides with the major calving event described in the previous section (see Fig. 4), and strongly suggesting that the two processes are linked. The series of satellite images showing the evolution of the January to April 2007 calving event clearly shows glacier calving taking place after initial sea-ice breakup e.g. Fig. 4b-e. Furthermore, the smaller calving events of Sandford and Frost glaciers all take place after sea-ice had retreated away from the glacier terminus (Fig. 6). Indeed, throughout the study period, there is no evidence of any calving events taking place with sea-ice proximal to glacier termini. This suggests that glaciers in Porpoise Bay are very unlikely to calve with sea-ice present at their termini.

4.4 Longer-term glacier calving cycles

We now turn our attention to reconstructing calving activity and glacier frontal position change over a longer time-period, with a particular focus on the largest glacier – Holmes (West). Our terminus position change results indicate that glaciers in Porpoise Bay will only calve when sea-ice breaks away from glacier termini. Analysis of long-term sea-ice concentrations in Porpoise Bay from 1972 to 2014 suggests that there have been larger sea-ice break-up events prior to January 2007 (Fig. 7). The two largest break-up events occurred in April 1986 and February 2002, when monthly sea-ice concentrations suggest a near-complete removal of all sea-ice in the Bay, unlike in January 2007, where sea-ice remained in the west section of the bay in front of Holmes (West) Glacier (Fig 4). This suggests that the only time Holmes (West) Glacier's terminus was free of sea-ice during our observational period (from 1972-2014) was in April 1986 and February 2002. Moreover, although there are several other moderate negative monthly mean sea-ice anomalies (~20 to 30%) throughout the sea-ice concentration observational period (Fig. 7), we suggest these cannot have resulted in the Holmes West Glacier terminus being sea-ice free. For its terminus to be clear of sea-ice, the sea-ice in the outer regions of Porpoise bay closest to the open ocean must be removed before the sea-ice close to its terminus. Therefore, it is only the large sea-ice anomalies which can result in the Holmes (West) Glacier terminus being sea-ice free i.e. the removal of all sea-ice in the bay. Thus, it is very likely Holmes (West) Glacier calved in April 1986 and February 2002. Ideally, we would test this by analysing a series of satellite images (e.g. Fig 4). However, because there is no cloud-free satellite imagery available around the time of its proposed calving periods (April 1986 and February 2002), we rely on a comparison between satellite images that are as close as possible to before and after the major sea-ice break-up events.

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By analysing available satellite imagery from October 1997 and August 2002 (see Fig. 8), it is clear that there has been a large calving event at Holmes (West) Glacier at some point between these dates. This is because the August 2002 position is around 15 km behind the October 1997 position (Fig. 8b). As noted above, our observations of sea-ice concentrations (Fig. 7) suggest that the most likely time would be in February 2002, which is the only major negative sea-ice anomaly that might have been large enough to indicate an absence of sea-ice in front of the glacier's terminus. This is further supported by observations of Holmes (West) Glacier calving front in August 2002 (i.e. little crevassing) (Fig. 8b), which is entirely consistent with a calving event having taken place a few months beforehand.

The nearest available satellite imagery either side of the April 1986 sea-ice break-up event is in January 1973 and February 1991 (Fig. 9) and, again, it is clear from the position of the glacier terminus in February 1991 that there has been a calving activity at some point between these dates, which we suggest occurred in April 1986 based on the major negative sea-ice concentration data. Indeed, the terminus position of Holmes (West) Glacier in February 1991 is entirely consistent with a calving event in April 1986, assuming that it calves to a similar position following each calving event e.g. perhaps losing the unconstrained section of its glacier tongue. That is, if the glacier calved in April 1986, as we suggest, we would expect it to have advanced by the time of the next available image in February 1991 (Fig. 9b). Therefore, we suggest that these observations are entirely consistent with two major calving events at Holmes (West) Glacier in April 1986 and February 2002. We now turn our attention to extending this record by analysing imagery from 1963 and 1973.

The 1963 ARGON satellite image shows Holmes (West) Glacier terminus (and indeed most of the glacier termini) very close to the August 2002 position, which we suggest is just a few months after a major calving event in February 2002. Thus, the 1963 image might suggest that Holmes (West) Glacier (and other glaciers) had recently calved prior to 1963 (Fig. 10a). By January 1973, however, Holmes (West) Glacier had advanced around 9 km from its 1963 position (Fig. 10b). Given Holmes (West) Glacier's present-day velocity of ~1,400 m yr^{-1} (Rignot et al., 2011b), an advance of around 14 km would be expected in the ten year period between 1963 and 1973. This means that Holmes (West) Glacier either advanced at a slower rate in the 1960s (~900 m yr^{-1}) or that the glacier calved between 1963 and 1973. Analysis of the 1963 and 1973 images suggests that calving activity is unlikely. This is because individual icebergs can be tracked from the front of Holmes (West) Glacier in 1963 to the edge of the multi-year sea ice pack in 1973 (Fig. 11). This confirms that there has been no sea-ice break-up events and, as such, no major calving events between 1963 and 1973. Furthermore, Sandford Glacier tongue can be seen to advance several kilometres between October 1963 (Fig. 10a) and November 1973 (Fig. 10b). If there had been a sea-ice break-up, this ice tongue would likely calved and been transported away from the terminus. Moreover, in all available satellite imagery after 1973, the largest glacier tongue observed at Sandford glacier is only ~2 km. As Sandford Glacier is the closest glacier to the open ocean in Porpoise Bay, its terminus can be sea-ice free even during relatively small sea-ice break-up events. Therefore, in order to facilitate the growth of a ~10 km glacier tongue between 1963 and 1973 (Fig. 10), it suggests that there must have been high sea-ice concentrations in Porpoise Bay during this period, thus helping to preserve Sandford Glacier tongue. Thus, we suggest that it is highly unlikely that any glaciers calved in Porpoise Bay between 1963 and 1973 because there were no sea-ice break-up events. This implies that the velocity of the Holmes West Glacier between 1963 and 1973 was slower (~900 m yr^{-1}) during that era, and that the glacier velocity has approximately increased by 50% since that time.

Combining the known terminus position with the velocity estimates between 1963 and 1973, and the calving events in April 1986 and February 2002, allows us to reconstruct the long-term calving cycle of Holmes (West) Glacier (Fig. 12). In order to do this we make two assumptions. First, we simply extrapolate velocity linearly in between periods without observations. Secondly, to determine how far the terminus retreated after the calving event in 1986 and the date of calving before 1963, for which we have no imagery, we simply assume it retreats close to the position attained after the February 2002 calving event in August 2002. Our reconstruction suggests that, despite an increase in velocity, Holmes (West) Glacier tends to calve when its terminus reaches an extended position that is around 20 km from its known retreat positions in 1986 and 2002. Furthermore, we note that the very recent terminus position (austral summer 2016) is in a similar position to that which existed immediately prior to the calving events of April 1986 and February 2002, suggesting that a further major calving event is imminent.

4.5 2016 calving event

During the preparation of this manuscript, and consistent with our conclusion from the previous section, observations between March 19th and May 13th 2016, revealed that Frost glacier, Holmes (East) and Holmes (West) glaciers underwent a further disintegration event following the break-up of sea-ice from their glacier tongues (Fig. 13). This process has so far

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resulted in the loss of ~1,500 km^2 of ice from glacier tongues in Porpoise Bay. The calving event is likely incomplete and may continue, potentially also influencing Glacier 1 and 2. We note that the recent calving of Holmes (West) Glacier is entirely consistent with our earlier observations in that: 1) sea-ice must be removed in order for Holmes (West) Glacier and other glaciers in Porpoise Bay to calve (Fig.14); 2) Holmes (West) glacier undergoes a major calving event after reaching a similar position in each calving cycle (e.g. Fig. 12); 3) Holmes (West) glacier retreats to a similar position after each calving event. Furthermore, we can now estimate that the previous three calving cycles of Holmes West glacier have been in ~29 (~1957-1986), 16 (1986-2002) and 14 (2002-2016) year cycles.

