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Sub-decadal variations in outlet glacier terminus positions in Victoria Land, Oates Land and George V Land, East Antarctica (1972–2013)

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Abstract: Recent work has highlighted the sensitivity of marine-terminating glaciers to decadal-scale changes in the ocean–climate system in parts of East Antarctica. However, compared to Greenland, West Antarctica and the Antarctic Peninsula, little is known about recent glacier change and potential cause(s), with several regions yet to be studied in detail. In this paper, we map the terminus positions of 135 glaciers along the coastline of Victoria Land, Oates Land and George V Land from 1972–2013 at a higher temporal resolution (sub-decadal intervals) than in previous research. These three regions span a range of climatic and oceanic conditions and contain a variety of glacier types. Overall, from 1972–2013, 36% of glaciers advanced, 25% retreated and the remainder showed no discernible change. On sub-decadal timescales, there were no clear trends in glacier terminus position change. However, marine-terminating glaciers experienced larger terminus position changes compared with terrestrial glaciers, and those with an unconstrained floating tongue exhibited the largest variations. We conclude that, unlike in Greenland, West Antarctica and the Antarctic Peninsula, there is no clear glacier retreat in the study area and that most of the variations are more closely linked to glacier size and terminus type.

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Introduction

Recent observations have shown that mass loss from the Greenland and Antarctic ice sheets has accelerated over the last few decades (Joughin & Alley 2011, Rignot *et al.* 2011b, McMillan *et al.* 2014). Current mass balance estimates for 1992–2011 are -142 ± 49 for the Greenland ice sheet (GrIS) and -65 ± 26 Gt yr^{-1} for the West Antarctic Ice Sheet (WAIS) (Shepherd *et al.* 2012). A significant portion of this mass is lost via marine-terminating outlet glaciers (Rignot *et al.* 2013, Joughin *et al.* 2014), which have undergone rapid thinning, acceleration and retreat (Moon & Joughin 2008, Pritchard *et al.* 2009, Carr *et al.* 2013b). These changes have been linked to warming trends in air and ocean temperatures (Pritchard *et al.* 2009, 2012, Joughin & Alley 2011), raising concerns about the future stability of the GrIS and WAIS (Pritchard *et al.* 2009, Joughin *et al.* 2014) and their contribution to global sea level rise, which is currently estimated to be 0.59 ± 0.20 mm yr^{-1} (Shepherd *et al.* 2012).

In contrast, the East Antarctic Ice Sheet (EAIS) is generally believed to be in balance or gaining mass (Zwally *et al.* 2005, Shepherd *et al.* 2012) and is perceived to be much more stable. However, mass balance estimates for the EAIS show considerable variation (Zwally *et al.* 2005, Rignot *et al.* 2011b, Shepherd *et al.* 2012, McMillan *et al.* 2014). For 1992–2006, for example, Rignot *et al.* (2008) estimated the mass balance of the EAIS to be -4 ± 61 Gt yr^{-1} using mass budget techniques, whereas King *et al.* (2012) estimated it to be +60 ± 13 Gt yr^{-1} for a similar period (1992–2010) based on satellite gravimetry techniques. Despite the ice sheet being in balance or slightly gaining mass, some coastal areas of the ice sheet (e.g. Wilkes Land and Oates Land) have been identified as losing mass (Rignot *et al.* 2008, Pritchard *et al.* 2009, King *et al.* 2012). A study by Miles *et al.* (2013) reported rapid and synchronous climate-driven changes in outlet glaciers along the Pacific coast of East Antarctica, which includes Wilkes Land, an area where large marine-terminating outlet glaciers may be particularly vulnerable to changes in sea ice and ocean temperatures (Greenbaum *et al.* 2015, Miles *et al.* 2016, 2017). Indeed, analysis of decadal-scale trends in glacier terminus position suggests that Wilkes Land is the only drainage basin in East Antarctic to show a signal of retreat between 2000–12. However, very little is known about the terminus position changes of marine-terminating outlet glaciers on sub-decadal timescales and some regions have evaded detailed scrutiny.

Furthermore, there has been very little investigation of how non-climatic factors might modulate glacier frontal position change in East Antarctica, such as the configuration of the terminus (land-terminating,

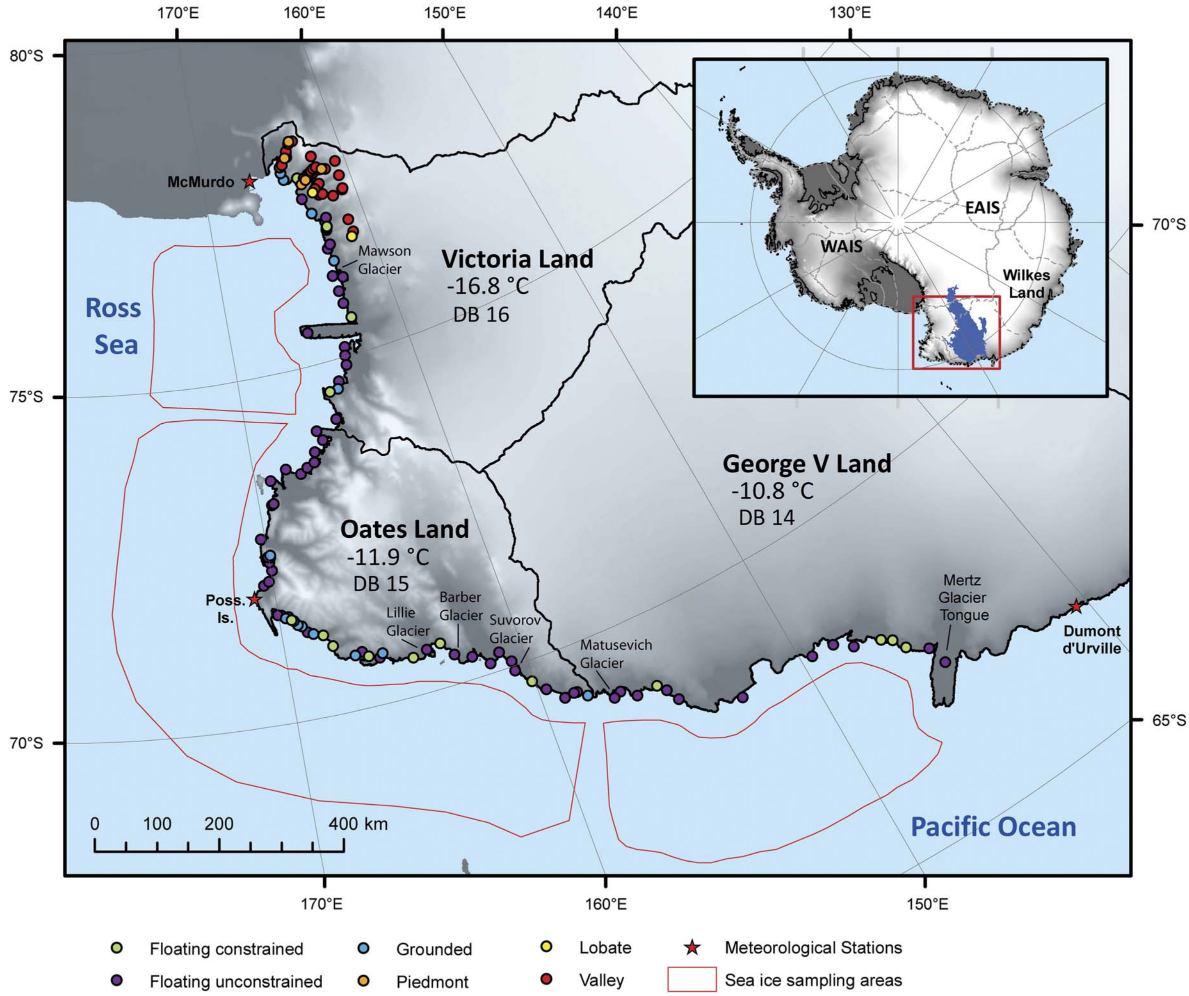

Fig. 1. Location of the study area showing the position of the different types of glaciers that were measured, the meteorological stations (red stars), the location and identification numbers of the George V Land, Oates Land and Victoria Land drainage basins (DB) and the sea ice sampling areas. The inset map shows the locations of Wilkes subglacial basin (in blue) and Wilkes Land. Background image: Bedmap 2 ice surface elevation grid. Glacier types are represented by coloured dots.

marine-terminating, floating tongue versus non-floating terminus, etc.), which have been observed to have an influence on marine-terminating outlet glacier change elsewhere (Moon & Joughin 2008, Carr *et al.* 2013b, 2014). In this paper, we investigate variations in the terminus position of 135 outlet glaciers in Victoria Land, Oates Land and George V Land at six time steps from 1972–2013, and analyse the results in the context of broad-scale regional climatic and oceanic forcing and glacier-specific controls, such as glacier size and terminus type. We build on and extend recent work by Miles *et al.* (2013, 2016, 2017) in this region by: i) mapping an additional 44 land-terminating glaciers which were not included in those studies, ii) mapping all glaciers at a higher temporal resolution (six time steps instead of three) and iii) investigating the influence of glacier-specific characteristics, such as terminus type, on terminus position behaviour.

