Dynamics and mechanical integrity of a fast-ice stabilized ice tongue in Antarctica prior to break-off

Rodrigo Andres Gomez Fell¹, Wolfgang Rack², Heather Purdie¹, and Oliver J. Marsh³

¹University of Canterbury
²University of Canterbury, NZ
³British Antarctic Survey

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Abstract

The full length of Parker Ice Tongue on the Victoria Land Coast, Antarctica, calved in March 2020. Calving of this magnitude (18 km) is not previously seen for this location. The mean growth rate (189 m yr⁻¹) indicates that it is now at a historic minimum for at least the last 165 years. The 2020 calving occurred during a complete breakout of the land-fast sea ice. Here we link seasonal changes in ice velocity to the land-fast sea ice extent. With Summer/winter increase/decrease in velocity correlates with decrease/increase in land-fast sea ice extent (-0.62 with R-squared of -0.39). Although Parker Ice Tongue was relatively small compared to other ice tongues in the region, its sensitive behaviour highlights the vulnerability of ice tongues to a changing ocean environment, and poses questions about the future stability of larger floating ice masses if land-fast sea ice extent decreases more broadly in the future.
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R. Gomez-Fell\textsuperscript{1}, Wolfgang Rack\textsuperscript{1}, Heather Purdie\textsuperscript{2}, Oliver Marsh\textsuperscript{3}

\textsuperscript{1}Gateway Antarctica, School of Earth and Environment, University of Canterbury, New Zealand
\textsuperscript{2}School of Earth and Environment, University of Canterbury, New Zealand
\textsuperscript{3}British Antarctic Survey, Cambridge, United Kingdom

Key Points:

\begin{itemize}
  \item Periods of continuous ice tongue growth coincide with extended periods of land-fast sea ice coverage.
  \item The seasonal variability of ice tongue dynamics is linked to the stabilizing effect of land-fast sea ice buttressing.
  \item The complete 2020 ice tongue break-off was a unique event in at least 160 years as a result of two recent years of total fast ice break-out.
\end{itemize}

Corresponding author: Rodrigo Gomez-Fell, rodrigo.gomezfell@pg.canterbury.ac.nz
Abstract

The full length of Parker Ice Tongue on the Victoria Land Coast, Antarctica, calved in March 2020. Calving of this magnitude (18 km) is not previously seen for this location. The mean growth rate (189 m yr\(^{-1}\)) indicates that it is now at a historic minimum for at least the last 165 years. The 2020 calving occurred during a complete breakout of the land-fast sea ice. Here we link seasonal changes in ice velocity to the land-fast sea ice extent. With Summer/winter increase/decrease in velocity correlates with decrease/increase in land-fast sea ice extent (-0.62 with R-squared of -0.39). Although Parker Ice Tongue was relatively small compared to other ice tongues in the region, its sensitive behaviour highlights the vulnerability of ice tongues to a changing ocean environment, and poses questions about the future stability of larger floating ice masses if land-fast sea ice extent decreases more broadly in the future.

Plain Language Summary

Ice Tongue collapse or retreat can be an indicator of climate and oceanic changes at local and global scales. Ice tongues are the seaward part of marine-terminating glaciers, and are often embedded in land-fast sea ice (fast-ice), which is sea ice attached to land. Here we document a unique event in observational history, the complete break-off of the Parker Ice Tongue during exceptional seasons of fast-ice broke-off. We show that ice tongue integrity, evolution and motion are affected by sea-ice variability. Using satellite image time series, we observed that sea-ice delayed the break-off of the Parker ice tongue, protecting it from different ocean processes. All this shows the importance of sea-ice coverage for these floating ice masses and presents us with the question of what would happen to ice tongues if sea-ice coverage decreases in the future because of climatic and oceanic changes.

1 Introduction

The Antarctic ice sheet discharges its mass through outlet glaciers and ice streams forming at its grounding line either (to a larger part) ice shelves or (to a smaller part) ice tongues. These floating ice masses occupy 74% of the total Antarctic coastline (Bindschadler et al., 2011). Ice shelves are an important regulator of grounded ice discharge exerting a buttressing force that affects the ice flow dynamics in the interior of the ice sheet (Pritchard et al., 2012; Depoorter et al., 2013; Rack & Rott, 2004; Rott et al., 2018; Rignot et al., 2019). Ice tongues are unconstrained ice shelves, typically fed by one marine terminating glacier, and often embedded in land-fast sea ice (hereafter fast-ice). Exposure to atmospheric and oceanographic forcing and less protection to their sides makes them vulnerable to changing climatic conditions, and a sentinel for local environmental change (Truffer & Motyka, 2016). Here we report the complete break-off of the Parker Ice Tongue at the Borchgrevink Coast as an early sign of such a change.