5. Discussion

5.1 Climatic drivers of the January 2007 calving event

We report a major, synchronous calving event in January 2007 that resulted in ~2,900 km^2 of ice being removed from glacier tongues in the Porpoise Bay region of East Antarctica. This is comparable to some of the largest disintegration events ever observed in Antarctica e.g. Larsen A, 1995 (4,200 km^2), Larsen B, 2002 (3,250 km^2), and is the largest to have been observed in East Antarctica. However, this event differs to those observed on the ice shelves of the Antarctic Peninsula, in the sense that it is more closely linked to a predictable cycle of glacier advance and retreat (e.g. Fig. 12), as opposed to a catastrophic collapse that may be unprecedented. That said, it is intriguing that there is evidence of this cycle speeding up over the past 50 years, concomitant with an increase in glacier velocity(e.g. Fig. 12)

The disintegration event was driven by the break-up of the multi-year land-fast sea-ice which usually occupies Porpoise Bay. This link between sea-ice and glacier terminus position has been largely confined to studies in Greenland, where sea-ice melange dynamics has been linked to inter-annual variations in glacier terminus position (Amundson et al., 2010; Carr et al., 2013; Todd and Christoffersen, 2014; Cassotto et al., 2015). However, this is the first time sea-ice has been linked to large scale disintegration of glacier tongues in East Antarctica.

It is likely that multiple climatic processes operating over different timescales contributed to the January 2007 sea-ice break-up event. This is because the majority of sea-ice in Porpoise Bay is multi-year sea-ice (Fraser et al., 2012). Although there are no long-term observations of multi-year sea-ice thickness in Porpoise Bay, observations and models of the annual cycle of multi-year sea-ice in other regions of East Antarctica suggests that multi-year sea-ice thickens seasonally and thins each year (Lei et al., 2010; Sugimoto et al., 2016; Yang et al., 2016).

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Therefore, the relative strength, stability and thickness of multi-year sea ice at a given time period is driven not only by climatic conditions in the short term (days/weeks), but also by climatic conditions in the preceding years.

As the sea-ice break-up occurred during the peak of austral summer in January 2007, it is plausible that air temperature played an important role in initiating the sea-ice break-up. Analysis of RACMO2.3 mean monthly melt values in Porpoise Bay show that although January 2007 was above the average, it was not exceptional, lying within one standard deviation of the long term mean (1979-2015). However, analysing daily melt values throughout January 2007 suggests that there was an exceptional melt event centred on the 11th January (Fig. 15). This melt is the 11th highest day on record (1979-2015) and the 4th highest since 2000. Analysis of daily sea-ice concentrations in Porpoise Bay show an immediate drop after this melt peak (Fig. 15), suggesting the exceptional melt peak of the 11th January may have been important in initiating sea-ice break-up. As a consequence of a melt peak of this magnitude, the growth of sea-ice surface ponding would be expected. There is no cloud-free optical satellite imagery available for January 2007 to confirm this prediction. However, Landsat imagery from the 21st January 2014, which occurs shortly after a melt event of a similar magnitude, clearly demonstrates that substantial sea-ice melt ponding is possible near the coast in Porpoise Bay (Fig. 16). Indeed, this is the first time that sea-ice ponding to this extent has been observed in coastal East Antarctica. In the Arctic, sea-ice melt ponding along pre-existing weaknesses has been widely reported to precede sea-ice break-up (Ehn et al., 2011; Petrich et al., 2012; Landy et al., 2014; Schroder et al., 2014; Arntsen et al., 2015). However, because there have been similar magnitude melt events to that of mid-January 2007 which have not resulted in the break-up of sea-ice in Porpoise Bay, we suggest that whilst it may have driven the initial sea-ice break-up, it was probably dependent on other preceding factors.

In the austral summer melt season (2005/06) that preceded the break-up event in January 2007, there was an anomalously high mean melt in December 2005 (Fig. 17). Indeed, December 2005 ranks as the second warmest month on record (1979-2015) in Porpoise Bay. To place this month into perspective, we note that it would rank above the average melt value of all Decembers and Januarys since 2000 on the remnants of Larsen B ice shelf. High resolution optical satellite imagery reveal extensive sea-ice melt ponding and fracturing following this melt event in January 2006 (Fig. 18), and it is plausible that this exceptionally warm month may have weakened the multi-year sea-ice in Porpoise Bay and primed it for break-up the following year. Indeed, by the end of the 2005/06 melt season, the sea-ice pack in Porpoise Bay had retreated to the edge of Frost Glacier (e.g. Fig 6), suggesting that the sea-ice may have come close to complete break-up. Therefore, we hypothesise that the January 2007 sea-ice break-up event was driven by a combination of an exceptionally warm 2005/06 austral summer, which caused weakening of multi-year sea-ice, but with break-up initiated the following melt season after the January 11th melt event.

5.2 Calving cycle and increase in velocity of Holmes West Glacier

Our reconstruction of the calving cycle of Holmes (West) Glacier (Fig. 12) indicates that the glacier undergoes a major calving event when it reaches roughly the same position in each cycle. This suggests that calving is likely to be influenced by the bathymetry and topography of Porpoise Bay. However, sea-ice must still be removed in order for Holmes (West) Glacier to calve, suggesting a complex interaction between the stability of Holmes (West) Glacier's floating tongue, bathymetry, topography and sea-ice. In both Greenland (McFadden et al., 2011; Carr et al., 2013; Carr et al., 2015) and Antarctica (Wang et al., 2016), underlying bathymetry is thought to be crucial in determining the calving of floating glacier tongues. However, our results suggest that the bathymetry and topography of Porpoise Bay may only be a secondary control to the calving of Holmes (West) Glacier. This is because sea-ice must be removed from its terminus before calving. Indeed, we note that complete removal of sea-ice from Porpoise Bay only occurs when Holmes (West) Glacier is at an advanced position. If the break-up of sea-ice was solely driven by climate, complete break-ups would be expected under strong climatic warming events, irrespective of the position of Holmes (West) Glacier. Therefore, we speculate sea-ice break-ups must be at least in part influenced by the position of Holmes (West) Glacier tongue itself. That is, as Holmes (West) Glacier advances it slowly pushes multi-year sea-ice further out into the open ocean to the point where the multi-year sea-ice pack may become unstable. This could be influenced by local bathymetry and ocean circulation, but no observations are available. However, we note that once the glacier forces the sea-ice into a more unstable region, it still requires a strong climatic warming event to initiate the sea-ice break-up (see section 5.1) and subsequent glacier calving.

Despite Holmes (West) Glacier consistently calving in approximately the same position, the time taken for the glacier to calve in each cycle has decreased, demonstrating an increase in glacier velocity. Indeed, our estimates suggest that the present day-velocity of Holmes (West) Glacier is approximately 50% faster than its average 1963-1973 velocity. This is significant

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because, based on the flux gate calculations of Rignot et al. (2013), Holmes (West) Glacier is now exporting approximately 8 GT yr^{-1} more into the ocean than it was between 1963 and 1973. This also provides the first evidence of a long term increase in velocity of an outlet glacier in East Antarctica. A potential mechanism which could explain this increase in velocity is changes to the stability and strength of the sea-ice in Porpoise Bay reducing glacier buttressing. Alternatively, dynamic changes associated with incursions of warm subsurface ocean water and associated thinning could have driven the increase in velocity e.g. Pine Island Glacier (Rignot, 2008; Jacobs et al., 2011). However, with sea-ice concertation data only available after 1972, and with only limited atmospheric data, and no oceanic or sea-ice thickness data, it is impossible to be more conclusive.

6. Conclusion

Glacier terminus position changes are analysed at approximately monthly intervals between November 2002 and March 2012 for six glaciers in Porpoise Bay, Wilkes Land, East Antarctica. We identify a large simultaneous calving event in January 2007 which was driven by the break-up of the multi-year landfast sea-ice which usually occupies the bay. This provides a previously unreported mechanism for the rapid disintegration of floating glacier tongues in East Antarctica. Throughout the observational period, major calving activity only takes place following the near-complete removal of sea-ice from glacier termini. This is an important discovery because sea-ice and land-fast sea-ice are widely considered to be highly sensitive to changes in climate (Heil, 2006; Mahoney et al., 2007). Therefore, if the sea-ice which usually occupies Porpoise Bay became weaker or less permanent in a warmer climate, there could be an associated dynamic response of glaciers following the decrease in buttressing.

Reconstructions of the calving cycle of Holmes (West) Glacier show that its present day velocities are approximately 50% faster than between 1963 and 1973, making it the only glacier in East Antarctica known to exhibit a recent increase in velocity. As the interaction between sea-ice and floating glacier tongues is currently poorly represented in models, we suggest that this may provide another mechanism capable of explaining some of the rapid mass loss which may have happened in the past, and may be an important process in the context of future warming. We conclude by highlighting the importance of regular monitoring of glaciers in Porpoise Bay following the 2016 calving event, and in particular, the re-formation of the landfast ice following its break-up.