Study area

The study area covers ~ 1000 km of the East Antarctic coastline from the McMurdo Station, located on the Ross Ice Shelf in southern Victoria Land, to the Mertz Glacier Tongue in George V Land (Fig. 1). This study area was selected because it spans three major drainage basins (DB), with varying ocean–climate characteristics and varying glacier types. These regions have also been used previously to quantify Antarctic mass balance (King *et al.* 2012, Zwally *et al.* 2012). Victoria Land (DB 16) is the furthest south, bordering the Ross Sea. It has the coldest mean annual air temperature of -16.8°C (calculated from the 1957–2014 record from McMurdo Station, see Fig. 1 for location) and, according to recent GRACE estimates, is reportedly in balance or slightly gaining mass (King *et al.* 2012). Oates Land (DB 15) is the smallest of the three regions and borders both the Ross Sea and the

Table I. Summary of glacier terminus type in each region of the study area.

	Victoria Land	Oates Land	George V Land	All regions
Floating constrained	4	7	4	15
Floating unconstrained	17	34	11	62
Grounded	5	9	0	14
Valley	37	0	0	37
Piedmont	5	0	0	5
Lobate	2	0	0	2
All glacier types	70	50	15	135

Pacific Ocean. It has a warmer mean annual air temperature than Victoria Land of -11.9°C (calculated from the 1993–2013 record from Possession Island Station, Fig. 1) and has been identified as an area of mass loss, albeit with high uncertainty (Rignot *et al.* 2008, King *et al.* 2012). George V Land (DB 14) is the largest and furthest north of the three regions, bordering the western Pacific Ocean. It has the warmest mean annual air temperature of -10.8°C (calculated from the 1956–2014 record from Dumont d'Urville Station, Fig. 1) and has also been reported to be losing mass (Rignot *et al.* 2008). George V Land also contains the Wilkes subglacial basin and has been identified as an area potentially vulnerable to future marine ice sheet instability (Mengel & Levermann 2014, DeConto & Pollard 2016).

In addition to the ocean–climate variability, the study area contains a variety of different glacier types (Table I). Victoria Land hosts land-terminating glaciers, including small cirque and valley glaciers, and also marine-terminating glaciers. In contrast, Oates and George V have no land-terminating glaciers, but host different types of marine-terminating glaciers (ranging in terminus width from < 1 km to > 60 km), which can be categorized into glaciers grounded at the terminus, glaciers with a floating terminus constrained within a fjord and glaciers with an unconstrained floating ice tongue. This variation in glacier size, shape and type makes it ideal for investigating the influence of glacier-specific factors on terminus position change.

There have been very few studies that have investigated glacier terminus change in these three regions. Previous studies have primarily focused on individual or small numbers of glaciers with most attention paid to the mechanisms of large calving events on ice tongues such as Drygalski (Frezzotti & Mabin 1994) and Mertz (Massom *et al.* 2015). Larger scale studies of terminus position change in the area have tended to focus on the long-term (decadal) trends of marine-terminating glacier change and whilst early studies did not find any obvious trends in outlet glacier terminus positions (Frezzotti 1997, Frezzotti *et al.* 1998) a recent study by Miles *et al.* (2013) suggested that clear patterns of glacier retreat and advance were evident further west along the Pacific coast (in the neighbouring drainage basin in Wilkes Land) and were strongly linked to variations in air temperature and sea ice concentrations, linked to the Southern Annular Mode (SAM). As noted above, Wilkes Land has since been reported (Miles *et al.* 2016) as being the only drainage basin in East Antarctica to show a trend of glacier retreat (2000–12), with selected glaciers in Victoria Land, Oates Land and George V Land thought to be advancing slowly (~ 10 and 25 m a^{-1}) between 2000–12.

Methods

Image acquisition and co-registration

We acquired satellite imagery in the following years: 1972, 1988, 1997, 2001, 2005, 2009 and 2013. The primary sources of imagery were scenes from the Landsat 1 to 3 Multispectral Scanner (MSS), 4 and 5 Thematic Mapper (TM), 7 Enhanced TM Plus (ETM+) and 8 Operational Land Imager (OLI) Thermal Infrared Sensor (TIRS) satellites, courtesy of the US Geological Survey. Landsat images were chosen for their high spatial resolution (30 m for the Landsat TM and OLI TIRS satellites and 60 m for the Landsat MSS satellites) and coverage across the study area. Synthetic Aperture Radar (SAR) scenes from the European Space Agency's ERS (spatial resolution: 25 m) and ENVISAT (spatial resolution: 100 m) satellites were used where Landsat data were unavailable. Approximately 120 Landsat, eight SAR and six Advanced SAR scenes were used to cover all seven time slices. To minimize the effects of any possible seasonal cycles in advance and retreat, we selected imagery at the end of the summer (mid-January to mid-February). However, where imagery was not available, we also used scenes acquired in December. Although Landsat scenes from the same satellite were provided orthorectified, there were registration inconsistencies between different Landsat satellites and the ERS and ENVISAT imagery. Therefore, all images were co-registered to the Polar Stereographic projection in ESRI ArcGIS using the most recent year (2013), a Landsat 8 OLI TIRS scene, as a base image. We co-registered each image using a series of control points to match recognizable and non-moving landmarks from the image to the base image.

The co-registration error for each type of imagery was estimated by digitizing 16 points across the study area on easily recognizable fixed points, such as nunataks or islands. The mean distance between the points in each of the types of imagery and the corresponding points in the 2013 base image were calculated as the co-registration error. The upper limit of the error calculated for different satellite imagery were: Landsat TM, ETM and OLI TIRS (± 37 m), Landsat MSS (± 65 m), ERS (± 139 m) and ENVISAT (± 215 m). While the co-registration error between different sets of Landsat imagery was relatively low (~ 1 pixel), the error between the Landsat imagery and ERS and ENVISAT data was higher. The co-registration error of the ENVISAT data was particularly high because it had a coarser spatial resolution (100 m) than the Landsat data, making it more difficult to identify recognizable landmarks in the ENVISAT imagery. The digitization error was also determined by repeatedly digitizing 12 sections of the coastline and calculating the mean variation between the segments. This was found to be no more than the resolution error for the different imagery types: Landsat (± 30 m), ERS (± 25 m) and ENVISAT (±100 m) and was considerably lower than the co-registration error. The error per year was calculated for each epoch by dividing the co-registration error (which varies depending on which satellite imagery was used) by the number of years in each epoch (Table SI found at http://dx.doi.org/10.1017/S0954102017000074). Any terminus position changes that were less than the error per year were classified as 'no change'. The error calculated in this study is consistent with the error calculated in other glacier terminus position mapping studies using similar remote sensing methods (Howat & Eddy 2011, Miles *et al.* 2013).

Measuring glacier change

We manually digitized the termini of 135 glaciers in the study area for each time step using ESRI ArcGIS. In order to investigate a broad spread of glaciers over a large area, we focused on glaciers with widths > 500 m. This represents ~85% of the glaciers in the study area. A total of 26 marine- and 44 land-terminating glaciers were mapped in Victoria Land, 50 marine-terminating glaciers were mapped in Oates Land (no land-terminating glaciers exist), and 15 marine-terminating glaciers were mapped in George V Land (no land-terminating glaciers exist) (Table I). The classification of different glacier types was based on the GLIMS illustrated glacier classification manual (Rau *et al.* 2005). We divided glaciers into six terminus types: marine-terminating floating unconstrained (FU), floating constrained (FC) and grounded (G) glaciers, and land-terminating valley (V), piedmont (P) and lobate (L) glaciers. Marine-terminating glaciers with grounded termini were identified using Bedmap2 grounding line data (Fretwell *et al.* 2013).