Ice tongues are a distinctive feature of the Victoria Land Coast in the Western Ross Sea. This section of the Antarctic coast has 32 outlet glaciers that end as ice tongues (Fountain et al., 2017). A decrease in area for some ice tongues and ice shelves between 1960-63 and 1972-73 and an increase afterwards was documented (Frezzotti, 1993), but overall relatively stable frontal position in the last 60 years have been observed (Fountain et al., 2017; Frezzotti, 1993; Miles et al., 2013). Different reasons have been given to explain the relative stability of outlet glaciers and ice tongues in the Western Ross Sea, such as cooler air temperatures (Miles et al., 2013), the formation of marine ice at the base (Frezzotti, 1997), and a cold coastal ocean current (Stevens et al., 2017). Fluctuations of these and other related variables, such as the abundance of fast ice, could alter the boundary conditions which control the mass balance and length of ice tongues. We ex-
amine one of these variables, namely fast-ice extent, and its influence and stabilizing ef-
fect on the Parker ice tongue (PIT) prior to its collapse in 2020.

Sea ice is an important driver of change for coastal Antarctic land ice (Massom et
al., 2018; Baumhoer et al., 2021), and fast-ice has a significant role in various ice-ocean
related processes. Fast-ice has been associated with polynya formation (Fraser et al., 2019;
Nihashi & Oshihama, 2015; Brett et al., 2020), ice shelf disintegration/stability (Massom
et al., 2018), Ice Shelf Water formation (Haas et al., 2021), and ice tongue calving events
(Robinson & Haskell, 1990; Stevens et al., 2013). Fast-ice has been observed to protect
ice tongues and when absent calving events are more likely to occur (Robinson & Haskell,
1990; Stevens et al., 2013; Massom, 2003). It has been suggested that the existence of
fast-ice is essential for ice tongue growth (Wearing et al., 2020). Massom et al. (2010)
observed multiyear fast-ice mechanically coupled with the Mertz ice tongue and proposed
that fast-ice can have an important role in the stabilization of ice sheet maritime mar-
gins. Information about fast-ice stabilization of ice shelves or ice tongues is scarce (Robinson
& Haskell, 1990; Massom et al., 2010) and few studies exists on the seasonal relation-
ship between ice shelf dynamics and sea ice (Greene et al., 2018; Zhou et al., 2014). The
effect of ice melange, a consolidated agglomeration of icebergs and fast-ice, on glacier mar-
gins has been studied more broadly for Greenland. Ice melange is strongly correlated with
 glacier retreat and advance (Moon et al., 2015; Howat et al., 2010), can alter the but-
tressing effect of ice tongues affecting marine terminating glacier dynamics (Krug et al.,
2015; Todd & Christoffersen, 2014), and can stabilize the ice margin impeding calving
(Robel, 2017; Amundson et al., 2010; Cassotto et al., 2021).

Oceanic processes also have an effect on ice tongue stability affecting its mechan-
ics and dynamics. Tidal currents can exert considerable lateral force over glacier tongues,
creating lateral flexure and controlling along flow velocities which affect its dynamics (Legré
et al., 2004). Holdsworth (1982) showed that the curvature of the Erebus Ice Tongue is
a result of the ocean current pressure and in a two-way interaction ice tongues also af-
fect local oceanographic dynamics (Stevens et al., 2014, 2017). Tides generate vertical
displacement of ice tongues due to tide wave oscillation (Holdsworth, 1969; Padman et
al., 2018). Holdsworth and Glynn (1978) found that stresses induced by tides are higher
at the grounding line but at the same time that the grounding line is not a common point
of failure of ice tongues.

The objective of this paper is twofold; firstly we describe the PIT 2020 break-up,
and secondly we analyse the stabilizing properties of fast-ice and its relation with ice tongue
dynamics. We show evidence of fast-ice mechanical stabilization of the ice tongue, de-
laying its break-up, and seasonal changes in ice dynamics associated with oscillations in
fast-ice extent . Our observations are remote sensing based, mostly from Sentinel-1 SAR
images. We also use optical and historical aerial photography to better constrain the length
history of PIT.

