Intermittent structural weakening and acceleration of the Thwaites Glacier Tongue between 2000 and 2018.

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Abstract Evolving conditions at the terminus of Thwaites Glacier will be important in determining the rate of its future sea-level contribution over the coming decades. Here, we use remote sensing observations to investigate recent changes (2000-2018) in the structure and velocity of Thwaites Glacier and its floating tongue. We show that the main trunk of Thwaites Glacier has accelerated by 38% over this period, whilst its previously intact floating tongue has transitioned to a weaker mélange of fractured icebergs bounded by sea-ice. However, the rate of structural weakening and acceleration were not uniform across the observational period and we identify two periods of rapid acceleration and structural weakening (2006-2012; 2016-2018), separated by a period of deceleration and re-advance of the structurally-intact shear margin boundary (2012-2015). The timing of these accelerations/decelerations strongly suggest a link to variable ocean forcing. The weakened tongue now has some dependency on landfast sea ice for structural integrity and is vulnerable to changes in landfast ice persistency. Future reductions in landfast sea-ice could manifest from changes in climate and/or the imminent removal of the B-22A iceberg from the Thwaites embayment. Such changes could have important implications for the integrity of the ice tongue and future glacier discharge.

1. Introduction

Observations have shown that the Amundsen Sea Sector of the West Antarctic Ice Sheet (WAIS) is currently losing mass at a greater rate than anywhere else in Antarctica (Shepherd and others, 2018; Rignot and others, 2019). Ice shelves in the region have been rapidly thinning (Paolo and others, 2015) and ice discharge has increased 77% between 1973 and 2014 (Mouginot and others, 2014), resulting in inland thinning and grounding line retreat (McMillan and others, 2014; Konrad and others, 2018; Milillo and others, 2019). These changes are thought to be in response to periodic intrusions of warm Circumpolar Deep Water that increase basal melt rates beneath ice shelves and ice tongue (Thoma and others, 2008; Jenkins and others, 2010; 2018).

Whilst the present day mass loss of the Amundsen Sea Sector is of significant concern, there is a potential for a much higher rate of mass loss in the near-future (Golledge and others, 2015; DeConto and Pollard, 2016). Of particular concern is the Thwaites Glacier Catchment, which holds enough ice to raise global mean sea level by 59 cm (Holt and others, 2006) and, together with adjacent catchments, the West Antarctic Ice Sheet holds enough ice to raise global mean sea level by more than 3 m (Scambos and others, 2017). As most of the ice in the Thwaites catchment is grounded on bedrock that lies below sea level and that deepens inland (Fretwell and others, 2013), there is potential for marine ice sheet instability to accelerate mass loss beyond that which might be expected from external forcing alone (Mercer, 1978; Schoof, 2007), unless ice shelves provide a sufficent amount of butressing (e.g. Gudmundsson and others, 2012; Gudmundsson, 2013; Gudmundsson and others, 2019). Indeed, some numerical models (Joughin and others, 2014; Seroussi and others, 2017) and observations (Rignot and others 2014) have raised the possibility that the early-onset of this irreversible process may already be underway in the Thwaites Basin. If floating ice shelves are lost at some point during this process, resulting in the formation of unstable ice cliffs, there is potential for much higher rates of mass loss (DeConto and Pollard, 2016). However, at present, there are very few observations to constrain this process and it may not be required to explain past changes in sea level from Antarctic ice loss (Edwards and others, 2019).

Given the above, it is clear that the evolving conditions at the ice front of Thwaites Glacier are likely to be an important control on the rates and timing of future sea level contributions (e.g. Scambos and others, 2017). In this paper, we use satellite imagery to investigate the changes in structure of the Thwaites Glacier Tongue over the past 18 years (2000 to 2018). We analyse how the observed changes in structure relate to changes in both its calving pattern and its velocity, and then discuss the observed changes in relation to the near-future evolution of Thwaites Glacier.

2. Data and Methods

2.1 Ice-front positions 2000-2018: MODIS

We measured annual changes in the ice-front position and velocity of Thwaites Glacier, extending the observations from MacGregor and others (2012), which spanned the period 1972 to 2011. We digitized ice-front positions using MODIS imagery, obtained from the NASA WorldView application, and acquired every March from 2000 to 2018 (Dataset S1). In some cases, the heavily fractured nature of the Thwaites Glacier Tongue made mapping the ice front difficult. For consistency, we took the same approach for each image and always mapped the outer edge of connected ice blocks at each time step (Fig. S1). Changes in ice-front position were quantified using the box method, which takes into account uneven changes along the ice front (Moon and Joughin, 2008; Miles and others, 2016).

2.2. Annual velocity fields (2000-2017)

Velocity fields from 2000 and 2002 were obtained from Mouginot and others (2014). These datasets were processed using Radarsat-1 data from the austral winter and are available at a spatial resolution of 450 m, with errors of ± 5 m yr^{-1} (Mouginot and others, 2014). Annual velocity fields between 2005-2006 and 2016-2017 were obtained from the MEaSUREs dataset (Mouginot and others, 2017). These products are derived from the stacking of multiple velocity fields derived from a variety of sensors between July and June in the following year, and are available at 1 km spatial resolution. Errors in these products are estimated by a combination of the standard deviation and count of scenes and vary from year to year (Mouginot and others, 2017). For simplicity we assume the error to be the largest error estimate (±32 m yr^{-1}) for all years.

2.3 Sub-annual velocity fields (2013-2018): Landsat-8 and Sentinel-1

In addition to the annual velocity datasets described above, we also used Landsat-8 and Sentinel-1 satellites for ice velocity measurements at a higher temporal resolution (16 days and 6/12 days, respectively). We used the pre-computed raw Landsat-8-derived velocity fields available from the GoLive dataset (Fahnestock and others, 2016), that are available at a 600 m spatial resolution from November 2013 onwards. To maximise temporal coverage, we used all six Landsat-8 scenes which cover Thwaites Glacier and include all velocity fields generated from image pairs separated by 16, 32 and 48 days (Dataset S1). The raw velocity fields were post-processed to improve their overall quality. This was done by removing pixels that had the following properties: (i) peak correlation values below a threshold of the normalized cross-correlation algorithm from the GoLive workflow of less than 0.3; or (ii) values outside the range of ±50% of the MEaSUREs velocity product. Once these pixels were removed, the final velocity product was computed by applying a 3x3 low pass filter.

For Sentinel-1 data we used an automated workflow from the European Space Agency Sentinel Application Platform (SNAP) to compute velocity fields. We first download Interferometric Wide Swath (IW) Ground Range Detected (GRD) images from the Copernicus Sentinel Hub before applying precise orbits and calibration. These images have been consistently available over Thwaites since late 2015 (Dataset S1). Pairs of images on the same orbit path, separated by either 6 or 12 days, are then co-registered using precise orbits. We use the SNAP offset tracking algorithm to produce initial velocity fields using a window of 128 x 128 pixels, before projecting it onto a WGS 84 grid at a pixel spacing of 300 m. Erroneous pixels were then removed if the difference from the MEaSUREs velocity product was greater than ±50%, before a 3x3 low pass filter was applied. Similarly high temporal resolution velocity time-series have been presented from Greenland using Sentinel-1 data (Lemos and others, 2018). We also use Sentinel-1 imagery to map changes in ice front position every 2 months between January 2014 and August 2018.