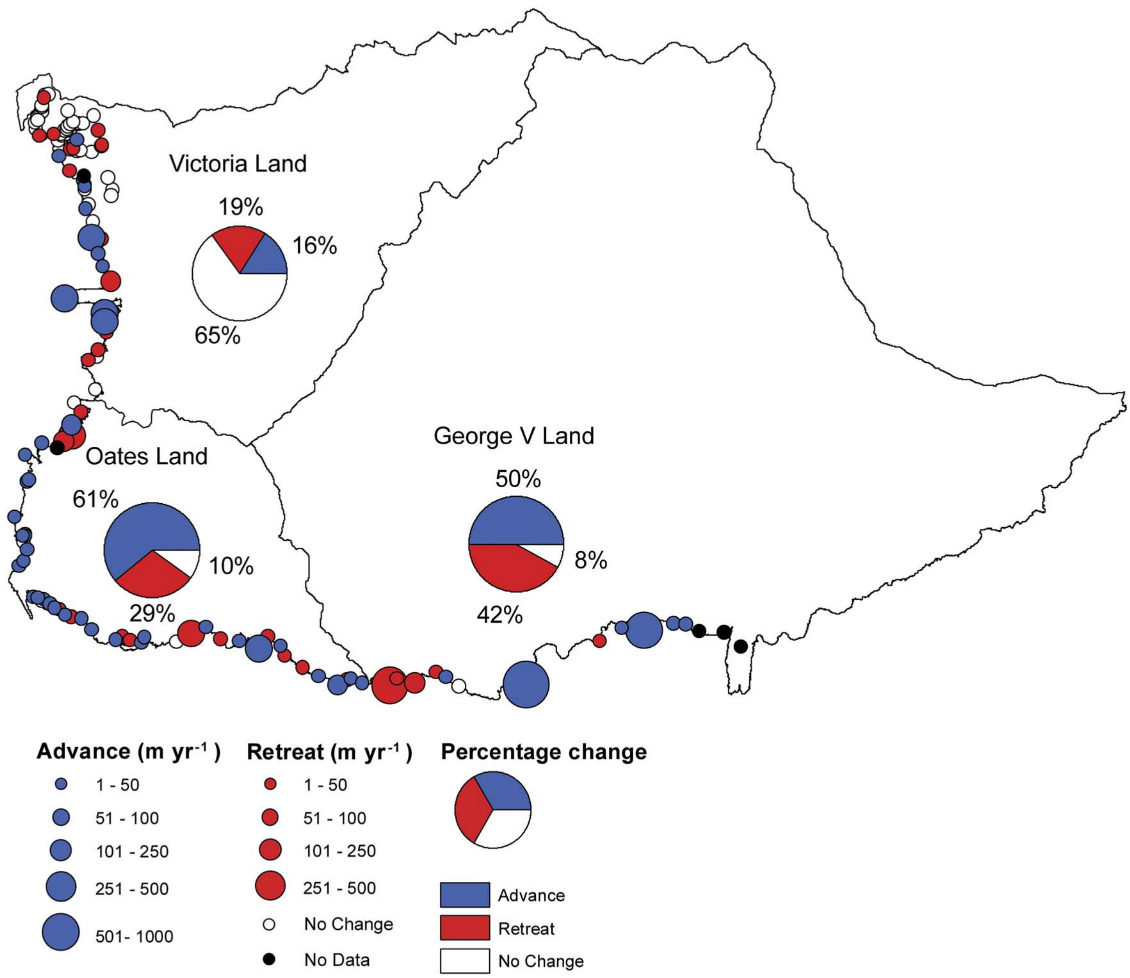

Fig. 2. Glacier terminus position change rates, 1972–2013. Pie charts show the percentage of glaciers within each region with advancing, retreating or stable termini.

Glacier termini that were obscured by cloud cover for a particular time step were not mapped. Due to a lack of imagery, no land-terminating glaciers in Victoria Land could be mapped for the 2005 time step. To circumvent this issue, all glaciers in Victoria Land were mapped using imagery from 2006. Glacier terminus position change was calculated using the well-established rectilinear box method (Moon & Joughin 2008, Carr *et al.* 2013b). Rectilinear boxes were drawn over each glacier terminus; the long sides of which were drawn approximately parallel to the glacier sides. For each time step, the area of each glacier terminus within the box was measured. Following this, the areal difference between subsequent time steps was divided by the width of the glacier to calculate the width-averaged terminus position change between time steps. Then the rate of glacier terminus position change (m yr^{-1}) was calculated between each time step by dividing the width-averaged terminus position change by the number of years between the time steps. Finally, for each time step, the median rate of the width-averaged glacier terminus position change was calculated for all glaciers and for glaciers within each region. The median was chosen as the main summary statistic for the glacier terminus position change rather than the mean, which is more easily influenced by outliers, such as a major calving event on a single glacier. Other glacier attribute data were gathered, including glacier terminus widths measured perpendicular to the central flow line, and velocity data was taken from Rignot *et al.* (2011a), which was sampled as point data 0.5 km up-glacier of the grounding line on the central flow line.

Air temperature and sea ice data

Monthly air temperature data were obtained from stations in each region: McMurdo Station (Victoria Land: 77.9°S, 166.7°E, 24 m a.s.l., 1957–2014), Possession Island automatic weather station (Oates Land: 71.9°S, 171.2°E, 30 m a.s.l., 1993–2013) and Dumont d'Urville (George V Land: 66.7°S, 140.0°E, 43 m a.s.l., 1956–2014) (locations shown in Fig. 1). Data were accessed from the Scientific Committee on Antarctic Research Met Reference Antarctic Data for Environmental Research project (Turner *et al.* 2004). Monthly sea ice data (from 1979–2014) were obtained from the sea ice concentrations from Nimbus-7 Scanning Multichannel Microwave Radiometer and Defense Meteorological Satellite Program Special Sensor Microwave/Imager (SSM/I) and SSMI Sounder Passive Microwave dataset from the National Snow and Ice Data Center (Cavalieri *et al.* 1996). We estimated mean monthly sea ice data for each region within digitized polygons that stretched between 50–200 km offshore (Fig. 1), using the zonal statistics as table tool in ArcGIS. Average annual sea ice concentrations were calculated for each region from the monthly mean data.

We acknowledge that ocean temperatures and basal and frontal glacier melting are potentially important controls on marine-terminating outlet glacier terminus position change, as has been postulated in Wilkes Land (e.g. Totten Glacier; Greenbaum *et al.* 2015). However, oceanic temperature data are not readily available across the study area and, as such, analysis of

Table II. Summary statistics of glacier terminus position change (m yr^{-1}) for all glaciers, and those in Victoria Land, Oates Land and George V Land with uncertainties derived from the co-registration error (in brackets in the column heading). Uncertainties are in m yr^{-1} and vary according to the number of years in each epoch and the satellite imagery used.

Summary statistics (m yr^{-1})	1972–88 (± 4.1)	1988–97 (± 15.4)	1997–2001 (± 34.8)	2001–05 (± 53.8)	2005–09 (± 53.8)	2009–13 (± 9.3)	Long-term: 1972–2013 (± 1.6)
All glaciers							
Median	-2.5	4.5	9.9	45.8	68.1	7.2	0.2
Mean	0.2	48.4	-25.3	47.4	81.1	-135.3	8.8
SD	150.7	131.8	415.2	243.0	235.9	1307.1	80.1
Min.	-758	-159	-4200	-939	-536	-14 177	-343
Max.	1101	854	602	1008	1022	743	574
Victoria Land							
Median	-1.1	-1.8	7.0	-2.9[a]	1.6[a]	5.4	-0.5
Mean	11.0	11.4	16.2	-17.7[a]	28.3[a]	-10.1	7.3
SD	66.2	74.3	72.6	192.1[a]	90.5[a]	147.4	42.8
Min.	-86	-91	-133	-148[a]	-60[a]	-1045	-75
Max.	471	451	467	188[a]	502[a]	343	218
Oates Land							
Median	-6.7	22.7	24.4	68.0	60.3	12.8	5.4
Mean	-10.9	32.0	2.8	33.6	37	-100.1	1.9
SD	58.2	66.4	154.9	153.0	141.9	431.2	47.6
Min.	-263	-159	-601	-464	-317	-2306	-242
Max.	108	193	210	276	415	266	129
George V Land							
Median	-49.8	195.3	-31.5	211.2	98.5	132.7	2.9
Mean	-17.8	264.7	-331.7	264.6	258.3	-899.8	45.6
SD	470.2	246.6	1238.9	314.9	391.7	4000.2	228.7
Min.	-758	-18	-4200	-89	-258	-14 177	-343
Max.	1101	854	602	1008	1022	743	574

[a]Glacier terminus positions in Victoria Land were measured in 2006 instead of 2005 due to a lack of suitable data in 2005. Therefore, the epochs for Victoria Land glaciers are 2001–06 and 2006–09 with uncertainties of ± 7.4 m yr^{-1} and ± 12.3 m yr^{-1}, respectively.

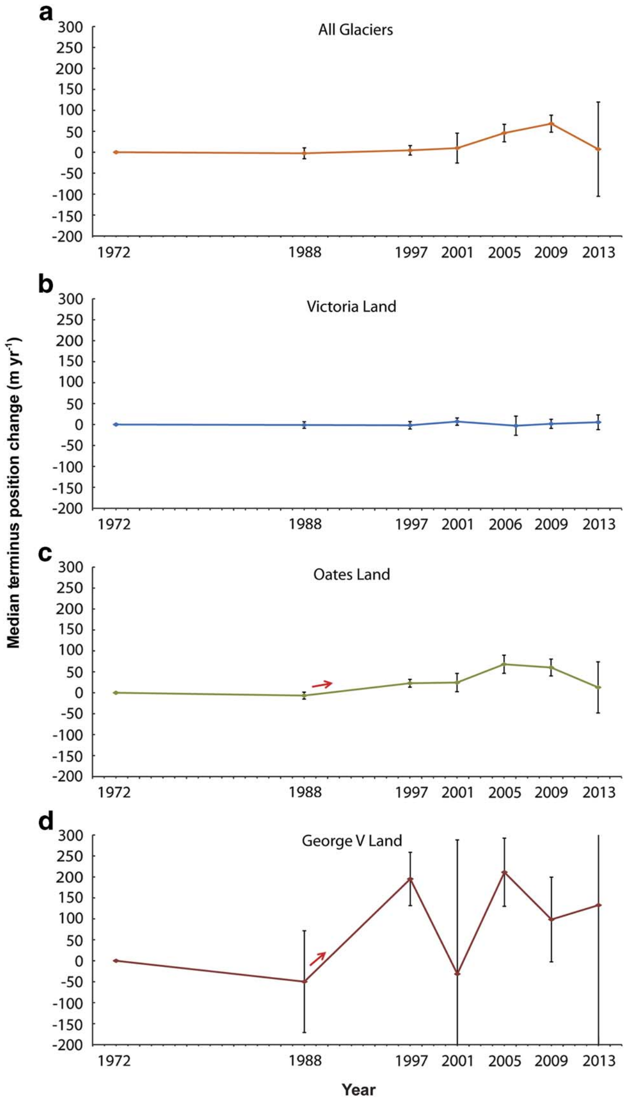

Fig. 3. Median terminus change (m yr^{-1}) per epoch for **a.** all glaciers in the whole study area, **b.** Victoria Land, **c.** Oates Land and **d.** George V Land. 1 standard error bars. Note that some error bars extend beyond the plot. Red arrows in **c.** and **d.** indicate where the glacier terminus position trend is significantly different from the previous epoch.