2 PIT and the ice tongues of the Western Ross sea

The Borchgrevink coast is part of the Transantarctic mountains, from its glaciers
19 ice tongues flow into the Ross sea. The most prominent ice tongues and glaciers in
this area are Aviator, Mariner, Borchgrevink and Tucker (Frezzotti, 1997). PIT is lo-
cated at Lady Newnes bay at 165.833 E and 73.857 S (figure 1A). Compared to some
of its neighbors the PIT has a smaller size and catchment. For example the Aviator IT,
Mariner IT and the massive Drygalski IT are all wider and longer, with grounded catch-
ments basins larger than 7000 km$^2$ (Frezzotti, 1997). Based on the analysis of the Antar-
ctic REMA DEM, Parker glacier has a catchment of 188 km$^2$. The length of the PIT has
varied between 16 to 21 km in the last 60 years (figure 2). Its width varies from 1.3 km
at the tip to 2.4 km near the grounding line. In relation to other Western Ross Sea ice
tongues, the PIT is long and narrow with its tip bending slightly northwards. We at-
Figure 1. Sentinel-1 SAR image sequence of the southern Borchgrevink coast acquired during complete fast-ice break-outs plotted with A) spring maximum (solid lines) and autumn minimum (dashed lines) extent of fast-ice between November 2017 and October 2019 (2017-18: orange, 2018-19: light grey, 2019: green). The box (yellow dashed line) delimits the area used for detailed fast-ice analysis. The ASAID grounding line (Bindschadler et al., 2011) is also shown (red); B) northward ice tongue shift during the 2017 fast ice break-out; C) rift formation in the grounding zone during the 2017 fast-ice break-out; D) drift of PIT after break-off in 2020. All images in Antarctic polar-stereographic projection EPSG:3031
tribute the bending to a northerly ocean current similar to the Erebus ice tongue (Holdsworth, 1982).

3 Data and Methods

3.1 Surface velocities from Sentinel-1

Ice surface velocities were derived from 93 pairs Sentinel-1 12-day repeat pass of synthetic aperture radar (SAR) images in Single Look Complex (SLC) format. Data were acquired in interferometric wide-swath (IW) mode and delivered with a pixel spacing of 2.3 m in slant range and 14.1 m in azimuth. The image time series used for ice surface velocity calculations spans from the 5 February 2017 to the 26 February 2020 acquired in exactly the same imaging geometry. We use a SAR intensity tracking algorithm to obtain the ice tongue surface velocities (Strozzi et al., 2002; Wegmüller et al., 2016). Intensity tracking has the advantage over InSAR in that it is less affected by coherence loss and can resolve velocity vectors, whereas InSAR resolves displacements only in line of sight of the radar sensor. The small baseline of Sentinel-1 orbits allows for a very accurate sub-pixel co-registration of the image (Wegmüller et al., 2016).

The intensity tracking algorithm uses a cross-correlation method over image patches of two previously co-registered images to estimate offsets from the SAR speckle pattern (Strozzi et al., 2002). For the estimation of the displacements we use a two step process where the first estimation is done using a window of 128 pixels (~ 294 m) in ground range and 64 pixels (~ 896 m) in azimuth. Afterwards the calculated offset field is used as a base for a second offset estimation using 64 pixels (~ 147 m) in ground range and 64 pixels (~ 896 m) in azimuth. A correlation threshold of 0.01 was set for the peak value of the correlation coefficient in order to reject poor image matches. Results are converted to map geometry and geocoded using the 100 m REMA DEM (Howat et al., 2019). To estimate the errors of the tracking algorithm we followed Vijay and Braun (2017), our error estimate for more than 89% of the pairs is < 0.215 m d$^{-1}$ or 78.4 m yr$^{-1}$ (see supplements).

For the post-processing of the velocity we followed (Lemos et al., 2018). We used a 8x8 median filter twice, before re-sampling to a 100 meter grid. The resulting velocity maps are stacked, and a running mean of 36 days applied in the time domain to further reduce noise.

3.2 Semi-automatic determination of land-fast sea ice area extent

For the satellite based detection of the fast-ice boundary we make use of the fact that pack ice is very dynamic whereas fast-ice being attached to land remains stagnant. Following a semi-automatic approach similar to the one described by Mahoney and Eicken (2004) and Li et al. (2018) we identify in pairs of consecutive co-registered Sentinel-1 images areas with similar radar intensity levels as fast-ice. Rapid changes in surface properties of fast-ice (e.g. by melting) can significantly alter the radar backscattering, creating errors when comparing two consecutive acquisitions. We found that Sentinel-1 12 day repeat pass images show normally sufficiently small change. Because we use exact repeat pass images with identical imaging geometry we can neglect variations in radar backscattering which arise from changing radar incidence angles. Image differences are post-processed using the following steps; a gaussian filter with a sigma value of 5, an edge detection filter, automatic thresholding to produce a binary result, and finally, the application of a morphology filter. After a visual inspection 5% of the results needed fine-tuning, mainly due to our algorithm underestimating fast-ice area. Our final product at 100 m pixel resolution was compared between February-2017 to February-2018 with a pan-continental fast-ice lower resolution data-set (1 km) (Fraser et al., 2020). We also
did a visual comparison of our results with MODIS optical data when possible; both data sets showed good agreement with our analysis.

