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Brief Communication
"The 2013 Erebus Glacier Tongue calving event"

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Abstract. The Erebus Glacier Tongue, a small floating glacier in southern McMurdo Sound, is one of the best-studied ice tongues in Antarctica. Despite this, its calving on the 27 February 2013 (UTC) was around 10 yr earlier than previously predicted. The calving was likely a result of ocean currents and the absence of fast ice. The subsequent trajectory of the newly created iceberg supports previous descriptions of the surface ocean circulation in southern McMurdo Sound.

1 Introduction

The Erebus Glacier Tongue (EGT) is a small glacier extending from the western coast of Ross Island into southern McMurdo Sound. Prior to the events described here the glacier tongue was approximately 12.9 km long (measured from the virtual line connecting the coastline where it intersects with EGT), about 1.5 km wide and was estimated to be 300 m thick at the grounding line. The glacier is protected by the Dellbridge Islands (including Tent and Big Razorback Islands) to the north (Fig. 1). The area is close to Cape Evans, the base for Robert Falcon Scott's 1911/1912 expedition, and so was the focus for some of the earliest geophysical observations in Antarctica (Taylor, 1922). Curious features are the glacier's aspect ratio (narrow width relative to length) and the striking side-lobes (Holdsworth, 1974, 1982).

On 27 February 2013 (UTC), and for only the 4th time in the brief recorded history of Antarctica, the Erebus Glacier Tongue calved. It broke off around 1 km west of a fast ice bridge extending south west from Big Razorback Island. In doing so it freed a ~3.3 km section of glacier (measured along its longest axis) to form a 3.2 km^2 penguin-like shaped iceberg (Fig. 1a, b). The reduced length of EGT to its new tip is about 9.9 km.

Previous calving events occurred in 1990, ~1942 and 1911. The 1911 calving of the Ross Island Tongue (as it was called then) was reported by Taylor (1922) as having broken off during a southerly blizzard on the night of 1 March 1911. There is some discrepancy in Taylor (1922) as to the position of the new end of the EGT after the calving. The position used here comes from Map I presented at the end of the text in Taylor (1922). The 1942 calving date and position are approximate (Holdsworth, 1982) as there was no occupation of the sound at that time. The 1990 event is the best documented previous calving (Robinson and Haskell, 1990), occurring on 1 March of that year – the same year day as the 1911 calving (Fig. 1 c, d). These authors identified ocean swell waves coming from the north, combined with an absence of sea ice, as being the primary driver of the calving.

In this brief communication we document the calving and contextualize this using available data on tip position and previous calving events. Furthermore, we use the trajectory of the detached tip interpreted from a sequence of MODIS imagery to examine aspects of circulation in southern McMurdo Sound. This is useful information as the ocean currents in this region are poorly known due to the challenges of high latitude ocean survey work.

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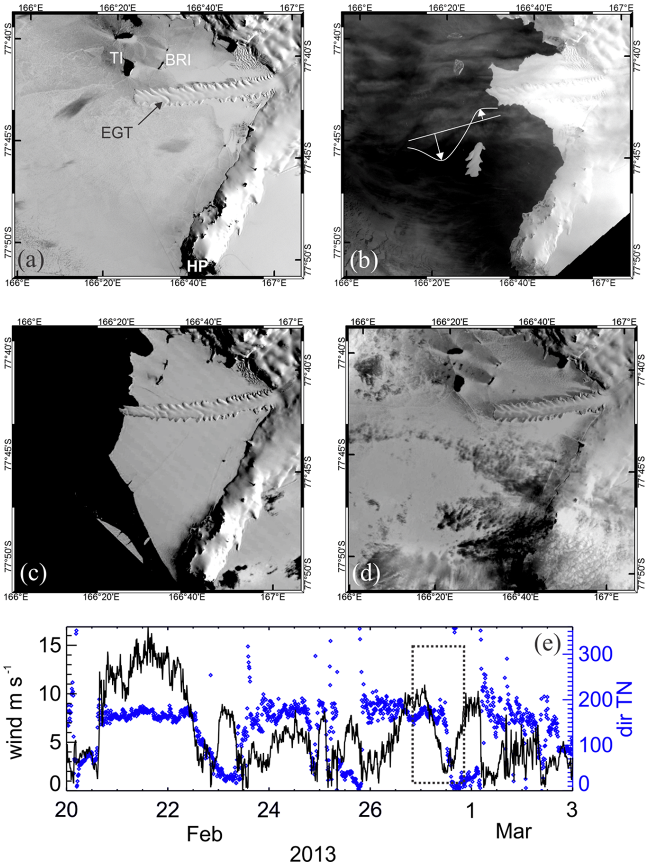