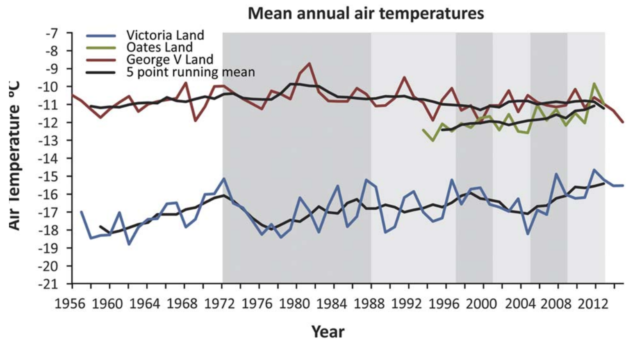

Fig. 4. Mean annual air temperatures from the three Antarctic stations that sit in each of the three studied regions. Epochs where glacier changes were measured are shaded in background.

ocean temperature trends have not been included in this investigation.

Statistical analysis

The relationships between termini change and possible drivers were analysed using statistical tests. The Wilcoxon rank sum test was used to test the significance of observed epochal differences within terminus position change (the null hypothesis being that rates of glacier termini change in the two epochs are the same) and the differences in the long-term terminus position changes between marine- versus land-terminating glaciers. The Kruskal–Wallis test was used to test the differences between the three marine-terminating glacier terminus types (FC, FU and G). These non-parametric tests were used to test the differences in the terminus position change data, rather than parametric tests, to avoid the results being influenced by outliers, such as extreme calving events on individual glaciers. The Student's *t*-test was used to test the significance of any observed epochal differences in mean annual and mean summer air temperatures, and mean sea ice concentrations. Linear regression analyses were used to test long-term trends in sea ice concentrations and mean annual and mean summer air temperatures in the three regions. Only statistical relationships that are significant are mentioned in the Results and Discussion sections, and we clearly acknowledge that correlation does not necessarily imply causation. Rather, we see these as a preliminary investigation of potential controls on glacier change.

Results

Time series of glacier terminus position change

Between 1972 and 2013, 36% of glacier termini in the entire study area advanced and 25% of glacier termini retreated, with the remainder showing no discernible change outside of the measurement error ($\pm$ 65 m or $\pm$ 1.6 m yr^{-1}) and classified as 'no change' (Fig. 2). The median terminus position change for all glaciers ($n = 135$) between 1972 and 2013 was 0.2 ± 1.6 m yr^{-1} (Table II). Over the same time period, but within each region, 16% of glaciers in Victoria Land advanced, 19% retreated and 65% exhibited no change with an overall median terminus position change rate of -0.5 ± 1.6 m yr^{-1}. In Oates Land, 61% of glaciers advanced, 29% of glaciers retreated and 10% showed no change (long-term median terminus position change rate: 5.4 ± 1.6 m yr^{-1}). In George V Land, 50% of glaciers advanced, 42% retreated and 8% showed no change (long-term median terminus position change rate: 2.9 ± 1.6 m yr^{-1}).

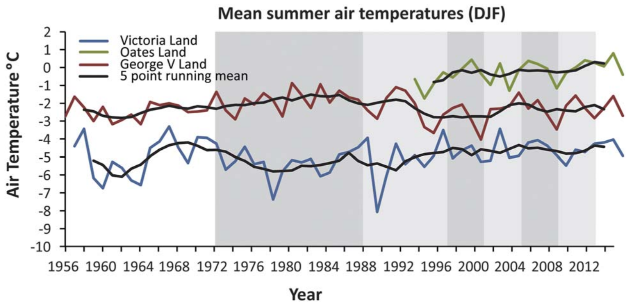

Fig. 5. Mean summer air temperature data (December, January, February) from the Antarctic stations used in this study. Epochs where glacier changes were measured are shaded in background.

There were no clear trends (outside of the measurement error) in glacier terminus position changes for the entire glacier population between epochs. While Fig. 3a suggests that there was a slight advance in all glaciers during the 2001–05 and 2005–09 epochs, the median terminus position change rates remained within the error margin for each epoch (Table II).

When terminus position change patterns are examined in each region, some differences in behaviour emerge. The glaciers in Victoria Land (Fig. 3b) experienced the least variation in terminus positions of the three regions with a standard deviation (SD) for the longest time step (1972–2013) of 42.8 m yr^{-1} (Table II). Median terminus position change values were within the error margins for each epoch.

Variations in glacier terminus position changes in Oates Land were slightly larger than in Victoria Land (SD 1972–2013: 47.6 m yr^{-1}). After a period of minor retreat during the 1972–88 epoch (median terminus position change: -6.7 ± 4.1 m yr^{-1}), the termini of glaciers in Oates Land (Fig. 3c) experienced a significant shift ($P < 0.05$) to a period of advance (median terminus position change: 22.7 ± 15.4 m yr^{-1}). This advance continued until 2005, when glacier terminus position change began to fall from a period of major advance (median terminus position change: 68.0 ± 53.8 m yr^{-1}) during the 2001–05 epoch to a period of minor advance (12.8 ± 9.3 m yr^{-1}) during the 2009–13 epoch, but the changes between these most recent three epochs were not significant.

Glaciers in George V Land (Fig. 3d) underwent the most extreme changes per epoch, experiencing both the largest advance (maximum advance: 1101 m yr^{-1} 1972–88) and the largest retreat distances (maximum retreat: -14 177 m yr^{-1} 2009–13) of all three regions in the study area (SD 1972–2013: 228.7 m yr^{-1}). During the 1972–88 epoch, glaciers in George V Land generally retreated (median terminus position change: -49.8 ± 4.1 m yr^{-1}). From 1988 onwards, however, there was a significant change ($p < 0.05$) to a period of advance (median terminus position change: 195.3 ± 15.4 m yr^{-1}). This advance was followed by a period from 1997–2001 when there was no strong trend (median terminus position change: -31.5 ± 34.8 m yr^{-1}) but 54% of the glaciers retreated. Glaciers then returned to a period of advance during the 2001–05 epoch (median terminus position change: 211.2 ± 53.8 m yr^{-1}). This was maintained to the end of the study period, although the median terminus position change rate was reduced to 98.5 ± 53.8 m yr^{-1} and 132.7 ± 9.3 m yr^{-1} for the 2005–09 and 2009–13 epochs, respectively.

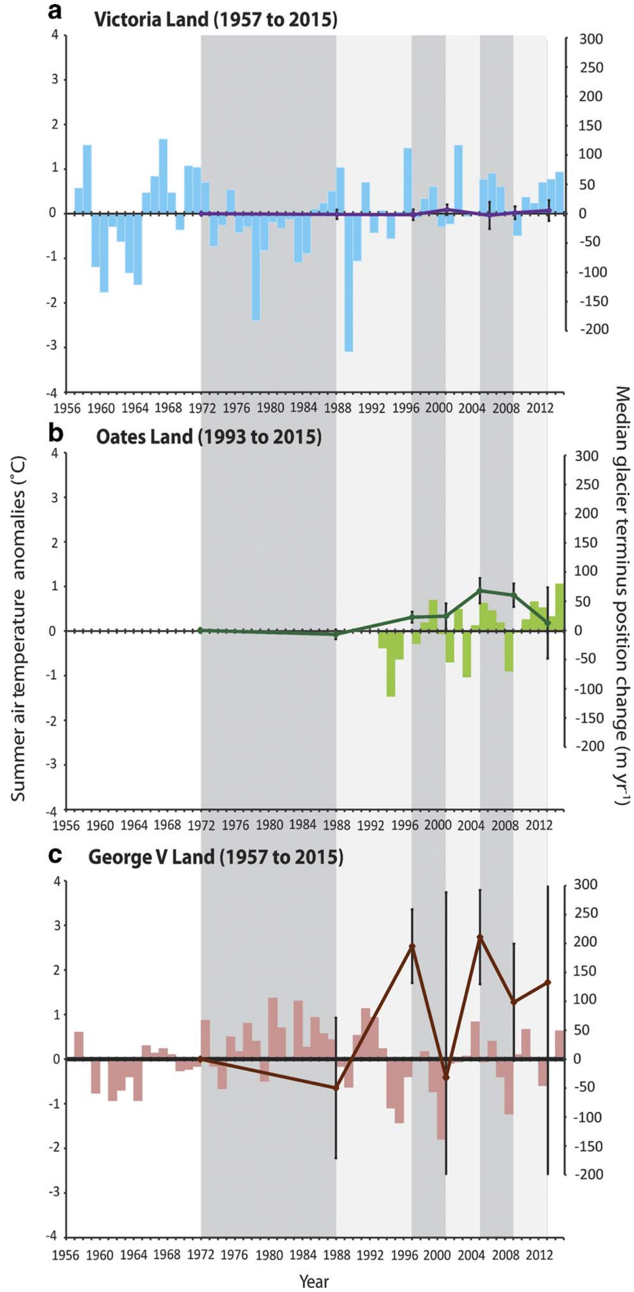

Fig. 6. Mean summer air temperature anomalies and median terminus change (m yr^{-1}) for **a.** Victoria Land, **b.** Oates Land, **c.** George V Land. 1 standard error bars for the median glacier terminus position changes. Note that some error bars extend beyond the plot. Epochs where glacier changes were measured are shaded in background.