To produce a time-series of changes in ice speed between 2000 and 2017, we extracted mean ice speed from a ~50 km^2 box over the 2011 grounding line ('GL' on Fig. 1) obtained from the MEaSUREs dataset (Rignot and others, 2011). In each epoch there were no missing pixels within the defined box. To produce further high temporal resolution time-series of ice speed between November 2013 and August 2018, and establish the spatial pattern of any change, we also extracted mean ice speed from three 50 km^2 boxes further down-ice on the floating ice tongue (see Fig. 1). These include two locations in the shear zone between the Thwaites Glacier Tongue and its Eastern Ice Shelf (referred to as the Northern Shear Zone (NSZ) and the Southern Shear Zone (SSZ)) and on the Thwaites Eastern Ice Shelf (TEIS). Because the relative changes in the speed of the shear zone and Eastern Ice Shelf (at NSZ, SSZ and TEIS) were much greater, we used the raw velocity fields i.e. without removing pixels greater than ± 50% of the MEaSUREs dataset. To account for any bias arising from missing pixels, we only include time steps where at least 95% of pixels are present within each box.

To estimate the relative error (precision) in our high temporal resolution time-series of ice speed we first calculated the difference in ice speed between each successive point in the time-series at each location (e.g. TEIS, NSZ, SSZ and GL). The difference between each successive point represents the sum of the relative error and the trend or absolute change in speed between the two image pairs. To isolate the relative error we then subtracted the trend in ice speed change at each point, which we take as the moving average of the previous 10 points in the time series. This produces median relative errors of ±0.22, 0.18, 0.17 and 0.07 m d^{-1} (±80, 66, 62 and 26 m yr^{-1}) for TEIS, NSZ, SSZ and GL, respectively. Some individual points have considerably higher relative errors, as reflected by the 90th percentiles of ±0.78, 0.59, 0.57 and 0.16 m d^{-1} (±284, 215, 208 and 58 m yr^{-1}), respectively. To account for these errors when comparing ice speeds at different time periods (e.g. difference between December 2015 and June 2018) we take a median of 10 consecutive velocity fields and assume a reasonable error to be the median relative error stated above.

3. Results

3.1 Annual observations (2000 – 2018)

Our ice front data show that in 2000, Thwaites Glacier extended approximately 120 km seaward as an intact and coherent floating ice tongue (Fig. 2a). Since then, there have been significant changes to both its extent and structural integrity. Initially, in March 2002, the calving of a 3,400 km^2 tabular iceberg resulted in ~75 km of ice-front retreat, before a re-advance occurred (Fig. 2a and 3a). Between 2006 and 2012 we observed the development of major rifting and fractures on the ice tongue around 20 and 35 km downstream of the grounding line and in the shear zone with the Thwaites Eastern Ice Shelf (Fig. 2b-e), but not further downstream near the ice-front. In 2012, another major tabular calving event resulted in the retreat of the ice-front 80 km behind its position in 2000 (see 2013 position on Fig. 2a and 3a). The 2012 calving event also marked the complete transition of the Thwaites Glacier Tongue from a largely intact ice tongue capable of the production of large tabular icebergs, to a mélange of fractured icebergs ranging from around 1-5 km in width and bound together by sea-ice (Fig. 2f-j). The exception to this was at the ice-front, where a ~470 km^2 iceberg remained fastened to the ice front, a relic of the 2012 calving event (Fig. 2f, k). Until January 2016, this iceberg was coalescent with the main Thwaites Tongue via dense ice mélange, which has known mechanical integrity (Rignot and MacAyeal, 1998). Between January and April 2016 it began to disintegrate.

Overall, annual speed at the grounding line (averaged from box GL) increased ~38% between 2000-2001 and 2016-2017 (from 1,957 ±5 m yr^{-1} to 2,696 ±32 m yr^{-1}). We note that there was little change in ice speed following the ~75 km retreat of its ice-front in 2002 (Fig. 3a, b). Most of the overall acceleration during the observation period took place between 2005-06 and 2011-12, where ice speed increased rapidly from 2,072 ±32 m yr^{-1} to 2,560 ±32 m yr^{-1} (Fig 3b). During this period of rapid acceleration there were no significant calving events and the ice-front steadily advanced (Fig. 3a). Thus, the period of rapid acceleration (Fig. 3b) coincides more generally with the onset of the structural weakening of the Thwaites Glacier Tongue between 2006 and 2012 (Fig. 2). From 2012-13 until 2015-16, there was a 6% slowdown in ice speed and the ice-front advanced (Fig. 3b). The largest annual increase in ice speed occurred between 2015-16 and 2016-17 where ice speed increased from 2,530 ±32 to 2,696 ±32 m yr^{-1} (Fig. 3b). Similar patterns in ice speed between 2000 and 2018 were present upstream of box GL, demonstrating that these changes in ice speed have not been caused by any ungrounding of ice in the vicinity of box GL, and are representative of wider changes in the system.

3.2 High temporal resolution observations November 2013 – August 2018

The high temporal resolution time series from Landsat-8 and Sentinel-1 (Fig. 4) shows substantial variability in glacier flow rates. Between November 2013 and December 2015 we observed a 9 km ice-front advance (Fig. 4e) and there was little change in ice speed at the grounding line; however, ice speed decreased along the eastern shear margin, by 22% in the northern shear zone (NSZ; Fig. 4b) and 10% in the southern shear zone (SSZ; Fig. 4c). In contrast, ice on the Thwaites Eastern Ice Shelf (TEIS; Fig. 4a) accelerated by 27% between November 2013 and December 2015. During this time period we observed no further structural weakening of the Ice Tongue and observed an advance of the structurally intact boundary between the Thwaites Ice Tongue and the Eastern Ice Shelf (Fig. 5), indicating a strengthening of the shear margins.

There was a notable change in glacier behaviour in early 2016, when the velocity patterns across Thwaites Glacier switched: between January 2016 and March 2017, ice flow at the grounding line steadily accelerated by 7% (GL; Fig. 4d). This coincided with a rapid change in behaviour of ice in the eastern shear zone where, between January and May 2016, the northern shear zone accelerated by 75% (NSZ; Fig. 4b). Simultaneously, ice at the Thwaites Eastern Ice Shelf accelerated by 57% (TEIS; Fig. 4a) over the 5 month period. Whilst the near-instantaneous acceleration at the northern shear zone was maintained up to the end of the observational period, ice speed at the Thwaites Eastern Ice Shelf decreased by 60% between June 2016 and August 2018 (TEIS; 4a). This included a near-instantaneous decrease in ice speed of 40% between June 2016 and September 2016 (Fig. 4a). By August 2018, ice speed in the southern shear zone had increased by 68% (SSZ; Fig. 4c). The magnitude of this increase in ice speed is comparable to that of the NSZ, but unlike the abrupt increase there, the acceleration at the southern shear zone was more gradual (Fig. 4c). Coinciding with this speed-up, extensive rifts developed in the southern shear zone and, by October 2018, these had propagated to within a few kilometres of the grounding line (Fig. 5). Comparing the spatial pattern of velocity change both before (Nov 2013 – Dec 2015) and after (June 2016 – Aug 2018) January 2016, the largest velocity increase occurred along the eastern shear margin (Fig. 4f).

Between January 2016 and August 2018 the ice-front retreated by 16 km (Fig. 4e). This period coincides with the break-up of the large iceberg fastened to the ice-front between January 2016 and April 2016 (Fig. 6a). Notably, the break-up of this iceberg coincides with the onset of the acceleration across the ice tongue (Fig. 4b-c). A second large calving event took place in February 2017 (Fig. 6b) but, there were no coincident changes in velocity on the Thwaites Glacier Tongue.