From our fast-ice area product, we get a maximum and minimum fast-ice area extent for each year and the total area in square kilometres for each pair of images. To compare fast-ice area changes with ice tongue dynamics, we defined a rectangular region of fast-ice influence around the PIT. This region satisfies the following conditions: (i) a good representation of the seasonal fast-ice coverage of the larger area, and (ii) encompassing the embayment between the adjacent ice tongues. We found that a polygon with 3 times the length of PIT corresponds well to these requirements. It results in a maximum fast-ice area of 1150 km$^2$ around the ice tongue which has a size of about 50 km$^2$ (Figure 1A).

3.3 PIT length

We use aerial photographs and satellite imagery to digitally map the outline of PIT from 1963 to 2020 (Table S4). The 1963 aerial photographs were from a U.S. Geological Survey (USGS) flight and the 1980 image is a declassified satellite image from the Key Hole (KH-9) mission (Burnett, 2012). We geo-referenced the USGS aerial photos and the declassified satellite images using a GIS software manually selecting tie points with a Sentinel-2 optical image from 2016. For 1973 and from 1988 onwards we used a series of different optical and radar satellite images from the Landsat (ETM, OLI), Sentinel-1 and -2 missions. This allowed us to estimate the frontal position of the ice tongue for the last 57 years (Figure 2). The length of the PIT was measured from the grounding line (Bindschadler et al., 2011) to the frontal position following the central flow-line. For the last 20 years of the time series we selected a yearly satellite image from the month of November, unless a sizable calving event occurred. The frontal advance rate of each period was calculated dividing the length difference by the amount of days between images. The accuracy of the length measurement depends on the pixel resolution of the sensor. For the USGS aerial photograph and KH-9 image also dependent on the quality of our geo-referencing. The latter was assessed by comparison to known independent ground control points which were not used for geo-referencing. For these images the error estimates are below 200 m, and for all images the errors are smaller than the symbol size on figure 2.

4 PIT dynamic behavior and fast-ice influence prior to break-up

As seen from our observations the PIT break-off event in March 2020 was unique over the entire period of almost 60 years (figure 2). From the growth rates we can infer that an event of that scale has likely not occurred over at least 165 years. The ice tongue dynamics appear to follow closely the seasonal fast-ice extent oscillation, and the surrounding fast-ice is most likely an important driver in its structural stability and for the longevity of the ice tongue.

4.1 PIT growth rate

The mean growth rate of the PIT prior to its break-off for the last 20 years disregarding any major calving is 197.9 ± 59.3 m yr$^{-1}$, and for the whole observation period 193.1 ± 57.4 m yr$^{-1}$. Considering the 1963-2020 growth rate it will take to the PIT 108.8 ± 24.9 yr of continuous growth to obtain the maximum observed length of (∼21 km).

We established five main periods of continuous growth between calving events (figure 2): 1963 to 1980 (187 m yr$^{-1}$), 1988 to 2005 (160 m yr$^{-1}$), 2005 to 2008 (201 m yr$^{-1}$), 2011 to 2016 (223 m yr$^{-1}$) and 2017 to 2020 (236 m yr$^{-1}$).

Over the last 20 years periods of continuous growth with rates similar to the surface ice velocity correspond well with periods of persistent fast-ice extent (see supple-
Figure 2. PIT length for the period 1963 to 2020 measured from the grounding line to the tip along the centre flow line. The black dashed lines connect positions with net growth. The gray dash-dot line indicates the possible growth path of the ice tongue. The red dash-dot lines indicate long periods of continuous growth between calving events with the corresponding growth rate between first and last image of the period (28-12-1963 to 07-09-1980, 15-12-1988 to 19-01-2005, 13-02-2005 to 11-11-2008, 03-09-2011 to 27-11-2016 and 13-03-2017 to 02-14-2020) Annual average net growth rates for periods longer than 2 years are shown. The 1963 length was obtained from the 1963 U.S. Geological aerial photographic Survey mission and the 1980 position from declassified KH-9 mission data. All other lengths are obtained from either Landsat (1973, 2001 to 2014), Sentinel-1 (2017 to 2020), or Sentinel-2 (2016) satellite images.