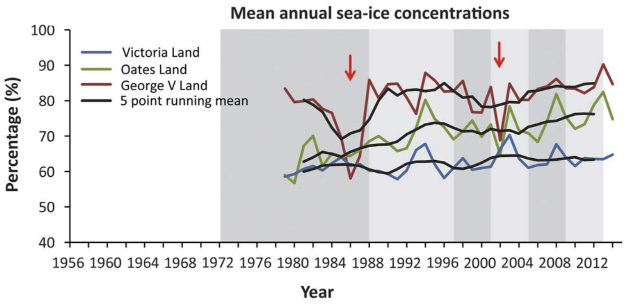

Fig. 7. Mean annual sea ice concentrations. Major decreases in George V Land marked with red arrows. Epochs where glacier changes were measured are shaded in background.

Climate and sea ice data

Victoria Land had the coolest mean annual air temperatures of the three regions between 1972 and 2013 (-16.6°C), ~6°C cooler than George V Land, and 5°C cooler than Oates Land for the mean annual air temperatures on record for that region (Fig. 4), but exhibited a warming trend between 1976 and 2012 ($R^2 = 0.6$, $P < 0.05$). Since records began in 1993, mean annual air temperatures in Oates Land experienced ~1°C of warming ($R^2 = 0.8$, $P < 0.05$), but the measurement record is, perhaps, too short to be considered a long-term trend. George V Land exhibited a cooling trend in mean annual air temperatures from 1980 onwards ($R^2 = 0.5$, $P < 0.05$) after a period of warming from 1958–79 ($R^2 = 0.7$, $P < 0.05$).

Victoria Land also had the coolest mean summer (December, January, February) air temperatures out of the three regions between 1972– 2013 (-5°C), exhibiting a warming trend ($R^2 = 0.5$, $P < 0.05$) from 1972–2013 (Fig. 5). Oates Land had the warmest mean summer air temperatures (-0.3°C), exceeding 0°C during 21 of the past 22 years and exhibited a warming trend of ~1°C during that time ($R^2 = 0.6$, $P < 0.05$). George V Land had cooler mean summer air temperatures (-2.2°C) than Oates Land, but exhibited no obvious long-term trends. When plotted as air temperature anomalies, Victoria Land had cooler than average mean summer temperatures from 1973–95 (Fig. 6a). George V Land experienced a period of generally above average summer air temperatures from 1972–94 (Fig. 6c). This was followed by a sequence of cooler than average summer temperatures up until 2001.

Mean long-term (1979–2014) sea ice concentrations in the study area were 62% in Victoria Land, 71% in Oates Land and 81% in George V Land. There were increasing trends in mean sea ice concentrations in all regions between 1981–2012 (Victoria Land: $R^2 = 0.5$, $P < 0.05$ and George V Land: $R^2 = 0.4$, $P < 0.05$) (Fig. 7). However, the strongest trend of increasing sea ice was in Oates Land ($R^2 = 0.8$, $P < 0.05$) with mean sea ice concentration increasing from 64% during the 1972–88 epoch to 77% in the 2009–13 epoch. Sea ice concentrations were most variable in George V Land, with the largest SD (6.6% 1979–2014), and experienced a noticeable decrease during the epoch 1972–88, with a minimum yearly averaged sea ice concentration of 58% in 1986. A smaller decrease in sea ice concentrations was experienced in both George V Land and Oates Land during the 2001–05 epoch, in 2002, with minimum sea ice concentrations dropping ~10% and ~ 6% below average, respectively.

Glacier change by terminus type

The study area contains 91 marine- and 44 land-terminating glaciers, but only Victoria Land contains land-terminating

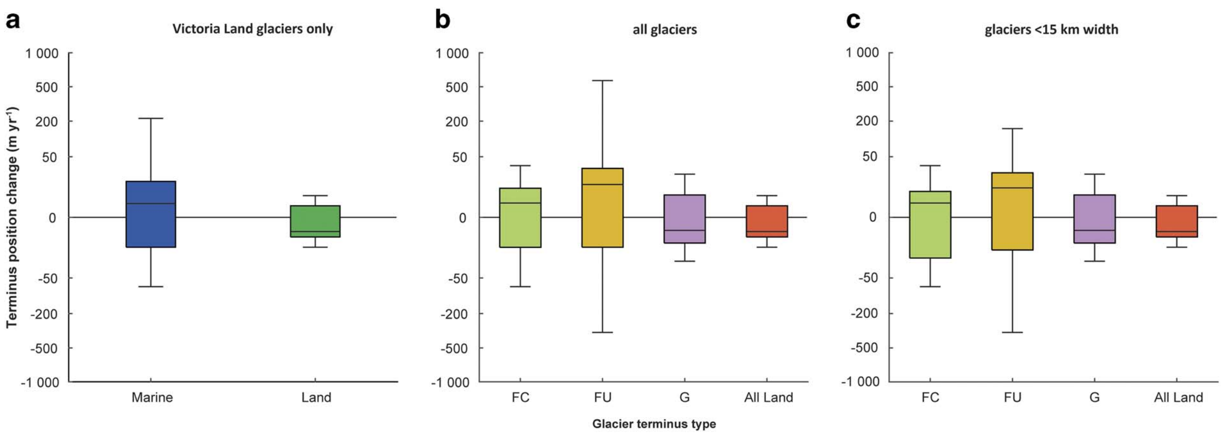

Fig. 8. Box plots of **a.** terminus position change (1972–2013) of marine- versus land-terminating glaciers in Victoria Land, which is the only region to contain land-terminating glaciers (Table I), **b.** terminus change of different marine-terminating terminus types, **c.** terminus change of marine-terminating terminus types for glaciers < 15 km width. FC = floating constrained, FU = floating unconstrained, G = grounded. All boxplots show median, 25th and 75th percentiles and whiskers that include all values that are < 1.5 times the interquartile range away from the 25th or 75th percentiles. All land-terminating glaciers are only in Victoria Land.

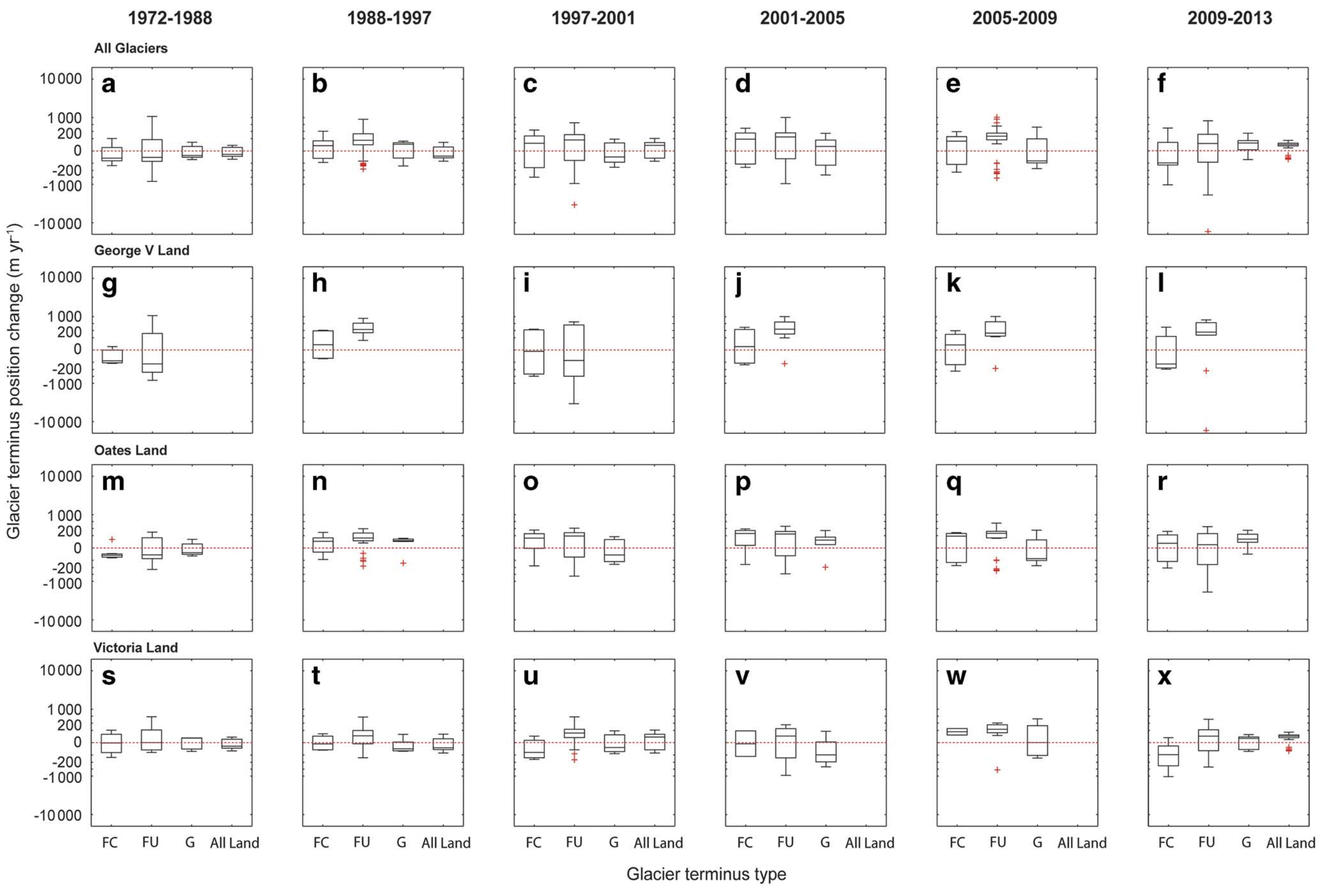

Fig. 9. Terminus change per epoch for **a.–f.** all glaciers, **g.–l.** George V Land, **m.–r.** Oates Land and **s.–x.** Victoria Land. FC = floating constrained, FU = floating unconstrained, G = grounded. All boxplots show median, 25th and 75th percentiles and whiskers that include all values that are <1.5 times the interquartile range away from the 25th or 75th percentiles. All values beyond this are considered to be outliers and are marked with a red cross.