Fig. 1. ASTER images from **(a)** year day 12 (12 January 2013), **(b)** year day 58 (27 February 2013) showing tip moving south and speculated current shear described in the text. Landsat 4 TM images from 1989 showing **(c)** year day 29 (29 January 1989) and **(d)** year day 349 (14 December 1992). The Erebus Glacier Tongue (EGT), Tent Island (TI), Big Razorback Island (BRI) and Hut Peninsula (HP) are marked in **(a)**. **(e)** Shows the wind velocity (direction is that of wind origin) recorded at Cape Royds, 20 km north of the EGT.

2 Calving

The weather at the time of the 2013 calving was clear with moderate wind conditions. The Automatic Weather Station at Cape Royds to the north of the EGT reported a maximum wind speed of 10 m s^{-1} over the few days prior to calving (https://amrc.ssec.wisc.edu/aws; Fig. 1e). A number of remotely sensed data products are available for the area. One hundred and fourteen granules from MODIS sensors aboard both TERRA and AQUA satellites were acquired over the period from year day 57 (26 February) to 80 (21 March) and processed to derive projected false colour composite images (bands 1, 2 and 3) at 250 m spatial resolution (Sirguey et al., 2009). The detached tip of the EGT was positively identified in 38 of these images. Furthermore, higher resolution (15 m) ASTER orthorectified VNIR images were obtained before (12 January 2013) and shortly after the event (27 February 8.25 p.m. and 3 March 2013). Finally, Landsat 4 TM images from before and after the 1990 calving were obtained (29 January 1989, 29 November 1989 and 14 December 1992) to revisit the mapping of the 1990 event in the context of the recent data.

Visual interpretation indicates that, prior to the calving there was loose pack ice in the vicinity but no large objects. A few days prior to calving this loose pack amalgamated in a region to the SE of the EGT tip, but was subsequently advected away leaving open ocean at the time of calving (Fig. 1a, b). The 2013 calving separated along a line running to the south east and so removed more from the southern side of the tongue (Fig. 1b). This was also seen in the 1911 calving, although less exaggerated than 2013, where contemporary maps showed perhaps 1 km more was lost from the south side as compared to the north (Taylor, 1922). Sketches and satellite data indicate that the calving line in the 1990 event was almost north–south (Fig. 1d). The variability in the orientation of this line adds to the ambiguity in tip position by as much as 1.2 km.

The EGT did not split off at the multiyear fast ice bridge from Big Razorback Island, but instead along one of the depression lines running SE–NW (Fig. 2a, b). GPS transects of glacier freeboard from December 2010 indicate that these depressions imply a marked localized thinning of the glacier (Stevens et al., 2013).

Glacier calving can be linked to climate drivers (Frezzotti, 1997). The timing of the calving can be placed in context by considering an update of Holdsworth's (1982) space-time trajectory of the glacier tip (Fig. 2c), which was developed prior to the 1990 calving. Whilst not statistically significant, it is nonetheless noteworthy that the time between calving for the 2013 event was the shortest of the observations so far. Robinson and Haskell (1990) had speculated that, based on previous behaviour, it should re-calve sometime in 2020–2030. By using the Landsat images pre- and post-1990, we estimate that the EGT was flowing at an average rate of 153 m a^{-1} at the time, thus allowing the position of the EGT to be approximated as of 1 March 1990. It appeared that the southwards breaking point of the 2013 calving matched precisely the location of the fracture in 1990, although the EGT extended about 600 m farther at that time.