4. Discussion

As reported in previous studies (MacGregor and others, 2012), there was no significant change in the speed of Thwaites Glacier following the 75 km retreat of its ice-front as a result of the 2002 calving event (Fig. 3a, b), which confirms that the calved ice was ‘passive’ and did not exert a significant buttressing effect (cf. Fürst and others, 2016). This lack of response in ice speed is consistent with theoretical explanations for an unconfined ice shelf (Sanderson, 1979). Indeed, longer-term observations show that there was no significant change in the speed of Thwaites Glacier between 1992 and 2005 (MacGregor and others, 2012; Mouginot and others, 2014). However, ice speed increased by 24% between 2006 and 2012, which coincides with the onset of the structural weakening and transition to mélange of the Thwaites Glacier Tongue and eastern shear zone (Fig. 2 and 3). Because shearing along the eastern margin of the Thwaites Glacier Tongue generates a stress that resists glacier flow (e.g. Rignot and others, 2006), any structural weakening of the ice tongue could create a positive feedback whereby structural weakening and accelerations reinforce each other (e.g. MacGregor and others, 2012). It has been hypothesized that this process could create a continuous process leading to further weakening of the shear margins until all resistance to ice shelf flow is lost (MacGregor and others, 2012).

Despite the major structural weakening and acceleration of Thwaites Glacier during the mid-2000s, it is clear that this has not been a continuous process. Between 2012 and 2015 ice speed on the main trunk of Thwaites Glacier decreased by 6% and there were no obvious signs of further structural weakening (Fig. 3 and 5). However, 2016 marks the beginning of another period of acceleration, structural weakening (Fig. 5), ice-front retreat (Fig. 4) and, indeed, grounding line retreat (Milillo and others, 2019). We now consider the extent to which these periods of structural weakening may have been triggered by an external forcing (Section 4.1), and we then examine the specific processes at play during the observed periods of change: the 2012-2015 slowdown (Section 4.2) and the 2016 acceleration (Section 4.3). We then explore the implications of the observed structural weakening on the interaction between the Thwaites Ice Tongue and landfast sea ice (Section 4.4).

4.1 Ocean temperature variability as a control on structural weakening of the Thwaites Glacier Tongue

Throughout the 20th and 21st centuries, oceanic conditions in the Amundsen Sea switched between periods of relative cool and extreme warmth (Jenkins and others, 2016; Jenkins and others, 2018). The onset of the structural weakening of the Thwaites Glacier Tongue coincided with a period of extremely warm oceanic conditions from the mid-2000s until the early 2010s, whilst the period of deceleration in the early 2010s coincides with cooler conditions (Fig. 3c). This hints that ocean variability could be triggering the intermittent behaviour of Thwaites Glacier. Typically, such ocean variability is associated with changes at intermediate depth, at around 300-700 m (e.g. Jacobs and others, 2013; Dutrieux and others, 2014; Jenkins and others, 2018), which is well below the ice tongue/mélange. However, increased melting in the vicinity of the grounding line could lead to the un-grounding of ice, reducing buttressing and subsequent acceleration of ice shelf flow, leading to a weakening of shear margins. Greater melting at depth and the associated shallower thermocline would also lead to more upwelling of warm water to the surface layers (Dutrieux and others, 2014), which could also directly weaken the ice shelf, mélange and shear margins, leading to further acceleration and ice-front retreat. A combination of both these processes could explain the link between ocean variability and the timing of the accelerations and structural weakening of Thwaites Glacier. In contrast, under relatively cool conditions, lower melt rates could slow down grounding line retreat and reduce melting of the ice tongue leading to a re-advance of the structurally intact shear margin boundary. In the following sections we discuss the importance of these physical mechanisms in the slowdown (2012-2015) and acceleration (2016-2018) of Thwaites Glacier using results from our high temporal resolution time series.

4.2 Slow-down of Thwaites Glacier between 2012 and 2015

The slow-down of the main Thwaites Glacier Tongue between 2012 and 2015 could only be explained by a re-grounding of ice and thickening, or a strengthening of the shear margins. There is no reported evidence of the former (e.g. Milillo and others, 2019), but our results show that the margin between the Thwaites Glacier Tongue and the Thwaites Eastern Ice Shelf strengthened over this time period. Between November 2013 and December 2015 the boundary of structurally intact ice between the Thwaites Glacier Tongue and Eastern Ice Shelf advanced by 6 km (Fig. 5a-c), indicating a partial strengthening of the shear margin. Consistent with this strengthening is the reduction in velocity gradient between the faster flowing Thwaites Glacier Tongue and the slower flowing Thwaites Eastern Ice Shelf over the same time period (NSZ and TEIS; Fig 4a, b). Specifically, this is shown by a 22% reduction in ice speed at the faster flowing Thwaites Glacier Tongue (NSZ; Fig 4b) and a 27% increase in ice speed at the slower flowing Thwaites Eastern Ice Shelf (TEIS; Fig. 4a). This section of the Thwaites Eastern Ice Shelf (e.g. box TEIS) had been accelerating since 2008 (Mouginot and others, 2014), which was attributed to a partial ungrounding of a pinning point near the Thwaites Eastern Ice Shelf ice-front (Tinto and Bell, 2011; MacGregor and others, 2012) or retreat of its grounding line (Rignot and others, 2014). Whilst these processes may be contributing to some of the longer-term acceleration, the pattern of velocity observed in our results (Fig. 4a, b) between November 2013 and December 2015 is entirely consistent with a partial recoupling in flow between the Thwaites Glacier Tongue and Eastern Ice Shelf between November 2013 and December 2015. This is where the faster flowing and more dominant Thwaites Glacier Tongue entrains the slower Thwaites Eastern Ice Shelf, resulting in its acceleration. Simultaneously, the greater shear stresses associated with a stronger shear margin results in a slowdown in velocity of the Thwaites Glacier Tongue.

Whilst our results suggest the strengthening of shear margins are likely to have been important in the slowdown of the Thwaites Glacier, other factors may also have contributed to the slowdown. One possibility is that the ice tongue may have re-grounded onto a pinning point or increased in grounded area. Based on the 2011 grounding line (Rignot and others 2011), the ice tongue was likely stabilised by at least three small pinning points (Fig. 1). It is possible that small changes in ice tongue thickness could have increased the grounded area and contributed to the slowdown. However, this is difficult to assess because no additional grounding line observations are available over this time period.

4.3 January 2016 acceleration

January 2016 marks the onset of a period of acceleration across the grounding line, weakening of the shear margins and a retreat of both the grounding line (e.g. Milillo and others, 2019) and ice-front. The most rapid changes in ice speed occurred at the NSZ and at the TEIS, where in January 2016 ice speed increased by 75% and 57%, respectively, over the course of a few weeks (Fig. 4a, b). This resulted in a rapid steepening of the velocity gradient between the Thwaites Glacier Tongue and the TEIS, which ultimately led to further structural damage and a decoupling in flow between the two ice shelves. Consistent with this is the rapid 60% deceleration of TEIS from August 2017 to February 2018 (Fig. 4a), associated with a reduction in shear from the faster flowing ice tongue. This pattern of velocity change is very similar to that reported by Mouginot and others (2014) at the onset of Thwaites Glacier's last major acceleration event in 2006. Thus, following the reported decoupling in flow between the two ice shelves in 2006, ice flow has since partially recoupled between 2013 and 2015, before decoupling again in 2016.