glaciers (Table I). Over the longest time step (1972–2013), there were no significant differences in terminus position change between marine- and land-terminating glaciers in Victoria Land (Fig. 8a). The median terminus position change rates for marine- and land-terminating glaciers were 0.6 ± 1.6 and -0.6 ± 1.6 m yr^{-1}, respectively. However, marine-terminating glaciers experienced far more variation than land-terminating glaciers. The range of glacier terminus position change was more than one order of magnitude higher for marine-terminating glaciers (293 m yr^{-1}) than for land-terminating glaciers (8 m yr^{-1}). When examining the entire dataset for all three regions, there were also differences in glacier behaviour within the marine-terminating glaciers (Fig. 8b). Although, there were no significant differences between each class of marine-terminating glacier in terms of advance or retreat, those with FU termini experienced the largest terminus position variation with a range of 918 m yr^{-1}, followed by glaciers with FC termini (range: 106 m yr^{-1}). Marine-terminating glaciers that were grounded (G) had the smallest terminus changes (range: 37 m yr^{-1}). These patterns are very similar for glaciers <15 km wide (Fig. 8c), which demonstrates that major and potentially stochastic calving events on large glaciers are not skewing the trends. Figure 9 shows the breakdown per epoch of glacier position change by terminus within each region and for all glaciers.

Major calving events and cyclical behaviour

Several glaciers (n = 16) experienced one or more large calving events. For the purpose of this study, a large calving event is when the length (long axis) of the glacier terminus lost during the time step is larger than the glacier width. It should be pointed out that the coarse temporal resolution of the glacier terminus position change dataset means that it is not possible to identify whether these large losses are the result of the calving of one large iceberg at a single point in time or the accumulated loss of numerous small icebergs throughout the time step. There was at least one of these major calving events in every epoch, but nine of these events (56%) occurred between 2009–13, the majority of them (n = 6) taking place in Oates Land. Major calving events occurred in glaciers of varying size

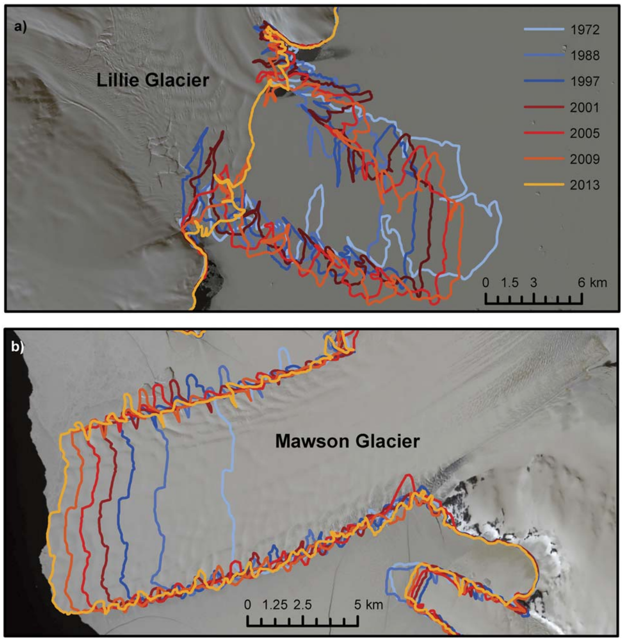

Fig. 10. Digitized terminus positions for **a.** Lillie Glacier, an example of a glacier that has experienced a major calving event (background Landsat 8 image from 24 February 2014), and **b.** Mawson Glacier, Victoria Land, an example of a glacier that has maintained the same terminus shape throughout the study period (background Landsat 8 image from 10 December 2013).

(3–40 km width) and in all three regions. All but one major calving event occurred on glaciers with FU termini. Two glaciers, Matusevich Glacier (9 km wide) and Lillie Glacier (12 km wide) (Fig. 10a; locations shown on Fig. 1), experienced more than one major calving event during the study period, separated by a period of advance. They both first experienced major terminus position retreat in the 1972–88 epoch and then Matusevich Glacier calved a second time in the 1997–2001 epoch, and Lillie Glacier calved in the 2009–13 epoch. This hints that the glaciers were calving and advancing in a cyclic manner. Approximately 50% ($n = 46$) of marine-terminating glaciers, in all three regions of the study area, showed signs of cyclic behaviour (calving followed by a period of advance). However, the temporal resolution of our data is not high enough to define the start and end of these cycles. There were also a number of glaciers ($n = 10$) that maintained their terminus shape throughout the study period, implying that they experienced no major calving events during the ~40 years of the study period (e.g. Mawson Glacier; Fig. 10b). These were all located in Oates Land and Victoria Land, but were spread out among the two regions.

In general, we observed heterogeneity in the calving behaviour of neighbouring glaciers. This is illustrated by a case study of six neighbouring marine-terminating glaciers in Oates Land (from Suvorov Glacier to Barber Glacier) (Fig. S1 found at http://dx.doi.org/10.1017/S0954102017000074) where there were asynchronous patterns in terminus position changes. Barber Glacier (70.4°S, 162.8°E) experienced a slight retreat from 1972–97, and then advanced in 2005 and 2009 before experiencing a major calving event in 2013. Rennick Glacier (70.1°S, 161.5°E), on the other hand, advanced consistently throughout the study period. Pryor Glacier (70°S, 160.6°E) advanced from the beginning of the study period until 2001, after which it retreated. It then advanced again until the end of the study period. Meanwhile, the termini of Suvorov (69.9°S, 160.6°E) and Svendsen (70.2°S, 160.9°E) glaciers changed very little throughout the entire study period.

Discussion

Spatial trends in glacier terminus position behaviour

The results show that between 1972–2013, 36% of glacier termini in the study area advanced, 25% retreated and 39% exhibited no change. However, our data reveal differences in the magnitude of outlet glacier terminus position changes in the drainage basins of Victoria Land, Oates Land and George V Land over the past 40 years. Glaciers in Victoria Land appear to be most stable in that they rarely show large advances or retreats beyond a few tens of metres (long-term SD: 42.8 ± 1.6 m yr^{-1}), glaciers in Oates Land show more variable behaviour (long-term SD: 47.6 ± 1.6 m yr^{-1}) and glaciers in George V Land exhibit the most dramatic changes, with both advances and retreats of several hundred metres (long-term SD: 228.7 ± 1.6 m yr^{-1}). These regional differences are not obviously correlated to differences in air temperature in each region. Whilst Victoria Land is clearly the coldest area (Figs 4 & 5) and the negligible changes in glacier terminus behaviour are consistent with its climate, the warmest temperatures in the three regions consistently occurred in Oates Land (mean: -0.3°C) where temperatures exceeded 0°C in 21 of the last 22 years. Indeed, areas of supraglacial meltwater pooling were observed on several marine-terminating glaciers in the region, three of which had large systems of supraglacial meltwater pools (covering an area > 40 km^2 with > 40 ponds) (Fig. 11). Air temperature-induced ice surface melt has the ability to impact on glacier terminus position behaviour via hydrofracture whereby the added pressure of the presence of water encourages crevasse propagation to the bed of the glacier or ice shelf and increases calving (Benn *et al.* 2007). This was observed during the catastrophic collapse of the Larsen B Ice Shelf in the Antarctic Peninsula in March 2002, which was directly preceded by the rapid and synchronous drainage of thousands of supraglacial meltwater pools on the ice shelf surface, strongly