Fast-ice holds the ice tongue flanks protecting its structure, preventing calving and promoting growth, similar to melange (Amundson et al., 2010; Krug et al., 2015; Todd et al., 2019). This can be noticed on the calving event of 2005 when an iceberg of ∼3.22 km$^2$ detached from the ice tongue tip. The iceberg broke at the same point where the minimum fast-ice extent was observed for that year, suggesting that calving is controlled by the variability of fast-ice extent and how this in return influences ice tongue growth.

In figure 2 we can identify 3 major calving events before the ice tongue break-off. We defined a major calving event as losing at least 2000 m, congruent with the 2005 and 2017 events. In the study period there appeared to be three of these events, the previous two mentioned and one between the October 1980 and December 1988 interval. Major calving events after 2000 are related with periods of low fast-ice coverage from Fraser et al. (2020) and from this study.

4.2 Fast-ice coverage in the proximity of PIT (2017-2020)

According to Fraser et al. (2020) data-set (2000-2017) and our own observations (2017-2020), complete break up of fast-ice in the vicinity of PIT has occurred seven times in the last two decades (2002, 2005, 2006, 2011, 2016, 2017 and 2020). It is not possible to determine the exact duration of fast-ice free conditions due to the restricted temporal resolution of the fast-ice product. But we observed that 2005, similar to 2017 and 2020, had a longer fast-ice free period. For the calving events in 2005 and 2017, and for all the growth periods that overlap these dates, the growth rate is either negative (major calving) or below 100 m yr$^{-1}$ (minor calving). Over the last 20 years of observations, 2004/05, 2016/17 and 2019/20 were exceptional fast-ice seasons with a long duration of...
Figure 3. A) Monthly average ice velocity fields of PIT derived from Sentinel-1 SAR offset tracking between February 2017 to February 2020. B) Fast-ice area surrounding PIT (blue) based on yellow rectangle in figure 1 plotted with mean surface velocity (green line).
low fast-ice coverage. On the other hand, over extended periods without break-out multi-
year fast ice persisted in some areas for as long as four years.

During the 2017-2020 period the PIT was mostly covered in fast-ice. The largest
but short-lived fast-ice extent was observed in October 2019. Winter 2018 had a max-
imum extent lower than the 2019 maximum for the whole embayment (figure 1, but it
persisted much longer at the full extent from end of May 2018 into the next year to Jan-
uary 2019. During the low extent periods from February to mid-March 2018 and from
beginning of March to the end of May 2019 (figure 3B) the ice tongue was still completely

The area of fast-ice assumed to be of influence for the PIT ice mechanics and dy-
namics is highlighted in yellow in figure 1A and the fast-ice coverage in this box is plot-
ted in figure 3B for the 2017-2020 period. The maximum extent in the box area is more
persistent during the 2018-2019 fast-ice cycle. As expected, these variations in fast-ice
are similar to those in Lady Newnes bay and differences are only observed during max-
imum fast-ice area coverage for the box area during the 2018-2019 fast-ice cycle, while
the maximum extension for the whole bay is during 2019-2020 cycle (figure 1A).

4.3 PIT rift formation prior to break-off

During the period of maximum fast-ice retreat in 2017 the tip of the ice tongue shifted
about 500 m north (figure 1B), creating a 2000 m long and up to 150 m wide rift in the
southern margin of the grounding zone (figure 1C). The start of fast-ice freeze-up shortly
after the opening of the rift is most likely the main reason for stabilization, delaying the
break-off for another three years. The effect of the fast-ice stabilization can be inferred
from the SAR image sequence as the build-up of (multi-year) fast ice makes the rift im-
perceptible on later image acquisitions. A rift compression might have been caused by
the buttressing effect of fast-ice holding its banks in combination with ice flow from the
interior reducing the width of the rift. It is also possible that continued snowfall on multi-
year fast ice, which filled the rift, made the radar intensity level in the rift similar to the
surroundings. Based on our SAR analysis it is almost certain that the breakoff in 2020
occurred along the rift which initially formed in 2017 and that the rifting event in 2017
preconditioned the final break-off.