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Table 1: Glacier velocities from Rignot et al. (2011b)

Glacier	**Velocity (m yr^{-1})**
Sandford	440
Frost	2000
Glacier 1	950
Glacier 2	500
Holmes (East)	600
Holmes (West)	1450

Table 2: Satellite imagery used in the study

Satellite	**Date of Imagery**	**Spatial resolution (m)**
ARGON	October 1963 (Kim et al., 2007)	140
Envisat ASAR WSM	August 2002, November 2002 to March 2012 (monthly)	80
Landsat (MSS)	January 1973	60
Landsat (TM)	February 1991	30
MODIS	March 2016	250
RADARSAT	September 1997 (Liu and Jezek, 2004)	100
Sentinel-1	February-May, 2016	40

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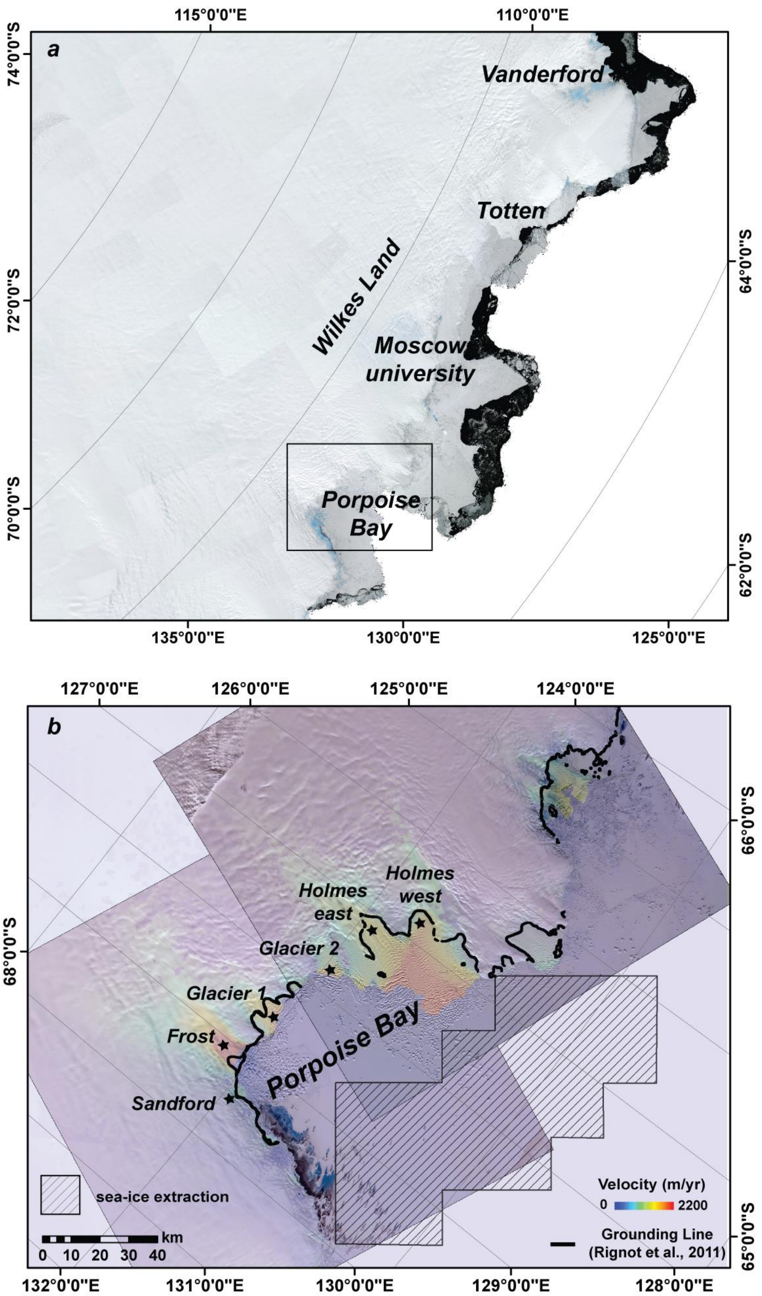

Figure 1: a) MODIS image of Wilkes Land, East Antarctica **b)** Landsat images of Porpoise Bay with glacier velocity (Rignot et al., 2011b) and grounding lines (Rignot et al., 2011a) overlain. The hatched polygon represents the region where sea-ice concentrations were extracted.

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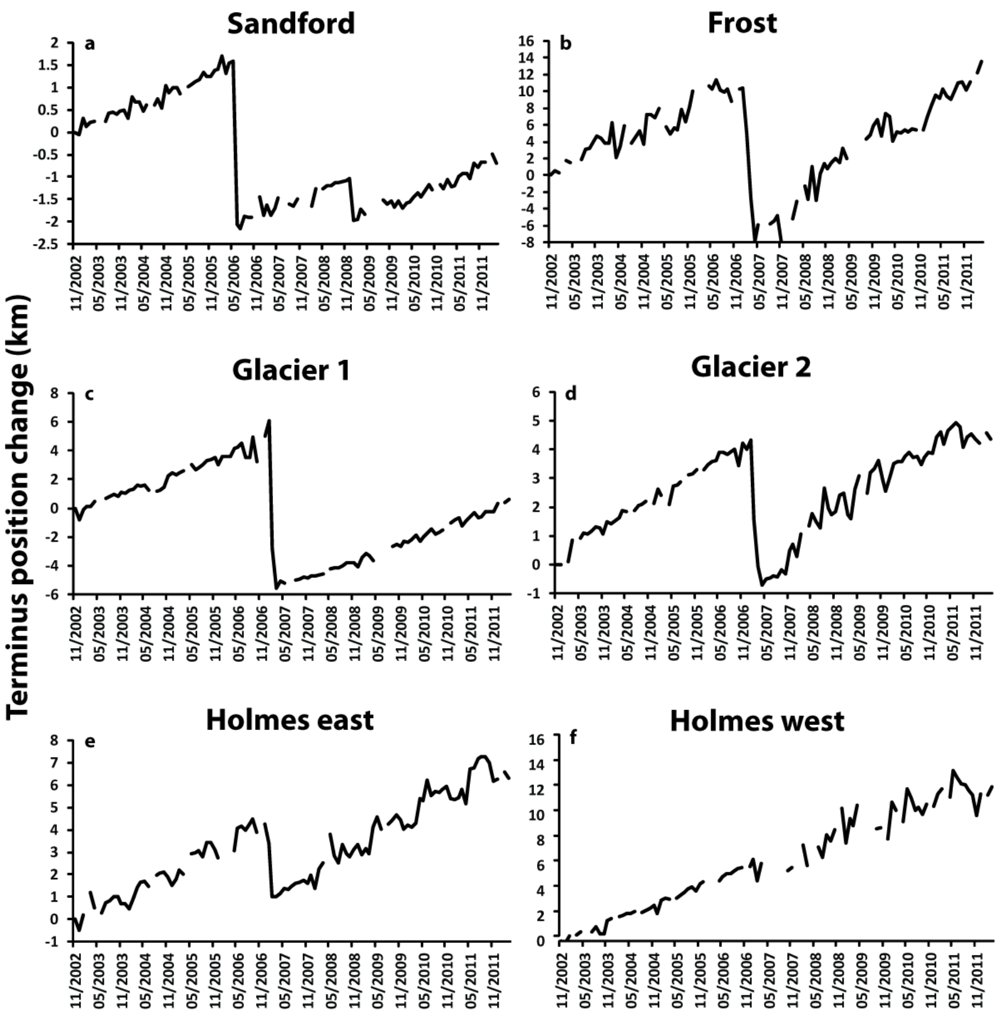

Figure 2: Terminus position change of six glaciers in porpoise Bay between November 2002 and March 2012. Note the major calving event in January 2007 for 5 of the glaciers. Terminus position measurements are subject to +/- 500 m.