The acceleration of ice in the SSZ (Fig. 4c) in January 2016 was at a comparatively slower rate than ice in the NSZ (Fig. 4b), creating a steep velocity gradient. Over the following months, the increased longitudinal stresses associated with the steep velocity gradient (e.g. Benn and others, 2007) resulted in the development of a series of rifts along the eastern shear zone and to within a few kilometres of the grounding line (Fig. 5). The loss of buttressing associated with the weakening of the shear zone, may have played an important role in the increase in ice speed observed at the grounding line (e.g. Fig. 4d). Consistent with this is the spatial pattern of velocity change, which indicates that the largest increases in velocity are concentrated along the entire eastern margin (Fig. 4f).

The mechanism responsible for the initial increase in ice speed towards the ice-front at the NSZ (Fig. 4b), in January 2016, is unclear. One possibility is that the rapid increase in speed at NSZ was a direct consequence of the break-up and calving of the large structurally intact iceberg fastened to the ice-front (Fig. 6a). This iceberg may have been acting as an obstacle, helping to pin the mélange in the shear zone, meaning the break-up of the iceberg resulted in a near-instantaneous loss of buttressing in the northern shear zone. Consistent with this is the near-instantaneous acceleration of ice at NSZ (Fig. 4b), which observations elsewhere have shown to be a typical response to calving events which reduce buttressing (e.g. Scambos and others, 2004). In addition, the mélange at in the northern shear zone may have been weakened through a combination of enhanced ocean melt, the seasonal retreat of landfast sea-ice, and by surface melt. Indeed, it is notable that in January 2016 an anomalously large amount of surface melt was produced in the Thwaites embayment (Nicolas and others, 2017). An alternative explanation is that the acceleration at the NSZ could be linked to a rapid grounding line retreat which occurred over a similar time period to the observed acceleration (Milillo and others, 2019), or un-grounding of any pinning points. However, this seems unlikely because the acceleration of the northern shear zone occurred before any large increases in speed upstream either at the southern shear zone or at the grounding line (Fig. 4a-d), which would be expected if grounding line retreat was the driver. Rather, after the initial weakening of the shear margins, grounding line retreat may have accelerated the inland propagation of structural weakening of the eastern shear margin. Regardless of the physical mechanism responsible for the initial increase in ice speed at NSZ, our results show that despite extensive structural weakening of the Thwaites Glacier Tongue, processes originating in the shear zone towards the ice-front between the Thwaites Glacier Tongue and Eastern Ice shelf are still playing an important role in ice dynamics towards the grounding line. This highlights the importance in understanding the mechanisms which may lead to future changes in the stability of the ice tongue in the future.

4.4 Interaction between the Thwaites Ice Tongue and landfast sea ice

The overall structural weakening of the Thwaites Glacier Tongue over the past two decades is likely to render it far more vulnerable to further retreat or disintegration in the near-future. For example, its present-day structure now strongly resembles Holmes Glacier in Porpoise Bay, (Fig. 7a, b) which is reliant on multi-year landfast sea-ice for structural integrity, and where sea-ice break-out events have been shown to trigger disintegration of large sections of its floating ice tongue (Fig. 7a; Miles and others, 2017). Elsewhere, the mechanical binding of landfast sea ice to the Mertz Glacier tongue has been shown to be important for the ice tongue's integrity (Massom and others, 2015). Given that the western margin of the Thwaites Glacier Tongue is also fastened to a band of multi-year sea-ice, we hypothesize that the recently weakened Thwaites Glacier Tongue may now also have some dependency on landfast sea-ice for structural integrity. The implication is that future break-outs of multi-year sea-ice in front of the Thwaites Glacier Tongue could result in further structural weakening or even disintegration. This is supported by observations of the initiation of a partial break-out of multi-year sea-ice in February 2019, which has resulted in the disintegration of a small section of the Thwaites Glacier Tongue on the western margin (Fig. 7b). Taken together, this means that the Thwaites Glacier Tongue would become more vulnerable to disintegration if landfast sea-ice or pack-ice were to become less persistent in the future.

Landfast sea-ice is sensitive to changes in the ocean-climate system (Mahoney and others, 2007; Fraser and others, 2012). Individual break-out events can be driven by extreme climatic events (Fraser and others, 2012; Aoki and others, 2017; Miles and others, 2017), but abrupt changes can be also be caused by changes in the local ice-scape (e.g. Tamura and others, 2012; Massom and others, 2013; Campagne and others, 2015). An important component of the local sea-ice regime in the Thwaites embayment is the grounded B-22a iceberg (e.g. Stammerjohn and others 2015), which lies ~130 km out to sea north-east of Thwaites Glacier (Fig. 7c). Several studies have highlighted the importance of grounded icebergs or ice tongues (e.g. Mertz) acting as 'anchors', which help to facilitate growth and stabilize landfast sea-ice regimes (e.g. Fraser and others, 2012; Massom and others, 2010; 2013; Stammerjohn and others, 2015). Notably, the band of multi-year landfast sea-ice attached to the western margin of the Thwaites Glacier Tongue is also anchored to the B-22a iceberg, suggesting that the iceberg is likely aiding the stability of the landfast sea-ice (Fig. 7c). Therefore, when the grounded iceberg is removed from the Thwaites embayment (likely in the near-future), a change to less favourable landfast sea-ice conditions is likely to occur. Any decrease in landfast sea-ice persistency or extent would ultimately increase the prospect of further retreat or disintegration of the Thwaites Ice Tongue. This is important because whilst the tongue may only be providing a small amount of buttressing through its interaction with the Eastern Ice Shelf, it still acts as an important buffer for the inner ice shelf, by limiting potential damage from ocean waves and swell (e.g. Massom and others, 2018). Moreover, changes in either the ice tongue or landfast sea-ice extent could also have important implications on regional ocean circulation, with potential implications for melt rates at the grounding line (e.g. Webber and others, 2017).

5. Summary

Over the last 18 years, Thwaites Glacier Tongue has retreated >80 km, accelerated by 38%, and has transitioned from a structurally-intact ice tongue capable of producing large tabular icebergs, to a mélange of smaller fractured icebergs bounded by sea-ice. However, the rate of change throughout the observational period has not been uniform and we identify two distinct acceleration phases, separated by a period of deceleration. The largest acceleration took place between 2006 and 2012 when there was extensive structural weakening of the ice tongue and shear margins, along with a 23% increase in ice speed. However, between 2012 and 2015 there was a 6% slowdown in ice flow on the main Thwaites Glacier trunk, and there was a partial recoupling in flow between the Thwaites Glacier Tongue and the Eastern Ice Shelf as the structurally intact shear margin boundary advanced. The most recent acceleration started in January 2016 and is characterised by a major weakening of the eastern shear margin, which initiated on the ice tongue and, over the following months, propagated towards the grounding line as velocity gradients increased. The timing of the first acceleration coincides with a period of relatively warm ocean conditions, whilst relatively cool ocean conditions coincide with the deceleration phase. This correlation suggests that the ocean may be acting as trigger for these distinct episodes of glacier behaviour.