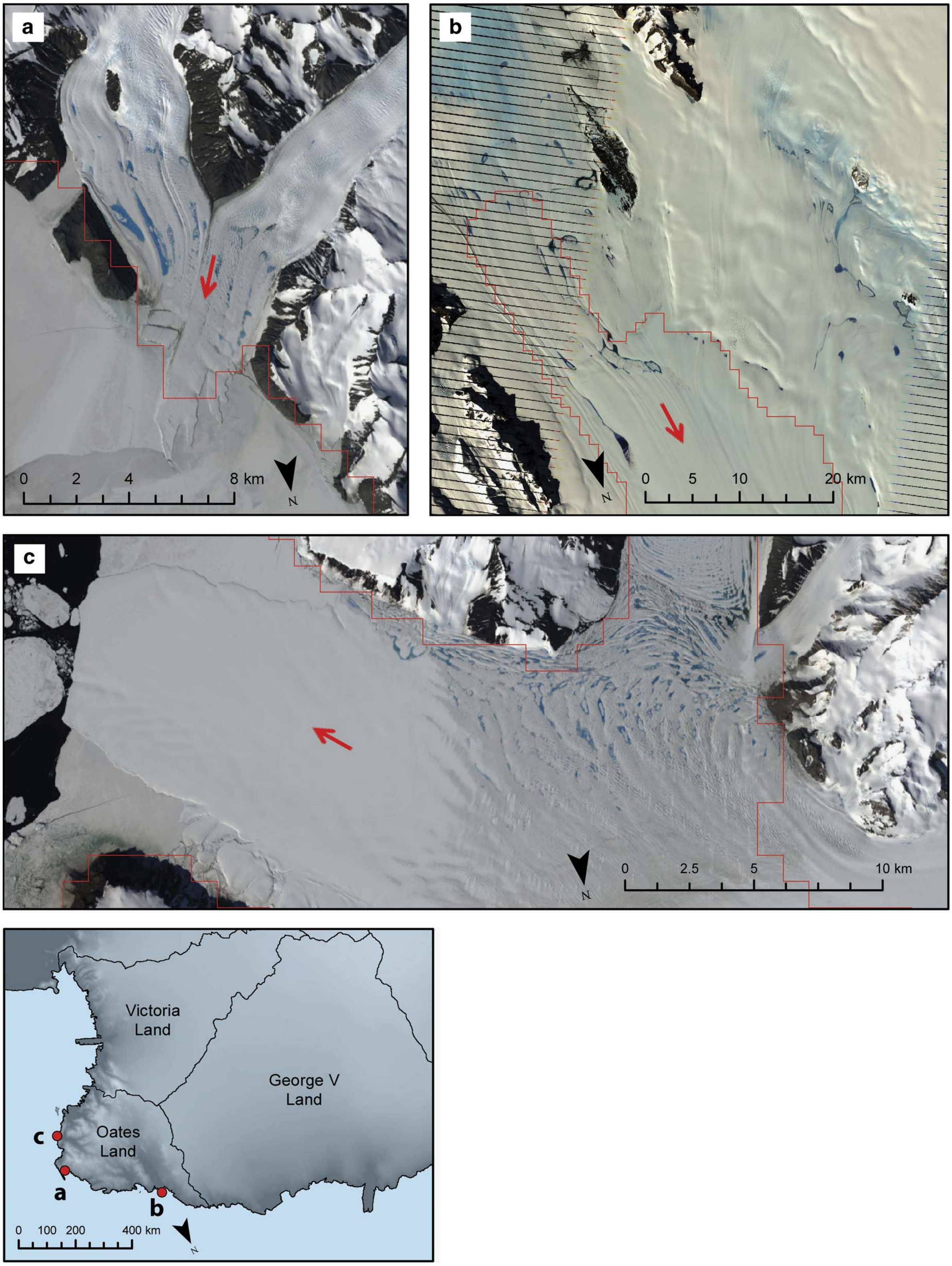

Fig. 11. Supraglacial meltwater pools observed on glaciers in Oates Land on **a.** Dugdale Glacier, up-glacier of the grounding line according to data provided by Bedmap 2 (Fretwell *et al.* 2013) (image taken on 2 January 2014), **b.** Rennick Glacier, up- and down-glacier of the grounding line (image taken on 3 February 2010), and **c.** Tucker Glacier, down-glacier of the grounding line (image taken on 2 January 2014). The grounding line is in red. Red arrows indicate glacier flow direction.

indicating that the collapse was triggered by meltwater pool-induced hydrofracture (Banwell *et al.* 2013). Recent observations suggest that supraglacial meltwater pools in crevasses on the floating ice shelf of Langhovde Glacier in Dronning Maud Land, East Antarctica, have also exhibited vertical drainage which may be a result of hydrofracture (Langley *et al.* 2016). However, we do not see evidence of this behaviour in Oates Land. All of the three glaciers with substantial meltwater ponding in Oates Land advanced between 1972–2013 (Rennick Glacier: 129 ± 1.6 m yr^{-1}, Dugdale Glacier: 19 ± 1.6 m yr^{-1}, Tucker Glacier: 17 ± 1.6 m yr^{-1}) and the largest fluctuations in retreating or advancing trends actually occurred in glaciers in George V Land, which had cooler summer temperatures than Oates Land (Fig. 5). This implies that the difference in magnitude of glacier behaviour in the three regions is not primarily related to air temperatures.

Sea ice has also been observed to have an impact on marine-terminating glacier terminus position behaviour where the presence of sea ice fastens together the mélange in front of the terminus and suppresses calving and iceberg removal, and the absence of sea ice coincides with accelerated calving (Amundson *et al.* 2010, Miles *et al.* 2017). While there were regional differences in sea ice concentrations in the study area (Fig. 7); mean sea ice concentrations were lowest in Victoria Land (62% 1979–2014) and highest in George V Land (81%). These regional differences in sea ice do not appear to correspond with the differences in glacier terminus position change magnitude because glacier termini in George V Land, which had the highest concentrations of sea ice, would be expected to be the most stable and glaciers in Victoria Land, with the lowest concentrations of sea ice, would be expected to be the least stable (Carr *et al.* 2013a).

Thus, the spatial trends we observe, with glacier termini showing least variability in Victoria Land and most in George V Land, do not appear to be closely correlated with the different air temperature and sea ice regimes. However, there is a clear gradient in glacier size (expressed in this study as glacier width) from Victoria Land, which tends to have the smallest glaciers in the study area, to George V Land, which tends to have the largest glaciers (Fig. 12). Larger glaciers in the region tended to have higher velocities ($R^2 = 0.32$, $P < 0.05$) (Fig. S2 found at http://dx.doi.org/10.1017/S0954102017000074) and glaciers with higher velocities tended to exhibit larger magnitude changes in advance and retreat ($R^2 = 0.49$, $P < 0.05$) (Fig. S3 found at http://dx.doi.org/10.1017/S0954102017000074). This tentative correlation leads us to hypothesize that the larger fluctuations in George V Land compared with Oates Land or Victoria Land (see Fig. 3) could be related to glacier size rather than any regional differences in sea ice or air temperatures.

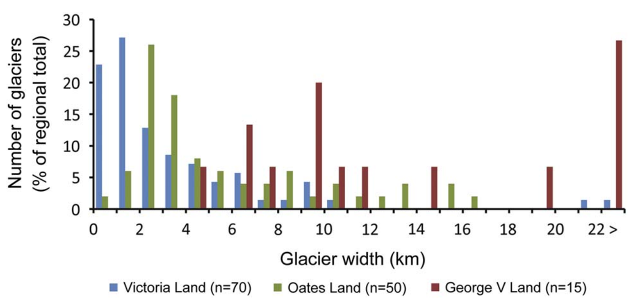

Fig. 12. Histogram of glacier widths in the three regions of the study area.

Temporal trends in glacier behaviour and ocean–climate forcing

With only limited climate and sea ice data from each drainage basin, we acknowledge the difficulty of implying causation from correlations between glacier change and trends in environmental variables. We also acknowledge that the response of individual glaciers can be driven by local glacier-specific controls such as subglacial topography and changes in fjord geometry (Carr *et al.* 2013a, Moon *et al.* 2015). Notwithstanding these limitations, we now discuss possible links between external forcing and glacier change that allow us to develop some hypotheses that future work might test with more detailed observations/data.

Previous work by Miles *et al.* (2013, 2016) suggested that glaciers in the warmer Pacific Ocean region experienced significantly more variation compared to the glaciers in the colder Ross Sea region and suggested that decadal variations in glacier terminus change in Wilkes Land (DB 13) were linked to changes in air temperature and sea ice, that were associated with changes in the dominant mode of atmospheric circulation, the SAM. Our data from Victoria Land, Oates Land and George V Land are at a higher temporal resolution than in the Miles *et al.* (2013, 2016) studies and include previously unmapped land-terminating glaciers in Victoria Land, but we find similar decadal-scale trends. Between 1974–90, Miles *et al.* (2013, 2016) found that the majority of outlet glaciers in Oates Land and George V Land retreated before switching to a period where they mostly advanced between 1990–2000. In contrast, they noted that glaciers in Victoria Land remained stable throughout both epochs. We also find a significant switch from glacier retreat to glacier advance in both Oates Land (Fig. 3c) and George V Land (Fig. 3d) from the first epoch (1972–88) to the second (1988–97), while glaciers in Victoria Land showed no overall trends. Unfortunately, the mean summer air temperature record in Oates Land is not long enough to observe whether air temperature changes correlate with this significant switch from retreat to advance (Fig. 6b), but it does coincide with a significantly increasing trend in sea ice in the region (Fig. 7). This is consistent with the theory that increased sea ice concentrations can suppress calving and promote terminus advance (Amundson *et al.* 2010, Carr *et al.* 2013a, Fukuda *et al.* 2014, Miles *et al.* 2017). In George V Land, the significant switch from glacier terminus retreat to advance coincided with a change from a period of unusually high mean summer air temperatures (1972–88) to a period of below average mean summer air temperatures (1988–97) (Fig. 6c). The retreat in the 1972–88 epoch also coincided with a reduction in sea ice concentrations, which dropped to a minimum of 58% in 1986 (Fig. 7). Thus we hypothesize that the significant change from a period of retreat to a period of advance from the 1972–88 epoch to the 1988–97 epoch could be linked to changes in sea ice in Oates Land and to changes in sea ice and mean summer air temperatures in George V Land, but further work is required to test these hypotheses, and we acknowledge that the response of individual glaciers will be modulated by the local topographical settings (Carr *et al.* 2013a, Moon *et al.* 2015).