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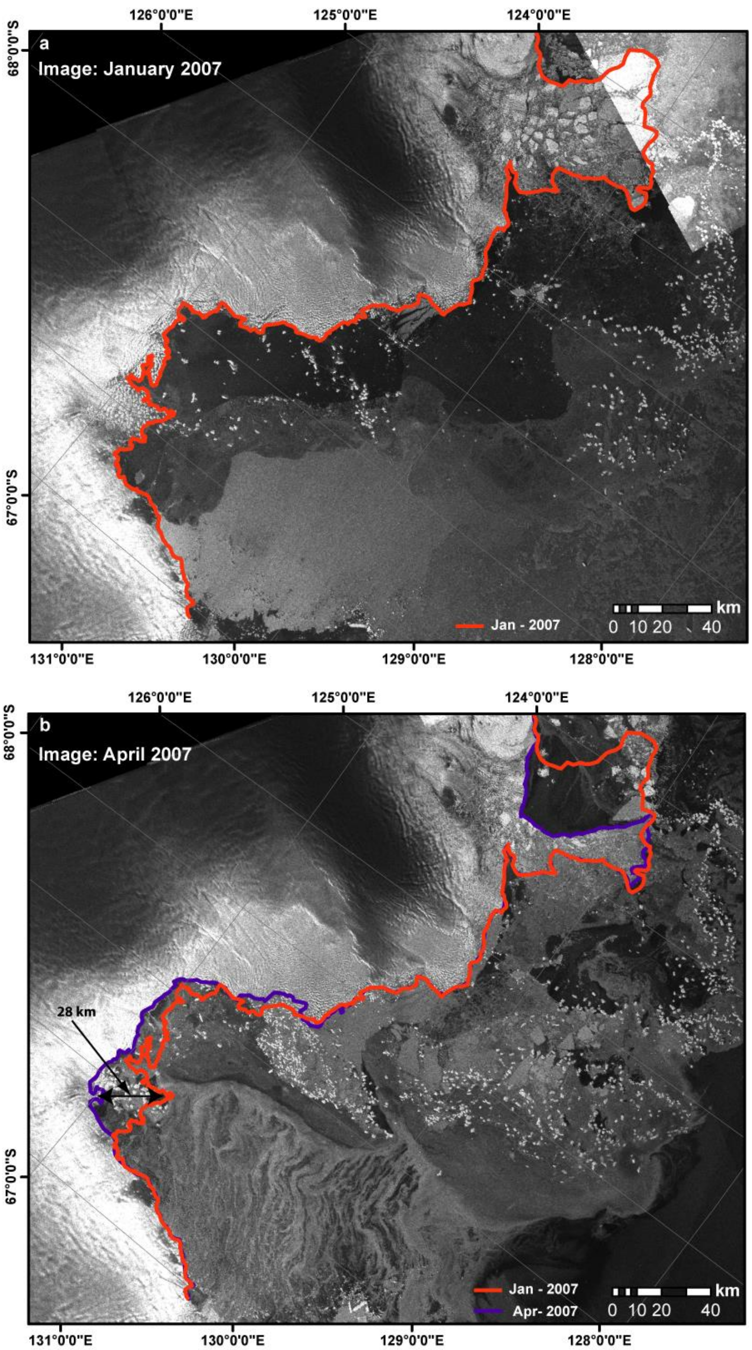

Figure 3: Envisat ASAR WSM imagery in January 2007 **a)** and April 2007 **b)**, which are immediately prior to and after a simultaneous calving event in Porpoise Bay. Red line shows terminus positions in January 2007 and blue line shows the positions in April 2007.

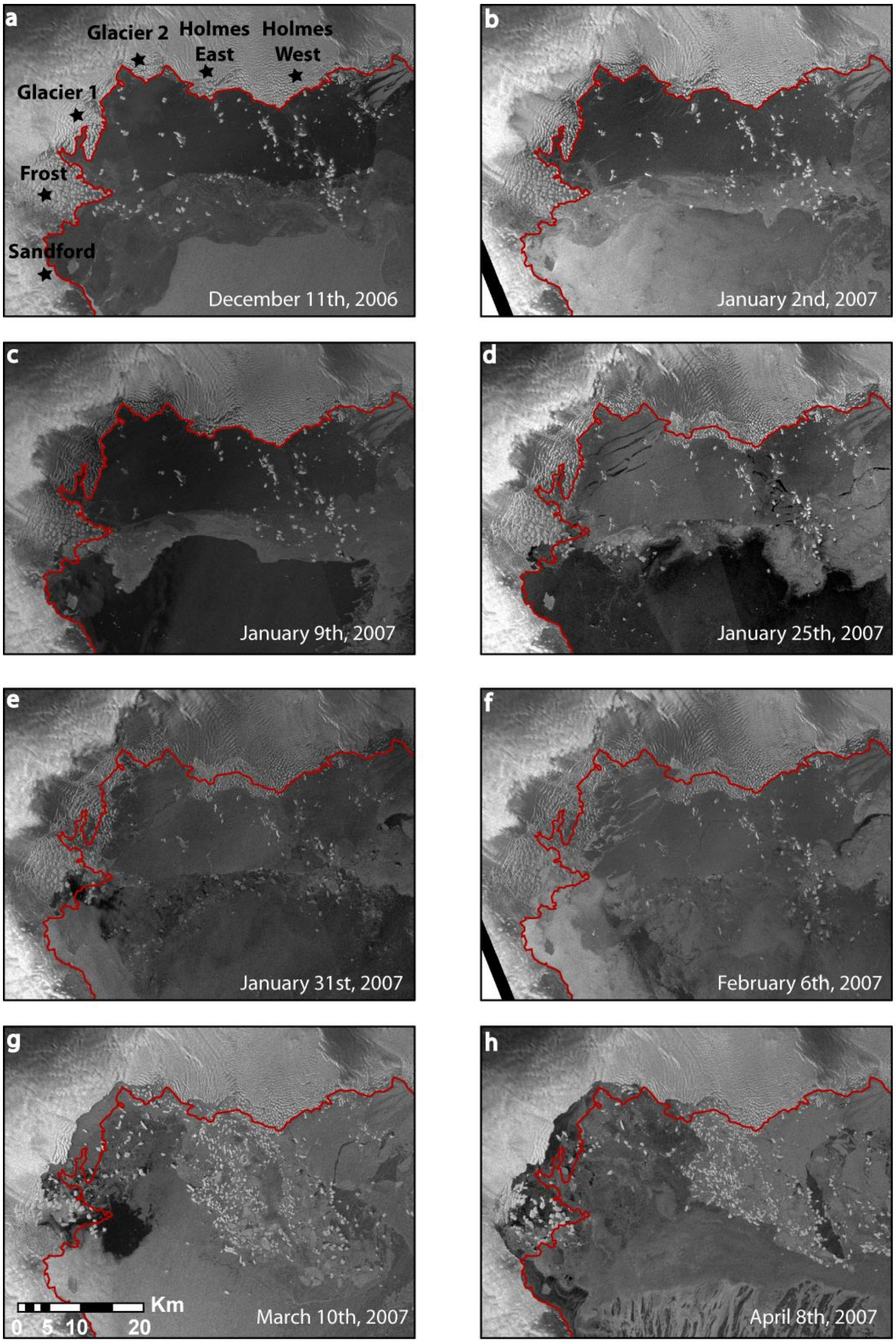

Figure 4: Envisat ASAR WSM imagery showing the evolution of the 2007 calving event. Red line shows the terminus positions from December 11th 2006 on all panels.

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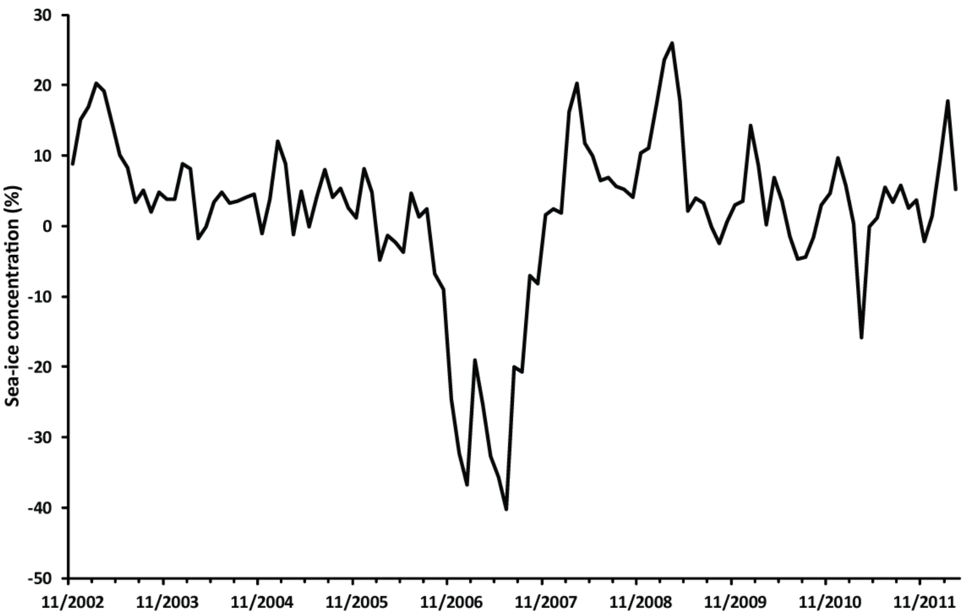

Figure 5: Mean monthly sea-ice concentration anomalies in Porpoise Bay.