Despite the major structural weakening of the Thwaites Glacier Tongue it may still be playing an import role in ice dynamics at the grounding line, meaning future changes in its extent are still an important consideration. As a result of the structural weakening over the past 18 years the Thwaites Ice Tongue now has some dependency on landfast sea-ice for structural integrity. The removal of iceberg B-22a from the Thwaites embayment could result in a regime change, in that a reduction in the persistency of landfast sea-ice would have detrimental impacts on the ice tongue's future structural integrity. There is a need for these complex processes associated with weakening ice tongues to be explored quantitatively through numerical modelling because they may have important implications for the rates of future sea level contributions.

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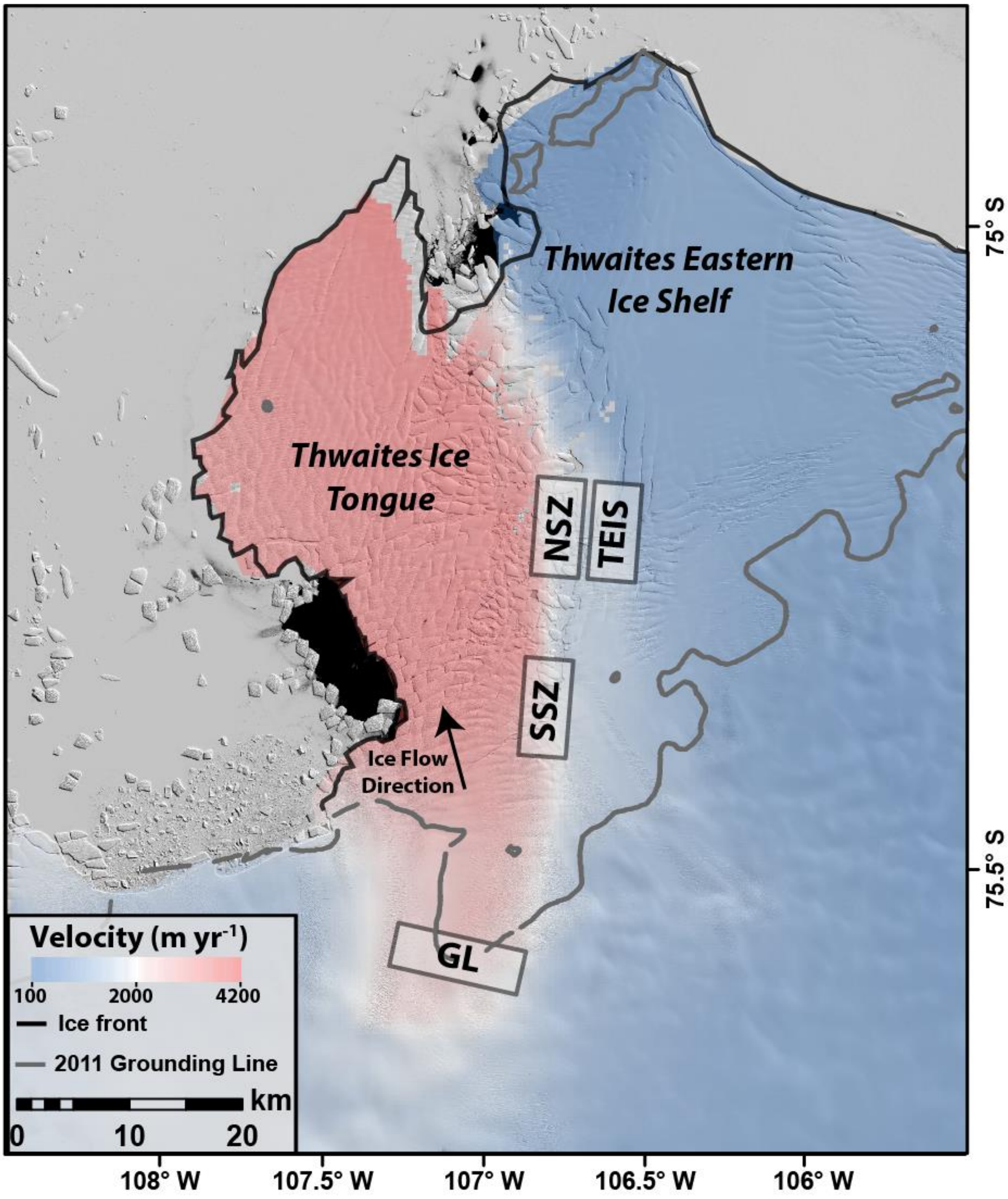
615 **Figures**



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617 **Figure 1:** Landsat-8 image from November 2013 of the Thwaites Ice Tongue and Eastern Ice
618 Shelf, overlain with the MEaSUREs 2011 grounding line (Rignot and others, 2011) and the
619 MEaSUREs composite velocity product. The boxes where our velocity time series are
620 extracted as spatial averages: Northern Shear Zone (NSZ), Southern Shear Zone (SSZ),
621 Thwaites Eastern Ice Shelf (TEIS) and Grounding Line (GL). Note the steep velocity gradient
622 between the Thwaites Ice Tongue and Eastern Ice Shelf.