4.4 PIT dynamics before break-off (2017-2020)

We observed seasonal variability of ice tongue surface velocity, with larger mean
velocities observed during February, March and April, and lower mean velocities between
July and October (figure 3A). The mean velocity of the ice tongue for the whole study
period is $217.9 \pm 11.1 \text{ m yr}^{-1}$ (figure 3B), in agreement with other studies (Rignot et al.,
2017; Mouginot et al., 2012). During the study period the surface mean velocity varies
between $194.4 \pm 8.3 \text{ m yr}^{-1}$ (October 2018) to $242.4 \pm 28.7 \text{ m yr}^{-1}$ (February 2020). The
standard deviation of mean velocity is higher during and after the 2017 period with no
fast-ice and before the 2020 break-off. This higher variability suggests that the dynam-
ics of the ice tongue not only varies seasonally with fast-ice area change, but also with
the presence/absence of fast-ice. There is a statistically significant relationship between
fast-ice area and the PIT surface velocity (correlation coefficient of -0.62, R-squared: 0.39
and p-value of 3.77e-11).

After break-off, the ice tongue floated first outwards and was then carried north-
east by a coast-parallel current that made it spin counterclockwise (figure 1D). During
the first 12 days the average drift velocity was $1.7 \text{ km d}^{-1}$. The drift stopped soon af-
fterwards when the fast-ice started freezing up in April and the ice tongue stayed trapped
at the tip of the Icebreaker IT during the 2020 fast-ice season about $\sim 40 \text{ km}$ from its orig-
inal position. In 2021, after the fast-ice receded, it continued its northward drift past Coulman Island and then around Cape Adere following a coastal current to the west.

5 Fast-ice variability and its implications for ice tongue stability and dynamics

Our observations support previous studies which show that reduced sea ice extent promotes damaging effects of ice shelves by ocean activity (Massom et al., 2018) or, vice versa, that increased fast ice extent stabilizes marine terminating glaciers (Rott et al., 2018). In a pan-Antarctic context, decreasing sea ice days have been linked with terminus position retreat in Antarctica (Miles et al., 2016; Baumhoer et al., 2021). We found that even relatively short periods of fast-ice break-out can cause serious damage and disintegration of an ice tongue. Furthermore, we can link variations in ice tongue dynamics to fast-ice extent.

The frequency of satellite image acquisition and pixel resolution steadily increased over the study period. Until around the year 2000, we focused on the analysis of the length change of the ice tongue and lower resolution information of the fast-ice extent. During this period, the steady growth of the ice tongue was limited by only two major calving events. The first calving happened sometime during the 1980s, the second in 2005. The maximum length of the ice tongue was measured on 19 January 2005 with 21 km just before a 3 km long iceberg calved off. The higher availability of satellite data after 2005 allowed us to constrain the periods of continuous growth and detect smaller calving events.

5.1 Fast-ice and ice tongue dynamics

The average velocity of the ice tongue for the 1996-2010 period as depicted in the MEaSUREs data-set (208 ± 13 m yr⁻¹) (Mouginot et al., 2012) compared well with our mean ice velocity of 217 ± 11 m yr⁻¹ for the period 2017-2020. Velocity measurements over the latest 3-year period are evenly distributed, whereas the MEaSUREs velocity dataset could be biased towards a particular season of the year. For the observation period 2017-2020, we linked the variability in ice dynamics of PIT to the seasonal variations of fast-ice coverage. The Sentinel-1 SAR ice velocity time series are relatively short but with a dense temporal resolution (12-day repeat pass over this entire 3 year period), which allowed us to continuously quantify seasonal ice dynamical changes. We found an inverse correlation of -0.62 between the fast-ice cover surrounding the PIT and its surface velocities. The seasonal variability observed is consistent with other studies that show melange and/or fast-ice control on tidewater glacier dynamics and growth (Reeh et al., 2001; Krug et al., 2015; Zhou et al., 2014; Greene et al., 2018). Monthly mean ice surface velocities in March are 11% higher compared to October for the 2017-2020 period.