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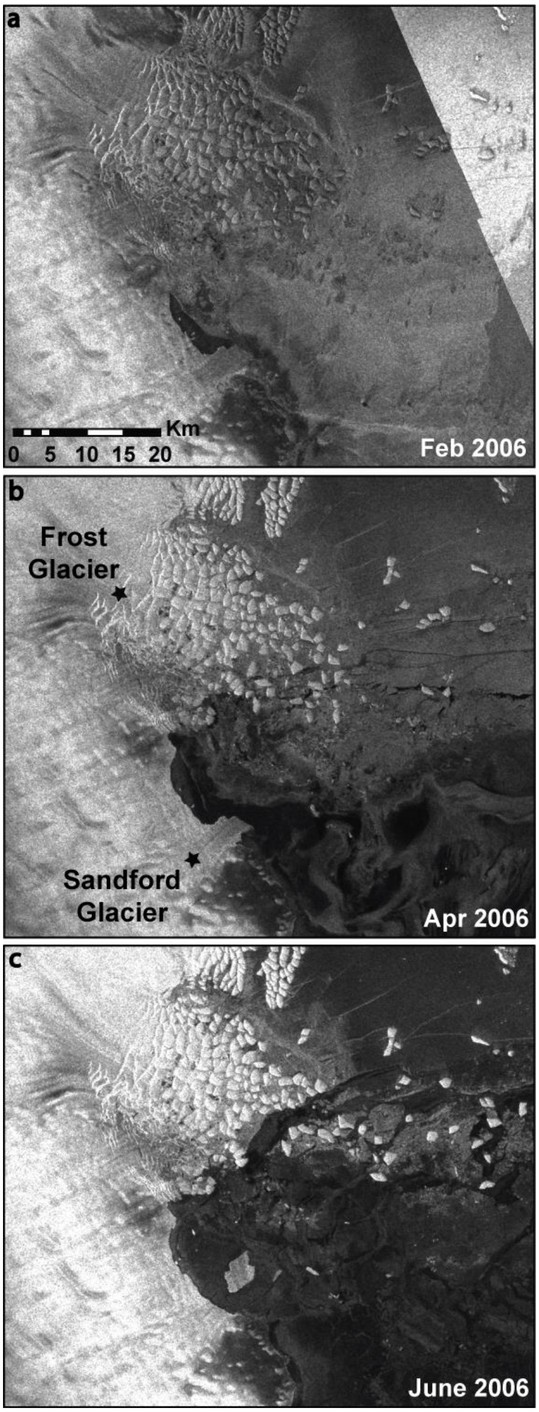

Figure 6: Time series of Frost and Sanford Glaciers calving showing that sea-ice clears prior to calving and dispersal of icebergs.

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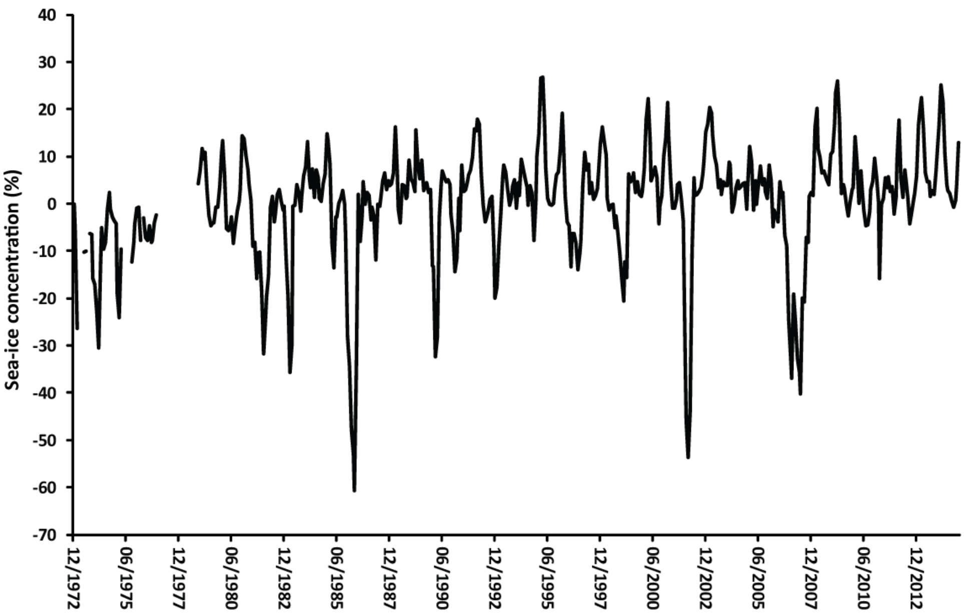

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630 **Figure 7:** Mean monthly sea-ice concentration anomalies 1972-2014. Note major anomalies
631 in April 1986, February 2002 and January 2007.

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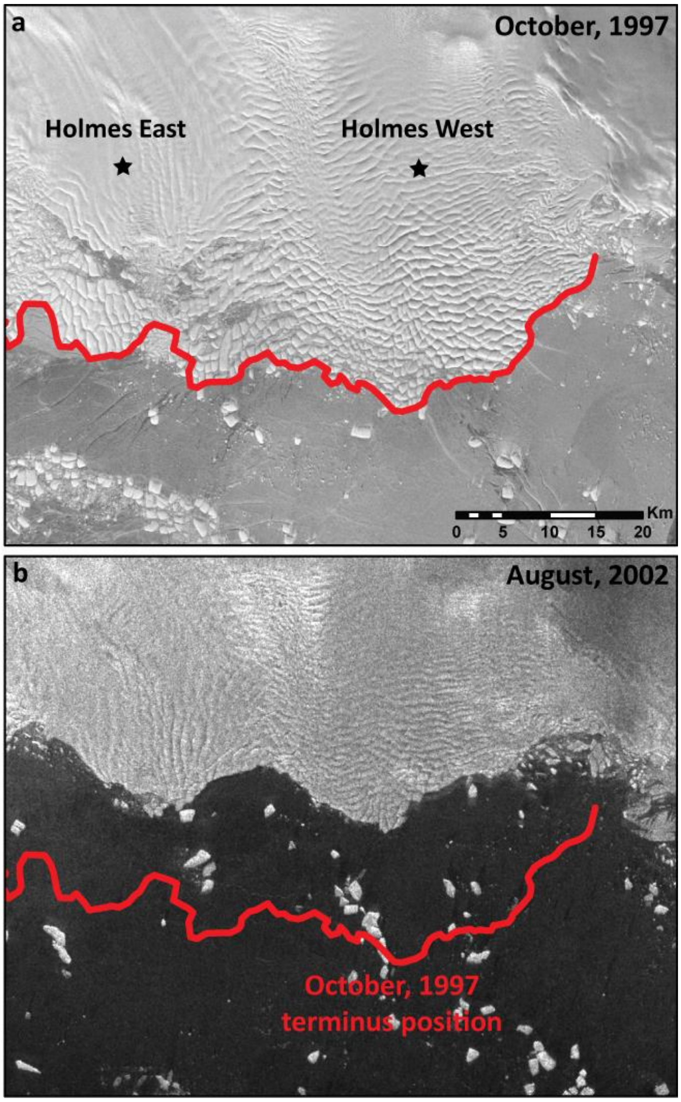

Figure 8: Comparison of terminus positon between **a)** October 1997 (red line) and **b)** August 2002, which indicates major calving event(s) at some point between these two dates.