The comparison with historical estimates suggest that the calving line varies. However, the two events in the satellite era show the southern edge of the calving line at least to be consistent. This break point may be related to the lobe features as these appear to form the end points for the depression features in the glacier that subsequently formed the calving line. This suggests tracking the evolution of such glacial structure would aid in prediction of ultimate failure (Frezzotti et al., 1998).

As well as confirming the "early" calving of the recent event, i.e. earlier than predicted by Robinson and Haskell (1990) based on previous calving intervals, it also indicates a curious arrest in propagation in the 1970s and

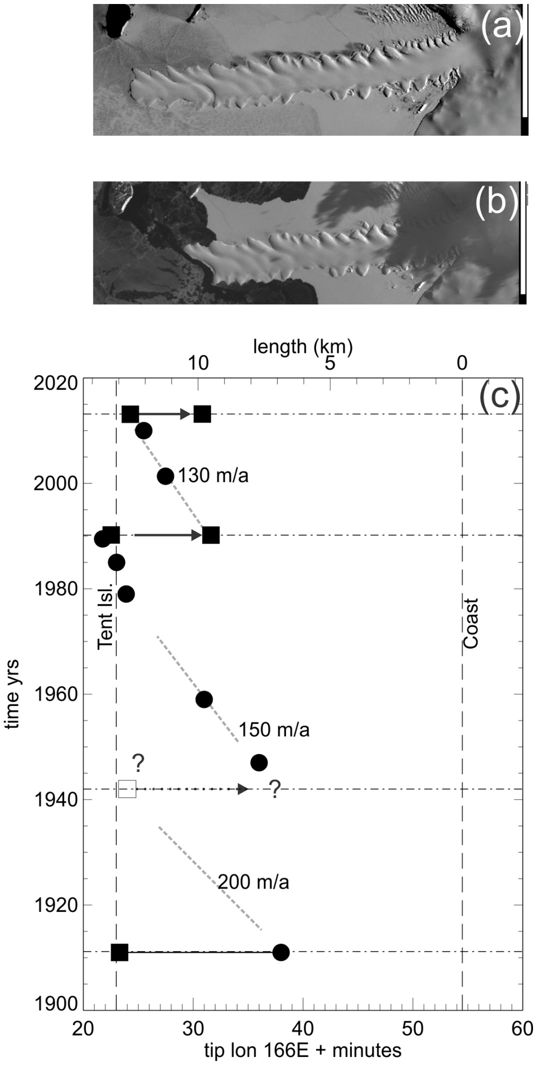

Fig. 2. ASTER images of EGT **(a)** before and **(b)** after the 2013 calving (zoomed from Fig. 1a, b), and **(c)** tip space-time diagram. The longitudes of Tent Island and the coast are marked with dashed lines. The indicated tip velocities are the slope of the dashed lines. Squares show longitude at calving (hollow square indicates the date is poorly constrained) whilst circles are tip positions at other times. The 1911/1912 data come from Taylor (1922), the 1940s estimates are from Holdsworth (1982), the 1950–1990 data from a mix of USGS aerial photographs, DeLisle et al. (1989) and vessel observations (Jacobs et al., 1981). The more recent data come from ASTER satellite images.

1980s. There is very little change from the tip position identified by Jacobs et al. (1981) and the point at which the glacier calved in 1990 despite the intervening 1985 aerial photographic observation reported by DeLisle et al. (1989). Did the side-lobes keep moving? i.e. was it still flowing and just sloughing off small bergs at the tip? The Landsat imagery indicates that a 1 km long section of the glacier calved from the south of the EGT tip during 1989.

This diagram also suggests a gradual slowing in the propagation speed of the tip over the last century by as much as a factor of nearly two. From the satellite era we estimate that the speed of the tip over the period January 1989 to December 1992 was 153 $\mathrm{m\,a^{-1}}$. It decreased to 113 $\mathrm{m\,a^{-1}}$ between December 2010 and February 2013. In a macro-sense it needs to be extending at around 130 $\mathrm{m\,a^{-1}}$ to grow sufficiently to match records (Fig. 2c). As a comparison the Drygalski Ice Tongue 250 km to the north moves at around 700 $\mathrm{m\,a^{-1}}$ (Wuite et al., 2003; Frezzotti et al., 1998). These decadal changes in glacier speed could potentially correlate with local climate variations (Frezzotti, 1998; Wuite et al., 2003). Frezzotti (1997) noted that southern McMurdo Sound glacier tongues had 20–50 yr cycles whereas these cycles were shorter farther north. This study was published prior to the 2000–2002 B-15, C-19 iceberg events that influenced sea ice in the region for four or more years (Robinson and Williams, 2012) and such events must play a role in the high degree of variability in that 20–50 yr cycle.