Similar temporal fluctuations on ice dynamics of ice shelves have been observed in other parts of Antarctica using more sparse data-sets (Zhou et al., 2014; Greene et al., 2018; Tomar et al., 2021). The reasons for these seasonal changes were partially explained with the advance/retreat of fast-ice, which showed a significant negative correlation with ice velocity fluctuations. Although we are unable to provide insights into the fast-ice thickness evolution for our study area, a previous study showed that modelled sea ice thickness has a good relationship with fluctuations in ice dynamics (Greene et al., 2018). This suggests that not only changes in the fast-ice area, but also the structural integrity or stability of fast-ice, could have impacted the observed ice tongue dynamics. Ice tongue thinning through basal melting could be another cause of seasonal acceleration, but this effect is likely not as strong over such a short period of time like changes in fast-ice/melange (Krug et al., 2015), and there is no indication that the thickness of floating ice masses in the area have significantly changed (Paolo et al., 2015; Adusumilli et al., 2020).
It has been suggested previously that ice melange buttressing can promote growth by suppressing the calving of glaciers with floating termini (Robel, 2017; Amundson et al., 2010; Krug et al., 2015). Our observations for the 2001 to 2020 interval show a considerable variability in growth rates, ranging from 50 to 271 m yr\(^{-1}\). When comparing growth rates with fast-ice coverage we found that faster growth is associated with periods of persistent fast-ice extent and periods of slow growth related to fluctuations in the fast-ice coverage. It indicates an inverse relationship between ice tongue calving and fast-ice extent. Longer periods of extensive fast-ice coverage protect the frontal area of the ice tongue and promote growth in return. These observations support modelling results that found that the presence or absence of fast-ice appears to be a determining factor on the growth of unconfined ice shelves (Wearing et al., 2020).

### 5.2 PIT 2020 Break-off

PIT completely detached from the ice in the grounding zone after a period of low fast-ice coverage in 2020. Although calving from ice tongues has been reported before (Massom, 2003), a complete break-off is unseen. Big calving events of ice tongues have been associated with strong storms (Frezzotti & Mabin, 1994), collision with bigger icebergs (MacAyeal et al., 2008; Massom et al., 2015; Young et al., 2010) and sea ice free periods (Stevens et al., 2013; Miles et al., 2017; Aoki, 2017). Major ice tongue calving events on the Western Ross Sea are rare (Frezzotti, 1997). During the last 30 years, similar types of calving events have been reported for the Erebus (Robinson & Haskell, 1990; Stevens et al., 2013) and Drygalski ice tongues (Parmiggiani & Fragiaccomo, 2005; Wuite et al., 2009; MacAyeal et al., 2008). The Drygalski calving events from 2005 and 2006 are a result of collisions with B15A and C16, which were giant icebergs originating from the Ross Ice Shelf (Wuite et al., 2009; MacAyeal et al., 2008). In this study, we can directly relate the rifting (February 2017) and break-off (February 2020) of the PIT to the prolonged absence of fast-ice, corroborating similar observations from the Erebus ice tongue (Robinson & Haskell, 1990; Stevens et al., 2013). The absence of fast-ice exposed the ice tongue to oceanic processes, which then affected the ice tongue integrity demonstrating the importance of fast-ice to maintain the structural stability of ice margins.

The precise causes of the break-off are yet to be determined. Considering a prolonged period of fast-ice retreat, offshore winds and the coast-parallel current might have exerted enough pressure to the side of the ice tongue to trigger such an event. Ice tongues represent a floating barrier for surface ocean currents, and the resulting force increasing with the distance to the coast must be balanced by the rotation of the obstacle (Stevens et al., 2017). Legrésy et al. (2004) observed that tidal currents generate lateral pressure on ice tongues, and Stevens et al. (2013) suggested that this kind of mechanism could cause structural failure. Different ice tongue geometries will respond differently to the forcing of surface ocean currents (Stevens et al., 2017). The geometry of PIT showed a very high length to width ratio representing an effective lever for a lateral force resulting in a drift immediately after calving of almost 2 km d\(^{-1}\).

A complete calving of an ice tongue just within a few ice thicknesses from its grounding line has not been reported before. Based on our observations, the ice tongue would need 108.8 ± 24.9 yr of constant growth to reach the maximum length observed. Expecting that periodic calving events reduce the ice tongue advance, the time needed for PIT to grow from the grounding line back to its maximum known length is likely much longer. However, considering the current growth rates and the present fast ice conditions, the regrowth of the ice tongue to a typical length observed over the past 60 years seems rather unlikely. In addition, the ice tongue might have acted as a pinning point for the formation of fast ice. The period after 2020 is too short to draw any conclusion on such feedback. Therefore, it is difficult to conclude if the break-off of a relatively small ice tongue, in comparison with the larger ice tongues in its vicinity, will enhance a further reduction of the fast ice area.
6 Summary and conclusions

Through the lens of an unique calving event we showed that fast-ice is a stabilizing factor delaying ice tongue disintegration, and that fast-ice affects seasonal ice tongue dynamics. We conclude that the stability provided by continuous (multi-year) fast-ice was critical in delaying the PIT break-off. In the absence of obvious changes in ice morphology or other forces such as iceberg collisions we conclude that a south-north oriented surface ocean current is the likely cause for the final ice tongue break-off. Our findings are supporting evidence that fast-ice can suppress major calving events of floating ice masses.