623

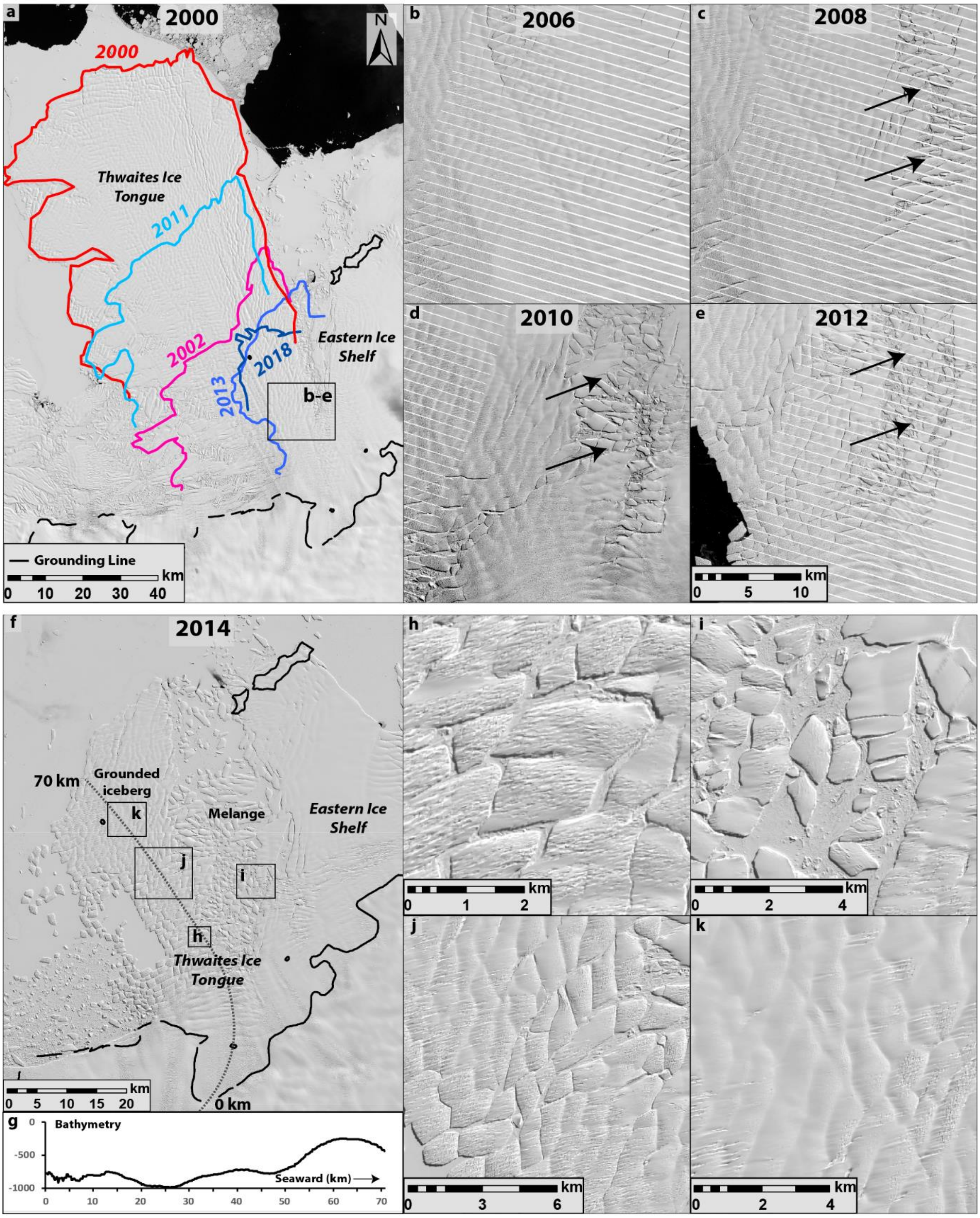

Figure 2: Structural transition of the Thwaites Glacier Tongue. **a)** Landsat-7 image of the 120 km long Thwaites Glacier Tongue in 2000 with digitized ice-front positions. The grounding line is from the MEaSUREs dataset in 2011 (Rignot and others, 2011). **b-e)** Landsat-7 images showing the changes in structure of the Thwaites Glacier Tongue. The black arrows point to the development of rifts in each successive image. The location of these

images is shown by the black boxes in 1a. **f)** Landsat-8 image in 2014 weakened ice tongue. Note the structurally intact grounded iceberg. **g)** Bathymetry (Millan and others, 2017) taken along the transect shown in 1f (dotted line). Note the presence of the offshore ridge. **h-k)** Close-ups of the Thwaites Glacier Tongue from 2014, the location of each image is shown in black boxes in f.

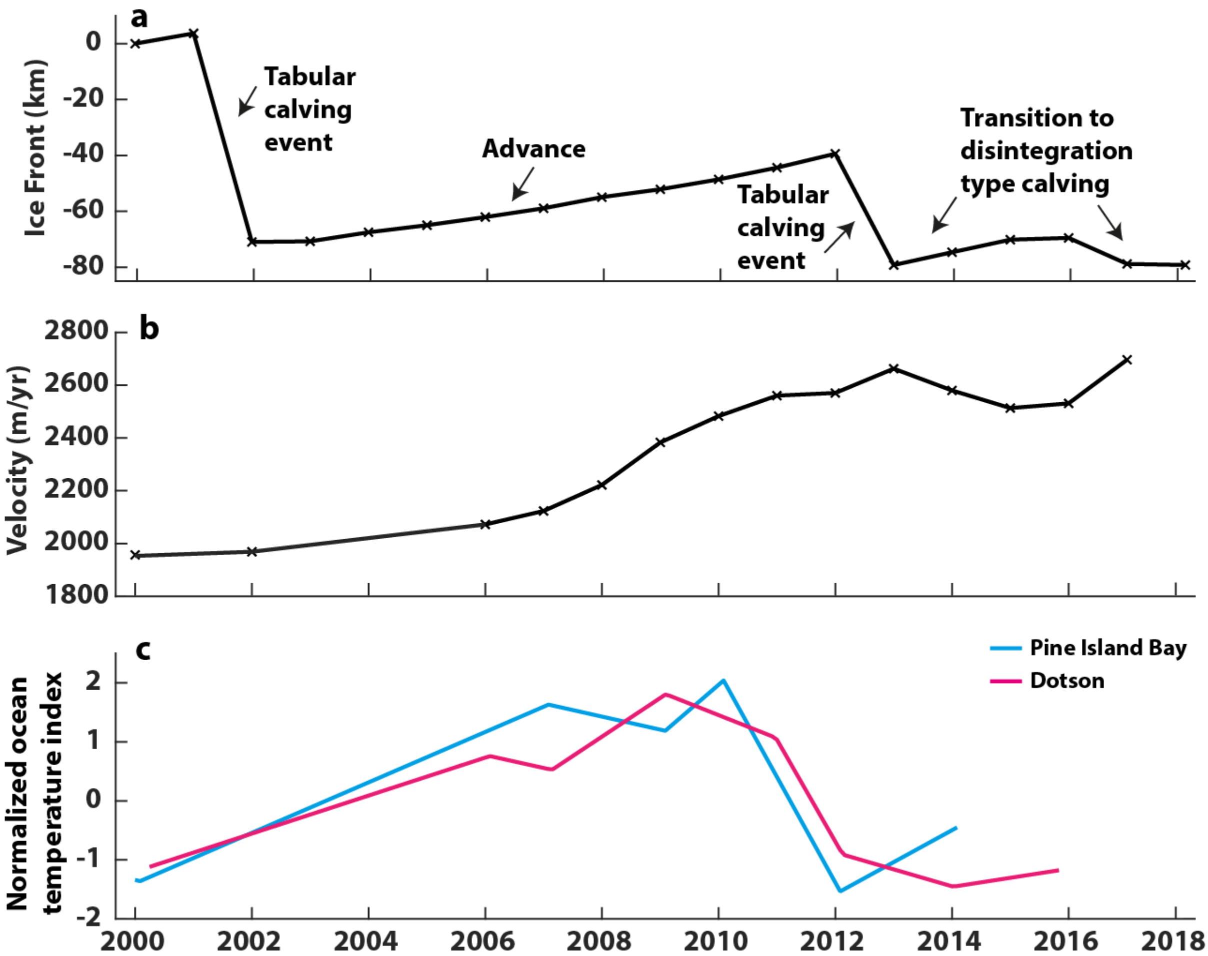

Figure 3: Annual ice-front (a) and velocity (b) changes 2000 and 2018. c) Normalized ocean temperature index from Pine Island Bay (blue line; Jenkins and others, 2016) and Dotson (cyan line; Jenkins and others, 2018). Note the switch to cooler conditions in 2012.