Additionally, the 2013 calving occurred only two days earlier in the year than previous documented occurrences (neither 1911 nor 1990 were leap years). The apparent consistency of this date calls into question the role of storm-driven ocean waves as they are unlikely to always occur in this small time window – and indeed did not in 2013. A number of mechanisms have been explored for failure including the role of ocean swell and excitation of standing waves in the glacier itself (Squire, 1994).

Tidal and ocean currents have not been a strong focus of earlier examinations of calving. Tidal currents certainly influence floating glaciers (Legresy et al., 2004) and might also be considered to be a driver of failure. Synchronicity of calving with spring tides would be evidence of this. However, the present calving took place a day prior to neap tides (Goring and Pyne, 2003). Conversely the calving in 1990 took place a few days before spring tide.

Several things happen to the EGT as it extends out to the longitude of Tent Island. First, it is exposed to currents and waves heading southward past Tent Island and second, it reaches a bathymetric shoal directly south of Tent Island where the water column nearly halves in depth (from around 340 m either side) to as shallow as 190 m. There is likely a feedback whereby the shoaling accelerates the flow.

While tides are not the obvious driver of failure here, the residual circulation flows are significant in the present system. Flow speeds in the region comprise 10 $\mathrm{cm\,s^{-1}}$ regional circulation and tidal speeds on top of this of as much as 15 $\mathrm{cm\,s^{-1}}$ (Stevens et al., 2011). The eastern side of the sound is generally thought to flow southward (Robinson and Williams, 2012). However, observations close to shore indicate a northward flow suggesting there might be flow separation around Tent Island and so flowing back towards the NW (Leonard et al., 2006; Stevens et al., 2013). Such currents were observed in observations near the EGT tip in 2010 (Stevens et al., 2013). This back eddy may be the reason