In addition, we established a clear relationship between the seasonal variation of ice-tongue velocity and fast ice extent. Ice velocities during summer, when less fast ice is present, are up to 11% higher compared to winter. We therefore conclude further, in absence of any other obvious causes, that fast ice exerts a significant buttressing force on ice tongues. The analysis of ice dynamics is based on a continuous 3-year long time series of 12-day repeat pass satellite data. Further analysis is required to better understand the interaction between fast-ice and floating land ice, how the size and shape of ice tongues alters this relationship, and if a two way relationship in the absence of ice tongues will affect fast-ice building and coverage.

Finally our observations of the relationship between ice tongue growth and fast-ice extent indicates that fast-ice is an essential component of ice tongue growth cycle where periods of prolonged fast-ice buttressing allows continuous growth. The unconfined nature of ice tongues and their relatively small size make them a suitable subject to study sea ice buttressing effects on floating ice, because they are potentially more sensitive to fast-ice changes. More important future changes in fast-ice coverage, thickness and duration could affect the growth rate and dynamics of Antarctic ice tongues.

Acknowledgments

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Supporting Information for ”Dynamics and mechanical integrity of a fast-ice stabilized ice tongue in Antarctica prior to break-off”

R. Gomez-Fell\textsuperscript{1}, Wolfgang Rack\textsuperscript{1}, Heather Purdie\textsuperscript{2}, Oliver Marsh\textsuperscript{3}

\textsuperscript{1}Gateway Antarctica, School of Earth and Environment, University of Canterbury, New Zealand

\textsuperscript{2}School of Earth and Environment, University of Canterbury, New Zealand

\textsuperscript{3}British Antarctic Survey, Cambridge, United Kingdom

Contents of this file

1. Text S1 - Estimation of the offset tracking errors

2. Figures S2 to S3 - Fast ice over polygon area (figure 1A) and Parker Ice Tongue length for the last 20 years.

3. Table S4 - Satellite Sensors used for mapping Parker Ice Tongue length.

Additional Supporting Information (Files uploaded separately)

1. Movies S5 - Movie of Parker Ice Tongue 2017 shift and 2020 break-off

Introduction

This supporting material contains information regarding the error estimation of the surface velocities, list of data used for the ice tongue length determination (table S3)
and two figures comparing ice tongue length vs total fast ice area (Fraser et al., 2020) (figure S2) and ice tongue length vs fast ice area trend (figure S3) for the years between 2001 and 2017.

Text S1 - Estimation of the offset tracking errors

When using offset tracking to determine surface ice displacement the main systematic source of error is associated with the matching algorithm and on the quality of image co-registration. To estimate the accuracy of our results we followed Vijay and Braun (2017). We estimated the root mean square error (RMSE) over 570 stable terrain measurements near the vicinity of PIT to assess the coregistration error. We found that 89% of the scene pairs have an RMSE $< 0.2$ m d$^{-1}$ or 70 m yr$^{-1}$. The uncertainty ($e_t$) associated with the offset tracking algorithm can be calculated as:

$$e_t = \frac{C \Delta x}{z \Delta t},$$

where $C$ is the error associated with the tracking algorithm (in pixels), assumed to be 0.1 (Mouginot et al., 2017), $\Delta x$ is the pixel resolution in ground range (1.7 to 3.5 m), $z$ is the oversampling factor (2) and $\Delta t$ time between acquisitions (12 days). Assuming a range resolution of 3.5 m, it resolves as $e_t = 0.015$ m d$^{-1}$. The total error for more than 89% of the pairs is $< 0.215$ m d$^{-1}$ or 78.4 m yr$^{-1}$. In addition from phase coherence over not moving targets we found interferometric phase coherence. Concluding that the co-registration accuracy is normally better that 1/10th of a pixel

Figures S2 and S3.
Figure S2. The length of the PIT for selected dates for the last 20 years (black dots). The total fast ice (Fraser et al., 2020) area covered inside the PIT defined polygon of influence (yellow rectangle in figure 1A) (gray).
Figure S3. The length of the PIT for selected dates for the last 20 years (black dots) is shown in comparison to fast ice area (Fraser et al., 2020) which is the decomposed trend for the 2000 - 2017 for the PIT defined polygon of influence (yellow rectangle in figure 1A) (blue).
**Data Set S4.** Dates and satellite sensors used for mapping of the Parker IT length.

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<th>Sensor name</th>
<th>Parker IT length [m]</th>
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**Movie S5.** Sentinel-1 based animation showing the PIT displacement and drift immediately after the break-off. Images are in polar stereographic projection.

**References**