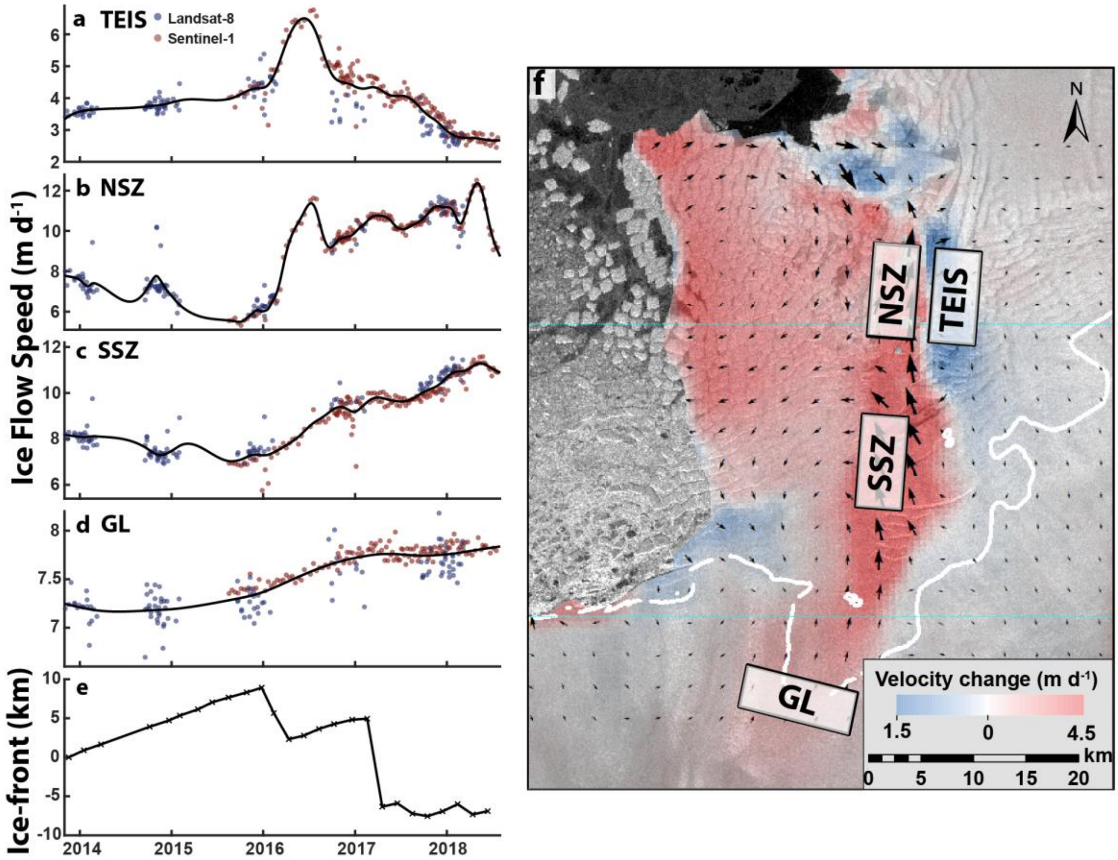

Figure 4: High temporal resolution ice speed and ice-front position changes between November 2013 and August 2018. a) Thwaites Eastern Ice Shelf (TEIS) b) Northern Shear Zone (NSZ) c) Southern Shear Zone (SSZ) d) Grounding Line (GL). The black line in each velocity panel is a smoothing spline. e) Changes in ice-front position. **f)** Difference in median velocity before January 2016 (Nov 2013-Dec 2015) and after (June 2016 – Aug 2018) overlain on a Sentinel-1 image from August 2018, with red indicating a velocity increase and blue a decrease. Note the largest increases in velocity occur in the eastern shear zone.

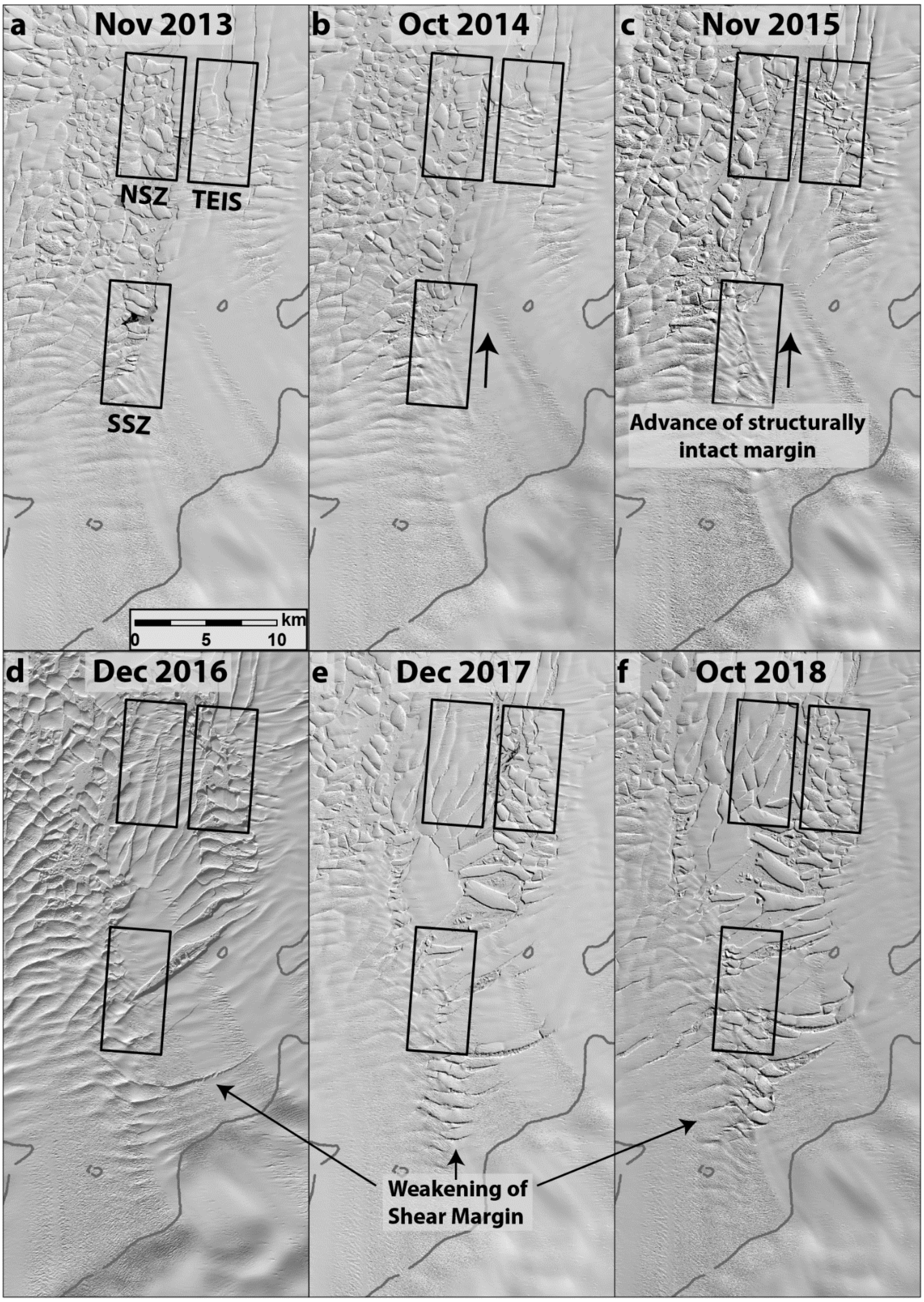

Figure 5: Landsat 8 images from 2013 to 2018 showing the structural changes at the shear margin between the Thwaites Ice Tongue and Eastern Ice Shelf. From 2013 to 2015 (a-c), there are no signs of further structural weakening and the structurally intact boundary between the ice tongue and Eastern Ice Shelf advances. From 2016 to 2018 (d-f) there is extensive structural weakening of the shear margin. The grey line is the 2011 grounding line (Rignot and others, 2011).