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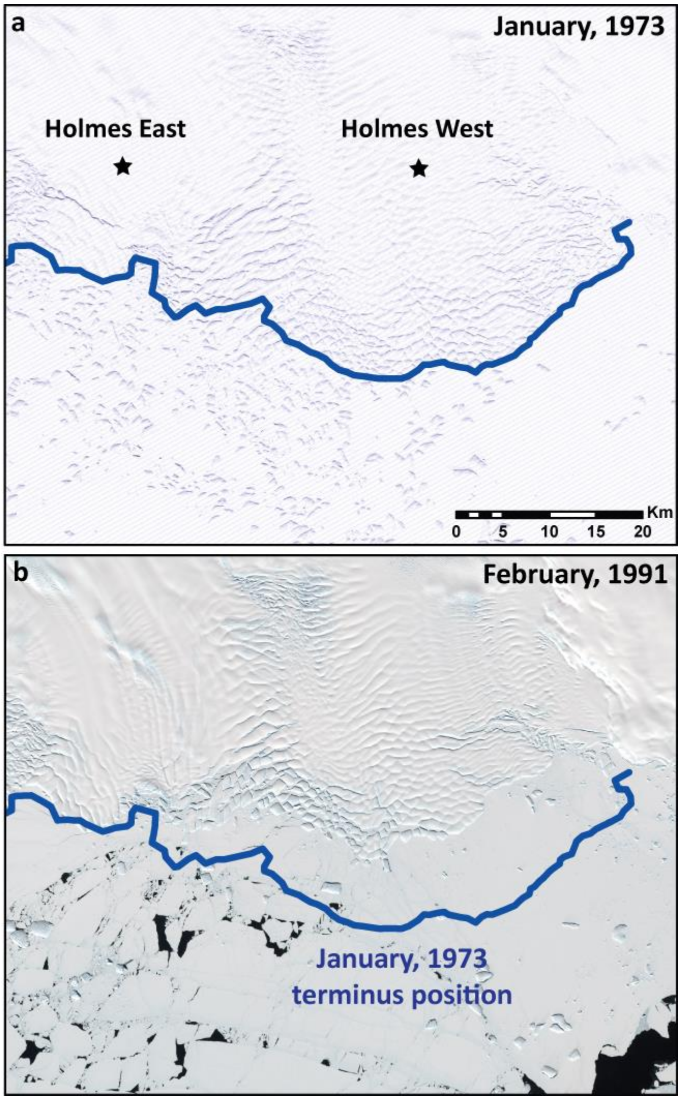

Figure 9: Comparison of terminus position change between January 1973 (blue line) and February 1991, which indicates a calving event at some point between these two dates.

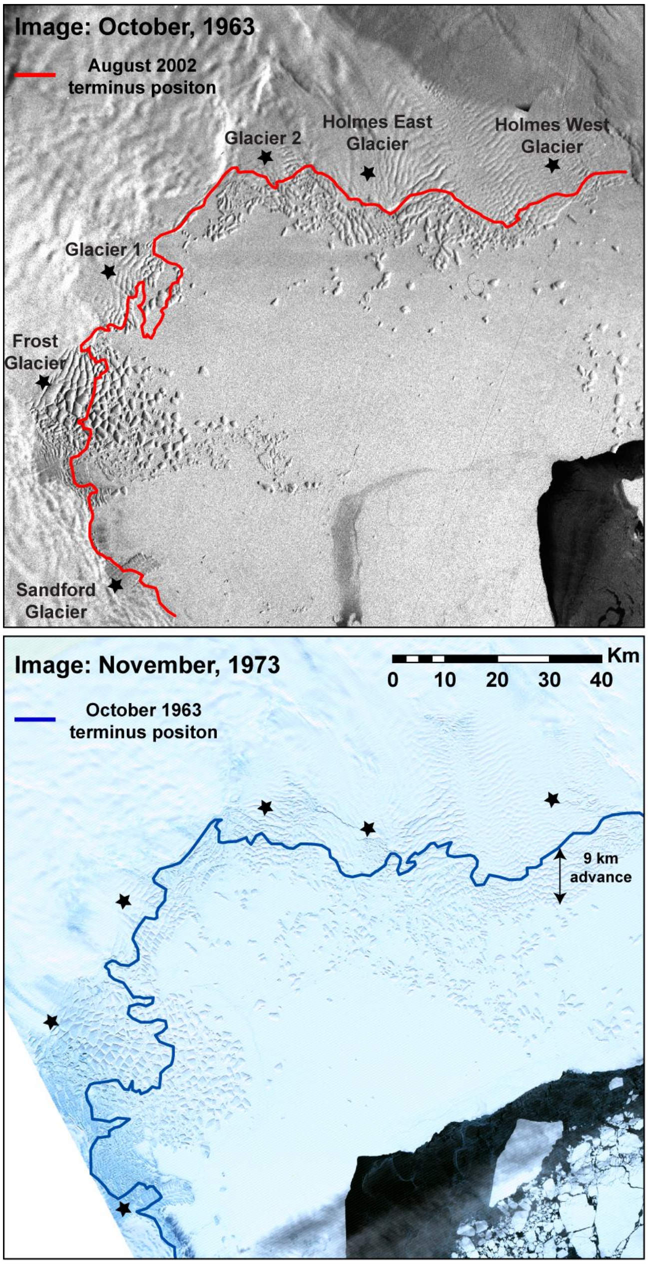

Figure 10: a) October 1963 terminus position. The red line shows the August 2002 terminus positon, which occurred a few months after a major calving event. Because Holmes (West) glacier (and other glaciers) is in a similar position, it suggests that there has been a calving event within a few years prior to this image i.e. late 1950s/early 1960s. **b)** November 1973 terminus positon in relation to 1963 (blue). The relative position of glacier in Porpoise Bay in 1973 suggests that there were no calving events between these dates.

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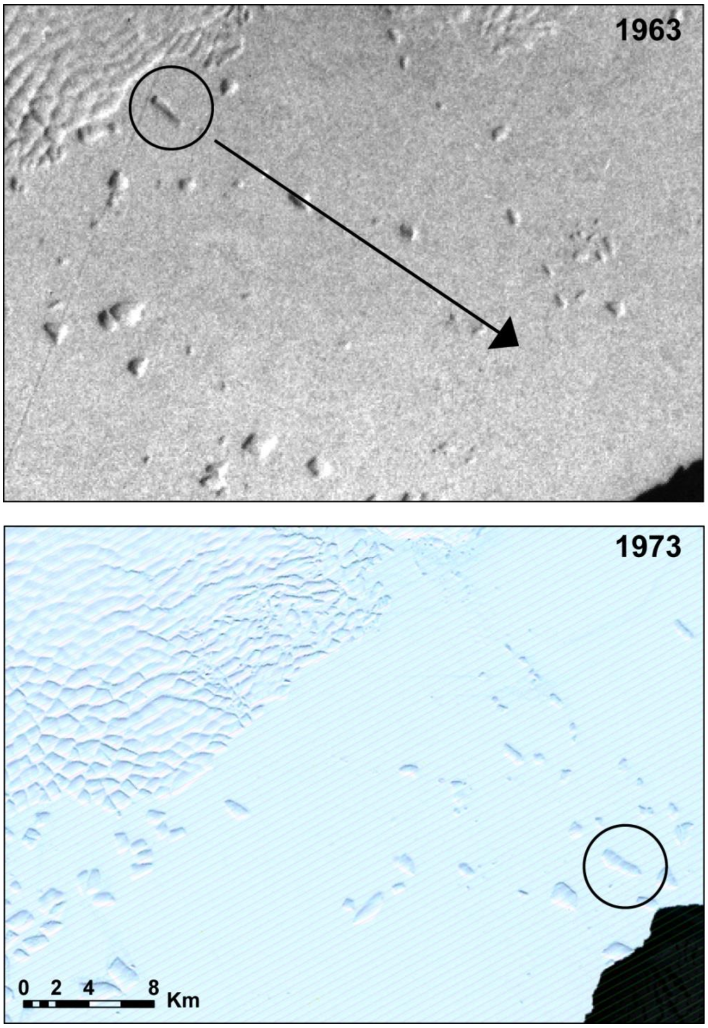

Figure 11: Iceberg tracking in front of Holmes (West) Glacier. The same iceberg can be seen in both 1963 and 1973 suggesting there has not been a sea-ice break-up event during this period (see also Figure 10 and the floating tongue on Sandford Glacier)