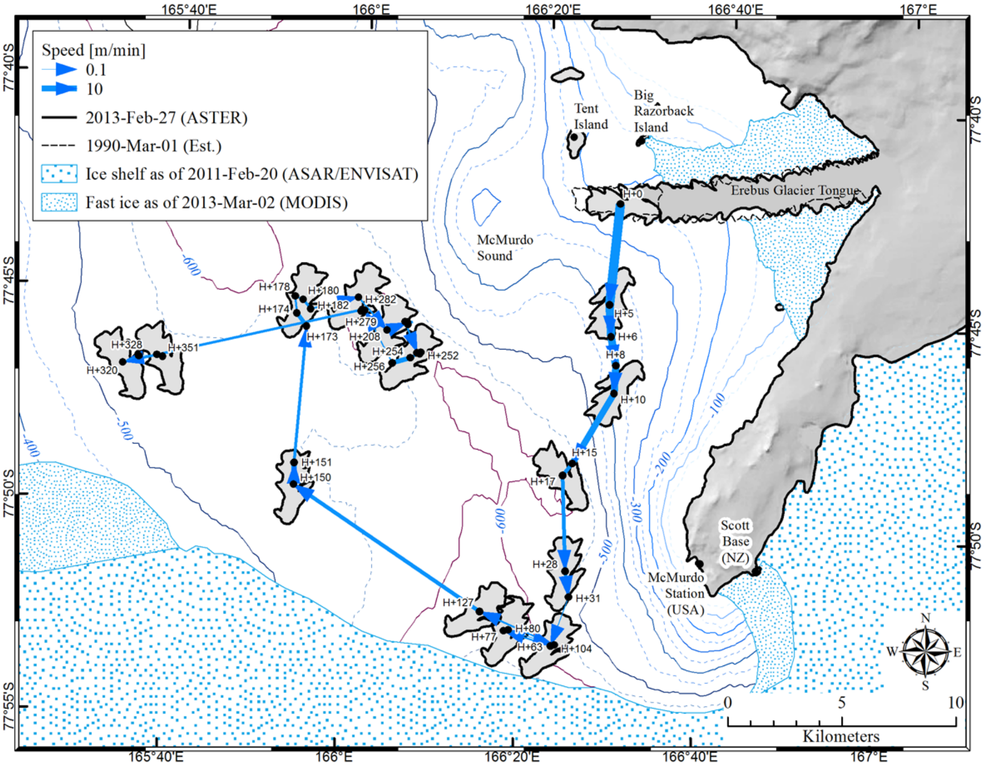

Fig. 3. EGT tip iceberg trajectory built from a sequence of 38 MODIS and 2 ASTER images from year day 57 (26 February 203) through to year day 80 (21 March 2013). Estimated time in hours since detachment is indicated at each location. The width of the arrow is indicative of the speed. Note the 180°rotation when passing McMurdo Station (H + 10 to H + 28).

for the northward bias in the glacier axis as it extends into the sound (although Holdsworth, 1982 suggested differential melting may drive this). The effect of the southward current at the tip is exacerbated by the northward inshore flow, thus applying an enhanced moment about a vertical axis to the glacier.

The ASTER image of the newly detached berg (Fig. 1b) also reveals information about the multi-year ice filling the spaces between lobes. The detachment process has removed these ice-bridges and so the lobes are far more exaggerated. This phenomenon was encountered during the experiments described in Stevens et al. (2013) where an upwards-looking side-scan sonar traversing beneath the glacier ice was expected to see glacier ice but instead only saw multiyear ice.

3 Iceberg trajectory

Iceberg trajectories are generally dominated by ocean currents, so the trajectory followed by the iceberg provides evidence of surface circulation in southern McMurdo Sound. The sequence of events that followed the calving started with an anticlockwise rotation as the berg is driven by the recirculation south of Tent Island. However, as it drifted farther south it moved out of the influence of this back eddy. At this point the berg virtually stopped and rotated about 180°clockwise. This can be explained if there is a southward flowing jet located west of Tent Island. This jet will have a faster flowing core so that an object moving across the jet experiences a change in the sign of the moment imparted to the berg (Fig. 1b).

By the end of day 59 (28 February) the berg reached the McMurdo Ice Shelf. The bathymetry is poorly mapped in this area, but what data there are indicate depths in excess of 500 m, so the berg was not grounded (see Fig. 3). It remained adjacent to the ice shelf, moving with the tide over a period of approximately 60 h, reaching speeds of 4 $\mathrm{cm\,s^{-1}}$. Robinson et al. (2010) found average flows of 18 $\mathrm{cm\,s^{-1}}$ to the SE in this region and tidal speeds up to 30 $\mathrm{cm\,s^{-1}}$. Clearly the berg was not able to accelerate sufficiently rapidly to reach tidal speeds. However, on day 64, the berg commenced moving to the NW at an average speed exceeding 10 $\mathrm{cm\,s^{-1}}$, carrying with it sea ice that remained attached to the berg until at least day 80 when the berg was visibly trapped within more forming sea ice. This trajectory matches the integrated distributions of platelet growth which is indicative that ice shelf influenced water flows to the northwest at some point as one moves to the west across McMurdo Sound (Gough, 2012).

On previous calving occasions the iceberg was later found grounded or locked in fast ice to the northwest. In 1911 it moved to Marble Point (77°15′ S, 164°20′ E) still with a pony chaff depot visible. Similarly, the 1990 berg was later observed near Dunlop Island 23 km north of Marble Point with a sampling station intact and visible. A very similar path was taken by an ice tethered profiler (ITP40 http://www.whoi.edu/itp/itp40data.html) mounted in fast ice that broke away in February 2011 and eventually grounded north of Dunlop Island.

The calving event suggests a number of questions for future research. (i) Analysis of the frequency of calving and implications for change in the region. (ii) Determination of the generation of lobes and importantly their transverse linkages (i.e. why did the highly angled grooves form in the most recently growth period?). (iii) Is there a jet-like surface current moving southward past Tent Island that reduces as one moves to the west and then ultimately turns northward?

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