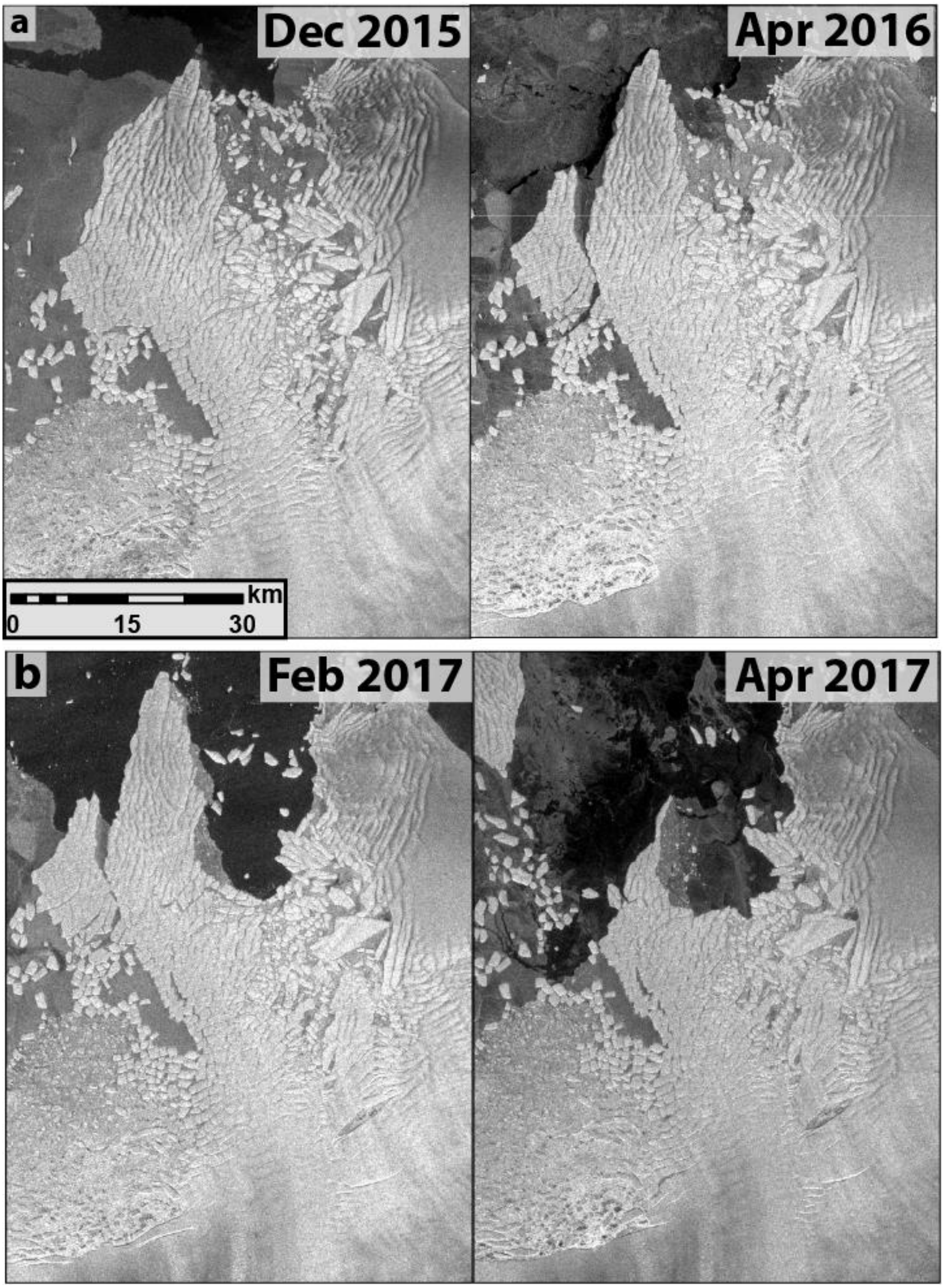

Figure 6: Sentinel-1 IW GRD images of the **a)** December 2015 - April 2016 calving event. **b)** February – April 2017 calving event.

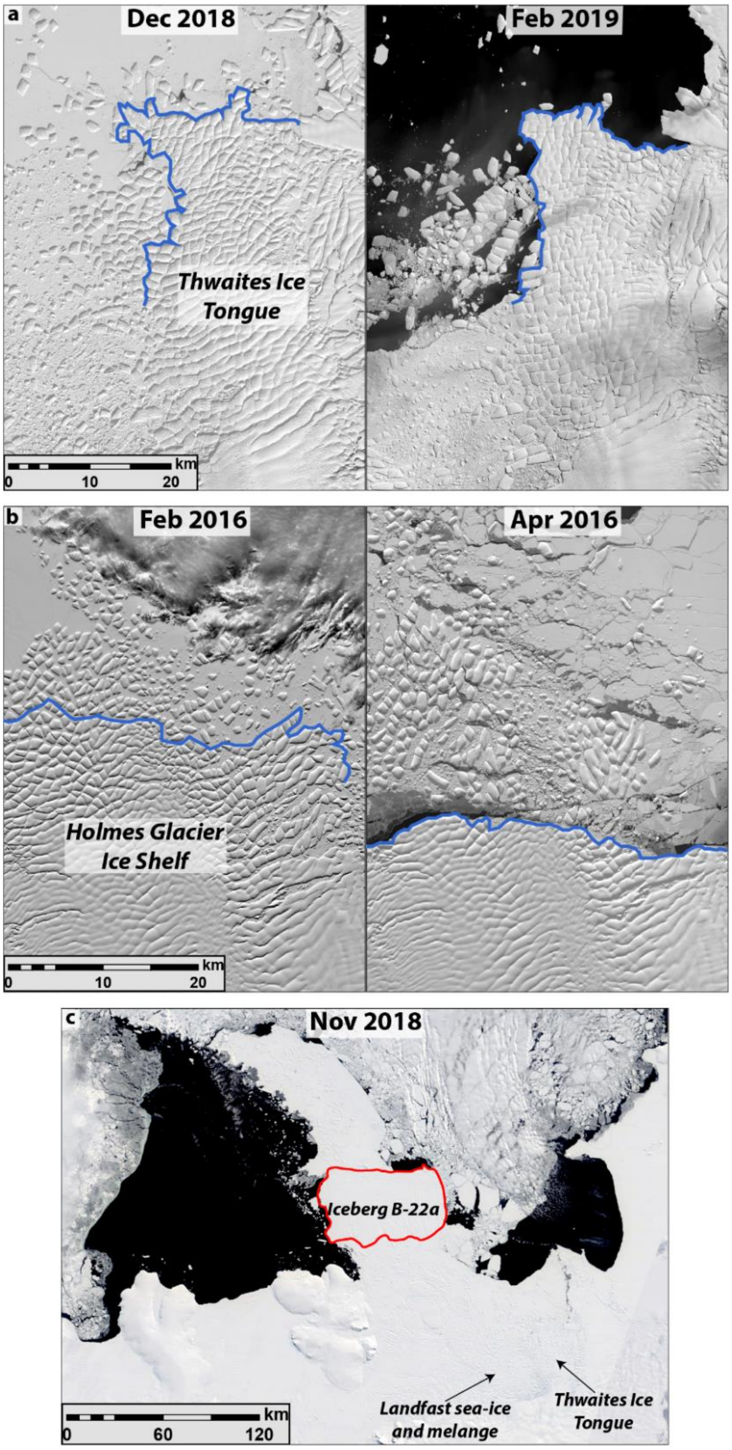

Figure 7: Landsat-8 images of Thwaites Glacier Tongue **(a)** and Holmes Glacier, Porpoise Bay, East Antarctica **(b)**. Note their similarities and structure. Holmes Glacier disintegrates during landfast sea-ice break out events (e.g. Miles and others, 2017). A small portion of the Thwaites Glacier Tongue has disintegrated in response to a partial landfast sea-ice break out. Ice-fronts are digitized in blue. **c)** A MODIS image of the Amundsen Sea embayment. Note the grounded B-22A iceberg (digitized in red) and the dense landfast sea-ice which is anchored on to it.