From 1997 onwards, our data from Victoria Land, Oates Land and George V Land are at a higher resolution than those reported in Miles *et al.* (2013, 2016) (Fig. 3). Miles *et al.* (2013, 2016) reported that glaciers along the coastline of the Ross Sea and Pacific Ocean were predominantly advancing during both the 1990–2000 and 2000–12 epochs, although with a significantly weaker trend of glacier advance during the latter epoch. Our data from shorter time intervals in Victoria Land, Oates Land and George V Land, also show that glaciers were predominantly advancing. Note, however, that we did not map any glaciers in DB 13 (Wilkes Land), which Miles *et al.* (2016) showed is the only major drainage basin in East Antarctica where the majority of glaciers have retreated in the last decade. More recently, Miles *et al.* (2017) have also documented multiple ice tongue collapses in the Porpoise Bay area of Wilkes Land, which they attributed to major sea ice break-up. This region was further west than our study area, but our mapping shows no evidence for similar calving events in Victoria Land, Oates Land and George V Land.

Links between mass loss and glacier terminus position change

Mass loss, albeit with very large uncertainties, was detected in Oates Land (-5 – -15 ± 10 Gt yr^{-1}) for 2002–10 using gravimetric techniques and GRACE satellite data (King *et al.* 2012) and potentially in Victoria Land (-2 ± 4 Gt yr^{-1}) and Oates Land (-2 ± 5 Gt yr^{-1}) for 2010–13 using altimetry techniques and Cryosat-2 data (McMillan *et al.* 2014). Both studies found George V Land to be predominantly in balance (-5–5 Gt yr^{-1} from 2002–10 according to King *et al.* (2012) and 1 ± 13 Gt yr^{-1} from 2010–13 according to McMillan *et al.* (2014)). However, it is interesting to note that in Oates Land and Victoria Land, we do not see any signal of retreat coincident with the mass loss detected in that drainage basin for 2002–10 using GRACE satellite data (King *et al.* 2012). Indeed, from 2001 onwards, glaciers in Oates Land increasingly advanced (Fig. 3c) and there is no obvious signal of retreat in Victoria Land during the last epoch (2009–13) (Fig. 3b). In the absence of any major changes in precipitation, of which we are unaware, there are two possible explanations. First, the mass losses detected in Oates Land and in the McMillan *et al.* (2014) study for Victoria Land were relatively small (-2 – -12 Gt yr^{-1}) and subject to large uncertainties. As such, the signal of mass loss could be negligible. Second, if mass loss is occurring, it could be via glacier thinning and basal melt rather than terminus calving. Thus, it might not necessarily be apparent through observations of glacier terminus position change (Pritchard *et al.* 2012). This is perhaps supported by satellite altimetry data which shows that parts of the Oates Land margin were thinning by up to 1.5 m yr^{-1} between 2003–07 (Pritchard *et al.* 2009) and by data from Rignot *et al.* (2013) which revealed that several of the largest outlet glaciers in Victoria Land and Oates Land (e.g. David, Nansen, Aviator, Mariner, Lillie and Rennick) lose more mass via basal melting than through calving. Despite altimetry data indicating that Rennick Glacier was thinning due to increased basal melt between 2003–08, (Pritchard *et al.* 2012), its terminus steadily advanced throughout the duration of this study (Fig. S1). It is possible, therefore, that if mass loss is occurring via these mechanisms, the response of the terminus is delayed, but might take place imminently unless glaciers undergo acceleration. This highlights the complexities of these systems and suggests that further work is required to understand the timescales of ocean–climate forcing and glacier response.

Influence of glacier terminus type

Our data show that advance and retreat patterns were similar between terminus types in Victoria Land, where both marine- and land-terminating glaciers coexist. That is, there were no significant differences between the terminus position change rates of marine-terminating (long-term median terminus change rate from 1972–2013: 0.6 ± 1.6 m yr^{-1}) and land-terminating glaciers (median terminus rate: -0.6 ± 1.6 m yr^{-1}) (Fig. 8a). This is in contrast with studies in other regions such as Novaya Zemlya, in the Russian Arctic, where retreat rates in marine-terminating glaciers were significantly higher than in land-terminating glaciers (Carr *et al.* 2014). However, the main reason we find no differences is that land-terminating glaciers are only located in Victoria Land and most glaciers in this region were stable (median change rate: -0.5 ± 1.6 m yr^{-1}).

A clear result, however, is that fluctuations of marine-terminating glaciers were consistently of a higher magnitude (long-term range (1972–2013): 292.8 ± 1.6 m yr^{-1}) than land-terminating glaciers (range: 8.4 ± 1.6 m yr^{-1}) throughout the study period (Fig. 9). This is because marine-terminating glaciers are capable of large calving events followed by glacier advance, so there is an inherent variability/cyclicity associated with calving (Bassis & Jacobs 2013). The difference in magnitude of glacier terminus position change was also evident among the different types of marine-terminating glaciers. As perhaps expected, glaciers with an FU tongue had a tendency to experience the largest variations in glacier terminus position through time (1972–2013 range: 916.7 ± 1.6 m yr^{-1}) (Fig. 8b). Glaciers with an FC tongue experienced the second highest degree of variation (range: 105.9 ± 1.6 m yr^{-1}) and G glaciers experienced the least (range: 36.9 ± 1.6 m yr^{-1}). This difference in behaviour is probably because glaciers that are floating and unconstrained by topography are more likely to experience major calving events (Bassis & Jacobs 2013), perhaps associated with tidal variations and their greater sensitivity to the buttressing effect of sea ice (Miles *et al.* 2017). These glaciers also tend to be larger and experience higher velocities, and therefore would be more likely to advance rapidly after a major calving event than glaciers with an FC or G terminus. The glaciers in the FU category were some of the largest glaciers in the study area (maximum 65 km width) and the glaciers in the G category were some of the smallest (maximum 8 km width). However, even when we excluded the largest glaciers (> 15 km width) (Fig. 8c), the results still showed that FU glaciers experienced more variation than FC glaciers.

Very little research has been conducted on variations in the behaviour of different terminus types in Antarctica but a study by Rau *et al.* (2004) in the Antarctic Peninsula noted that between 1986–2002, glaciers with completely or partially floating ice tongues exhibited the largest retreats in response to warming air temperatures compared with other marine- and land-terminating glacier types in the study area. Although not surprising, our data in Victoria Land, Oates Land and George V Land suggest that terminus type is important in controlling the magnitude of outlet glacier terminus position change.

Major calving events ($n = 16$) occurred on glaciers spread out across the study area and in all epochs. However, there was an unusually large number ($n = 9$) of major calving events that occurred in the most recent epoch (2009–13), and the majority of them ($n = 6$) were located in Oates Land, all on glaciers with an FU terminus. Despite the major calving events during this last epoch coinciding with higher than average mean summer temperatures in Oates Land, no evidence of meltwater pooling on the surface of these individual glaciers was found in the imagery prior to this final epoch suggesting that supraglacial melting was also not obviously an important driver of these calving events. They could have been triggered by an influx of warm ocean water to the region, but the variable timing of these events and the fact that the majority of other glaciers in Oates Land were exhibiting a slight advancing trend suggests that they were not externally forced.

Conclusions

This study has contributed to a small but growing set of observations on glacier terminus position change in the EAIS through investigation of both marine- and land-terminating glaciers on sub-decadal timescales in Victoria Land, Oates Land and George V Land, East Antarctica. Results show that unlike in the vast majority of mountain glacier regions and extensive marginal areas of the GrIS and WAIS (including the Antarctic Peninsula), we find no obvious trend of glacier retreat in Victoria Land, Oates Land and George V Land between 1972 and 2013. This supports previous analysis of glacier frontal position change in these regions over decadal timescales and confirms that recent glacier retreat in East Antarctica is restricted to Wilkes Land, further west of our study area. Indeed, examination of temporal trends at shorter sub-decadal timescales reveals there were few statistically significant trends in advance or retreat. There were no trends in Victoria Land, but we identified a significant switch from a period of glacier retreat to a period of glacier advance from the 1972–88 epoch to the 1988–97 epoch in both Oates Land and George V Land, which we tentatively link with increased sea ice concentrations, but which requires further testing.

We do, however, identify clear spatial differences in the magnitude of terminus position change between the three regions. Glaciers in Victoria Land exhibited the smallest variations in terminus position changes (long-term SD: 42.7 ± 1.6 m yr^{-1}), glaciers in Oates Land experienced larger variations in terminus position changes (long-term SD: 47.6 ± 1.6 m yr^{-1}), and glaciers in George V Land experienced the largest variations in terminus position changes (long-term SD: 228.7 ± 1.6 m yr^{-1}). We suggest that these variations area are a function of spatial differences in glacier size and type from a mixed population of smaller land- and marine-terminating glaciers in Victoria Land to larger, marine-terminating glaciers in George V Land. Within marine-terminating glaciers in all three regions, those with an unconstrained FU exhibited the largest variations (long-term range: 916.7 ± 1.6 m yr^{-1}). Thus we conclude that sub-decadal glacier terminus variations in these regions over the last four decades were more closely linked to non-climatic drivers, such as terminus type and geometry, than any obvious climatic or oceanic forcing.

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Author contribution

AML conducted the mapping from satellite imagery, carried out the data analysis and led the writing of the manuscript. All authors contributed to the discussion and interpretation of the results and edited the manuscript.

Supplemental material

A supplemental table and three figures will be found at http://dx.doi.org/10.1017/S0954102017000074.

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