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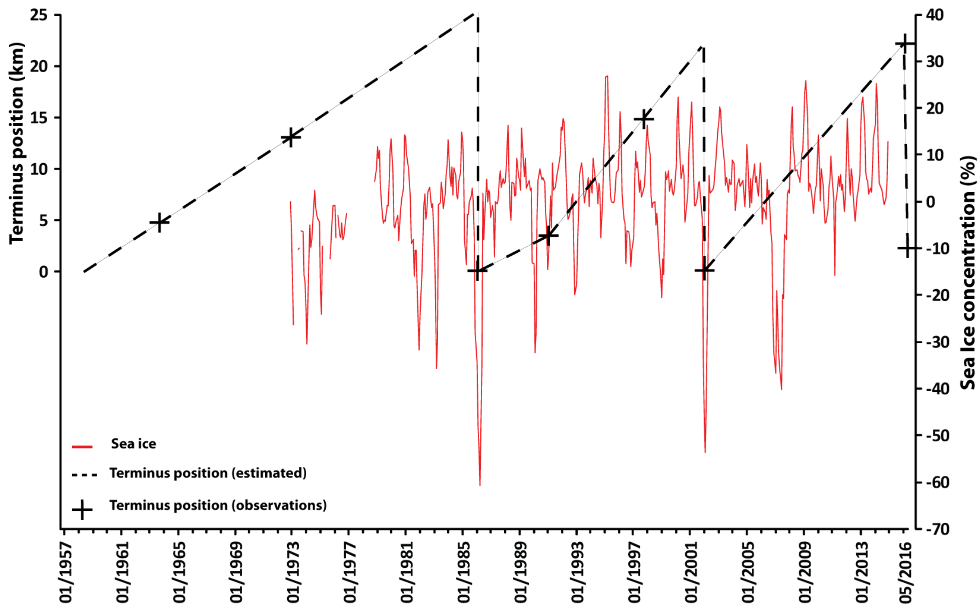

Figure 12: Reconstruction of the calving cycle of Holmes (West) Glacier. All observations are represented by black crosses. The estimated terminus positon is then extrapolated linearly between each observation, with major calving inferred to coincide with major negative sea-ice concentration anomalies in 1986, 2002 and 2016. This suggests the previous three calving cycles to be ~29 years (~1957-1986), 16 years (1986-2002) and 14 years (2002-2016).

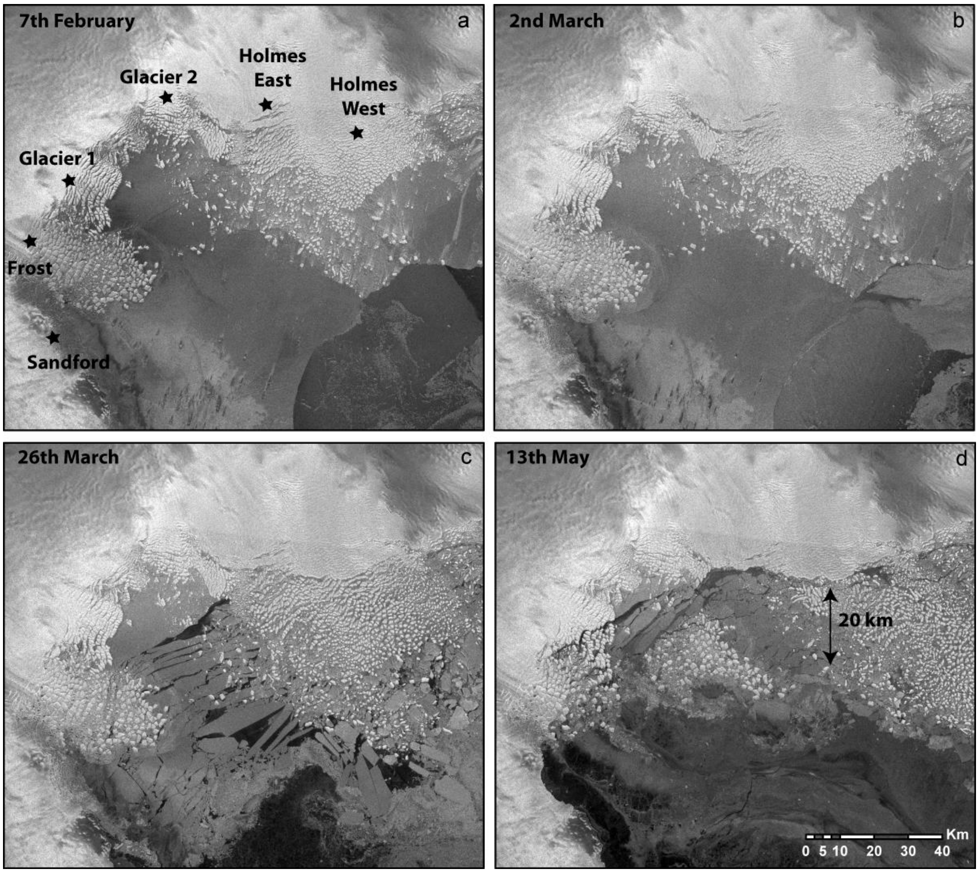

Figure 13: Time series of the (likely ongoing) evolution of the 2016 calving event in Porpoise Bay using Sentinel-1 satellite imagery. The disintegration event starts at some point between 2nd March and 26th March. By the 13th May Holmes (West) Glacier has retreated approximately 20 km and ~1,500 km^2 of ice had been lost from glacier tongues in Porpoise Bay.

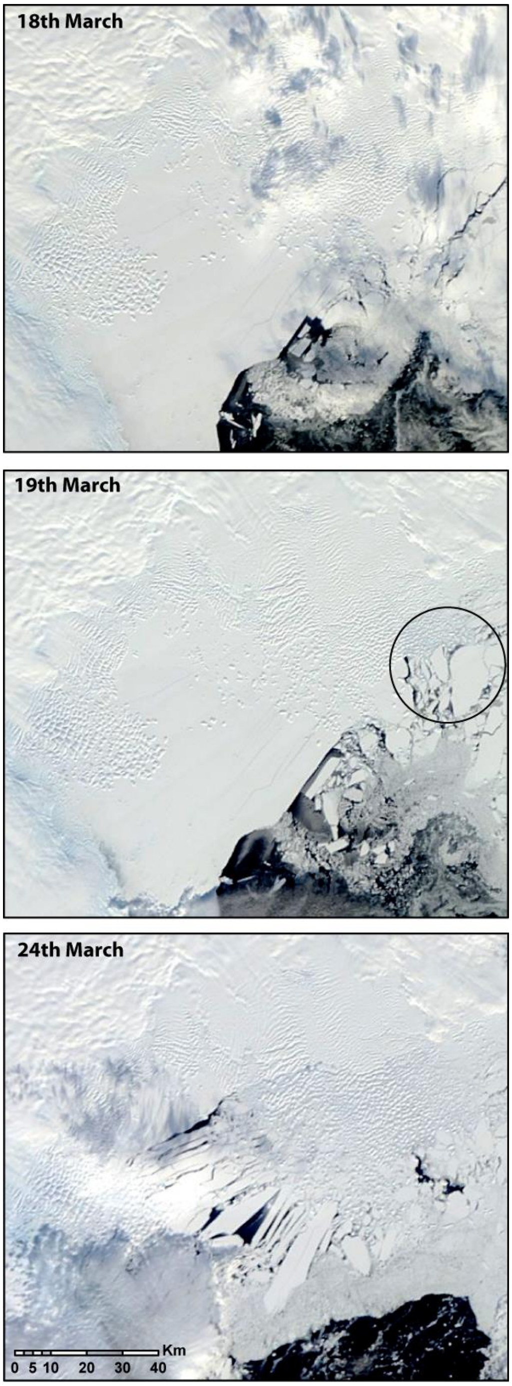

Figure 14: MODIS imagery showing the initial stages of disintegration of Holmes (West) Glacier in March 2016. On March 19th a large section of sea-ice breaks away from the terminus, initiating the rapid disintegration process.

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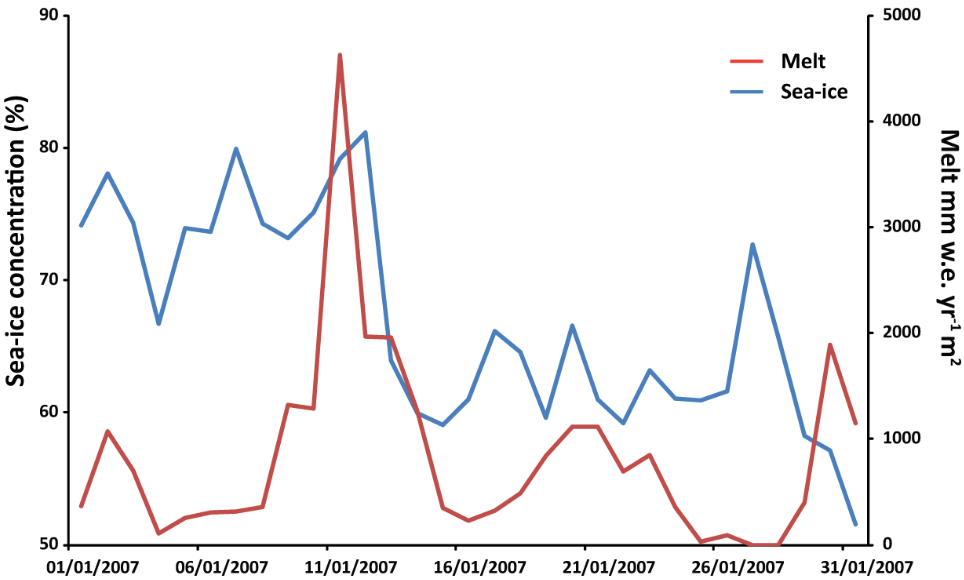

Figure 15: Daily sea-ice concentrations and RACMO2.3 derived melt during January 2007 in Porpoise Bay. Sea-ice concentrations start to decrease after the melt peak on January 11th.

The Cryosphere Discuss., doi:10.5194/tc-2016-151, 2016
Manuscript under review for journal The Cryosphere
Published: 14 June 2016

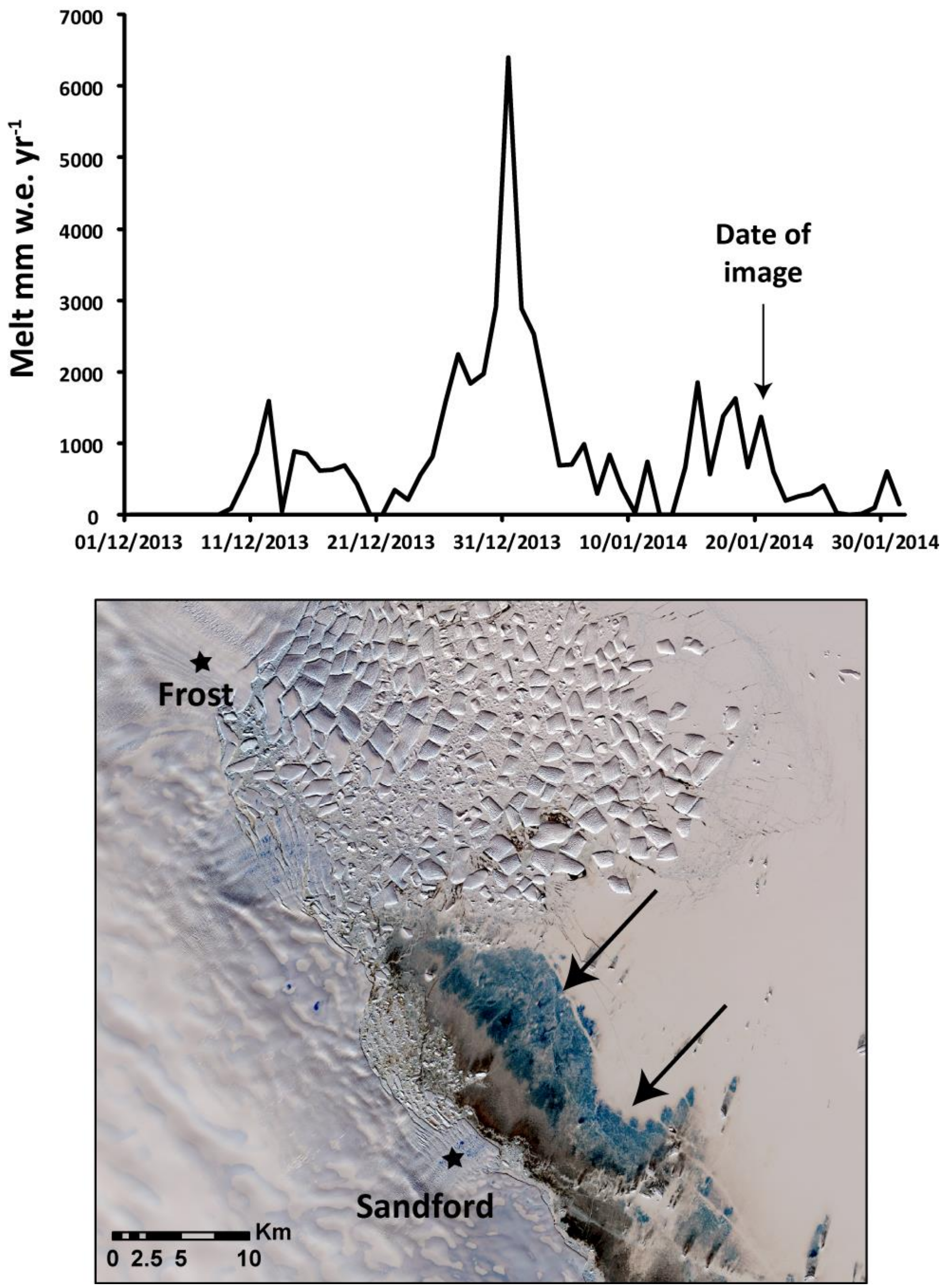

Figure 16: Evidence of substantial sea-ice surface ponding on the 21st January 2014 (arrows) following the exceptional melt event centred on the 31st December.

The Cryosphere Discuss., doi:10.5194/tc-2016-151, 2016
Manuscript under review for journal The Cryosphere
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689 **Figure 17:** Mean RACMO2.3 December melt 1979-2015 in Porpoise Bay.

The Cryosphere Discuss., doi:10.5194/tc-2016-151, 2016
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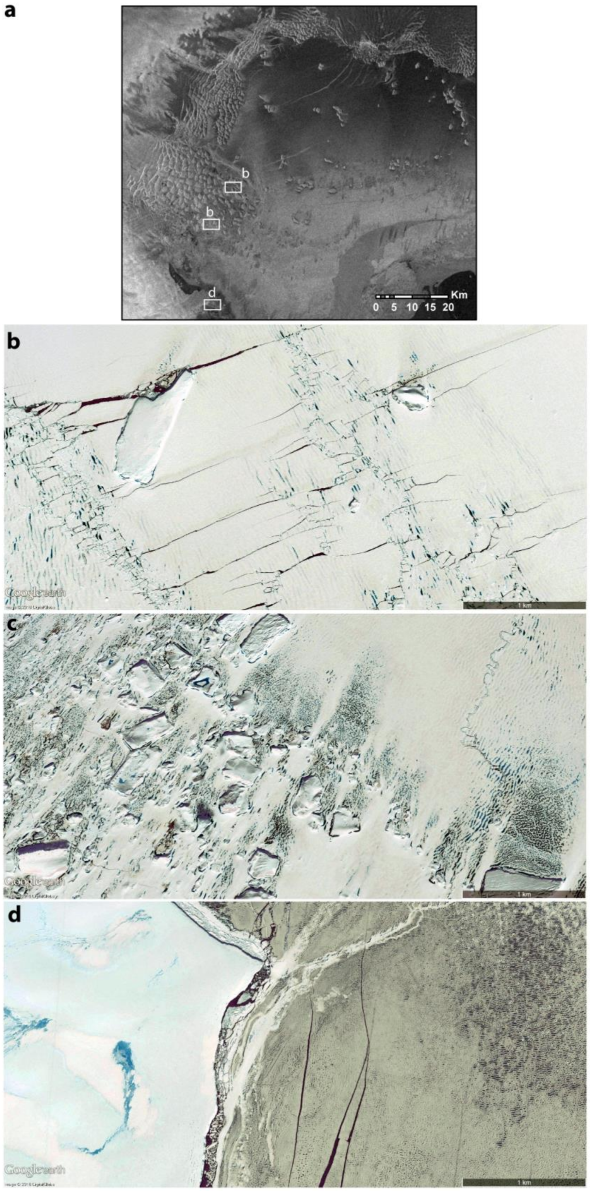

Figure 18: a) Envisat ASAR WSM image from January 2006. **b, c, d)** High resolution optical satellite imagery from 16/1/2006 showing sea-ice fracturing and surface melt ponds following the exceptionally high melt in December 2005, which were obtained from Google Earth.