The drivers of inter-annual outlet glacier terminus change in Victoria Land, Oates Land and George V Land, East Antarctica (1972-2013)

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Recent work has highlighted the potential sensitivity of marine-terminating outlet glaciers to decadal-scale changes in the ocean-climate system in some regions of East Antarctica. However, compared to Greenland and West Antarctica (including the Antarctic Peninsula), very little is known about the drivers of shorter-term inter-annual variation of outlet glaciers in East Antarctica. In this thesis, the terminus positions of 135 glaciers along the coastline of Victoria Land, Oates Land and George V Land were mapped from 1972 to 2013. These three regions span a range of climatic and oceanic conditions and contain a variety of different glacier types, including both land- and marine-terminating glaciers. Over the longest time step (1972-2013), 36% of glacier termini in the study area advanced, 25% of glacier termini retreated, with the remainder showing no discernible change. However, glacier terminus positions fluctuated at inter-annual time-scales, and the magnitude of these changes varied between regions. George V Land exhibited the most extreme fluctuations in terminus positions and Victoria Land exhibited the least. While potential links were found between sea-ice concentrations and glacier change on inter-annual time-scales, there was little correlation between air temperatures and short-term glacier behaviour. Marine-terminating glaciers experienced larger changes in terminus position compared with terrestrial glaciers, and within marine-terminating glaciers, glaciers with a floating unconstrained tongue exhibited the largest variations in terminus position. It is concluded that unlike in Greenland, West Antarctica, the Antarctic Peninsula and localised regions of East Antarctica (e.g. Wilkes Land), there is no clear trend of glacier retreat in the study area and most of the variations are more closely linked to glacier size and terminus type.

THE DRIVERS OF INTER-ANNUAL OUTLET GLACIER TERMINUS CHANGE IN VICTORIA LAND, OATES LAND AND GEORGE V LAND, EAST ANTARCTICA (1972-2013)

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Chapter 1: INTRODUCTION

1.1 The importance of measuring ice sheet change

The equivalent of ~65 m sea-level rise is currently locked up in the Greenland and Antarctic ice sheets (Gregory et al., 2004; Fretwell et al., 2013). The response of ice sheets to increasing CO_2 levels and the resultant atmospheric warming, therefore, raises concerns about their potential future contributions to sea-level rise and the social, economic and environmental consequences that will inevitably ensue. This is of particular importance because 10 % of the world's population live in coastal areas that are less than 10 m above sea level (a.s.l.) (McGranahan et al., 2007). It is known that ice sheets underwent substantial changes in the past in response to climate changes and ocean warming, leading to dramatic changes in global sea level (Scherer et al., 1998; Pollard and DeConto, 2009; Joughin and Alley, 2011). During the last interglacial (Marine Isotope Stage 5e –MIS 5e), often used as an analogue for future atmospheric warming projections, there is evidence that global sea levels were ~6.6 m higher than today (Kopp et al., 2009; Fogwill et al., 2014) suggesting that the Greenland ice sheet (GrIS) was substantially smaller than at present (Kopp et al., 2009) and that the West Antarctic ice sheet (WAIS) may have collapsed completely (Joughin and Alley, 2011). Until recently, the most significant contributions to sea level have been provided by melting mountain glaciers and ice caps (Alley et al., 2005). However, it is predicted that soon ice sheets will overtake mountain glaciers in terms of contribution to sea level (Rignot et al., 2011b) with the possibility that global sea levels could increase by ~1 m by 2100 (Stocker et al., 2013). Additionally, ice sheets can drive global climate changes through their influence on processes such as ocean circulation and albedo (Clark et al., 1999). Therefore, understanding how ice sheets behave and how they will respond to future changes in climate is of utmost importance.

Ice sheet mass balance is a function of accumulation (precipitation) and ablation (surface melt, basal melt and calving) (Hanna et al., 2013). Current knowledge about ice sheet mass loss is subject to large uncertainties that arise from the various techniques used to estimate ice sheet mass-balance and which reduce confidence in future ice sheet contributions to global sea levels (Hanna et al., 2013). This is a major limitation for climate change prediction models (Stocker et al., 2013). There is especial concern that current ice sheet models do not adequately represent the rate of ice sheet change, particularly in marine-terminating glaciers and ice streams, meaning that sea-level rise projections may be underestimated (Alley et al., 2005). Outlet glaciers are important channels of ice sheet mass loss (Moon and Joughin, 2008; Pritchard et al., 2009) and understanding the drivers of outlet glaciers is important for gaining an insight into how ice sheets behave. However, large uncertainties remain in terms of how these glaciers interact with various external and internal forcings (Carr et al., 2013a). While there is relatively comprehensive coverage of outlet glacier behaviour studies in the GrIS and WAIS (including the Antarctic Peninsula), less is known about the drivers of outlet glacier change in the East Antarctic ice sheet (EAIS). In particular, there is a gap in the data regarding the drivers of sub-decadal glacier terminus changes. This investigation addresses the inter-annual behaviour of outlet glaciers in a section of the EAIS, which spans a latitudinal and climatic gradient, to examine how glaciers have responded to external climatic and oceanic drivers and internal glacier dynamics over the last 40 years.

1.2 Aim, objectives and research questions

1.2.1 Project aim

The aim of this research project is to investigate and compare the recent (1972 onwards) terminus changes of outlet glaciers in the three regions of Victoria Land, Oates Land and George V Land (EAIS) (Fig.1.1) in order to identify the regional and glacier-specific controls on their terminus positions over the last few decades at inter-annual time-scales.

1.2.2 Objectives

To achieve this aim, the objectives of this research are as follows:

1. To use satellite observations to map the changes in glacier terminus position of 135 glaciers across Victoria Land, Oates Land and George V Land on an inter-annual time-scale (~ 4 year intervals) from 1972 to 2013.
2. To compare the behaviour of glaciers in the three areas in terms of terminus change.
3. To investigate the relationship of glacier terminus change with potential forcing mechanisms including air temperature and sea-ice concentrations.
4. To investigate the influence of glacier-specific factors such as glacier trough width and terminus type.

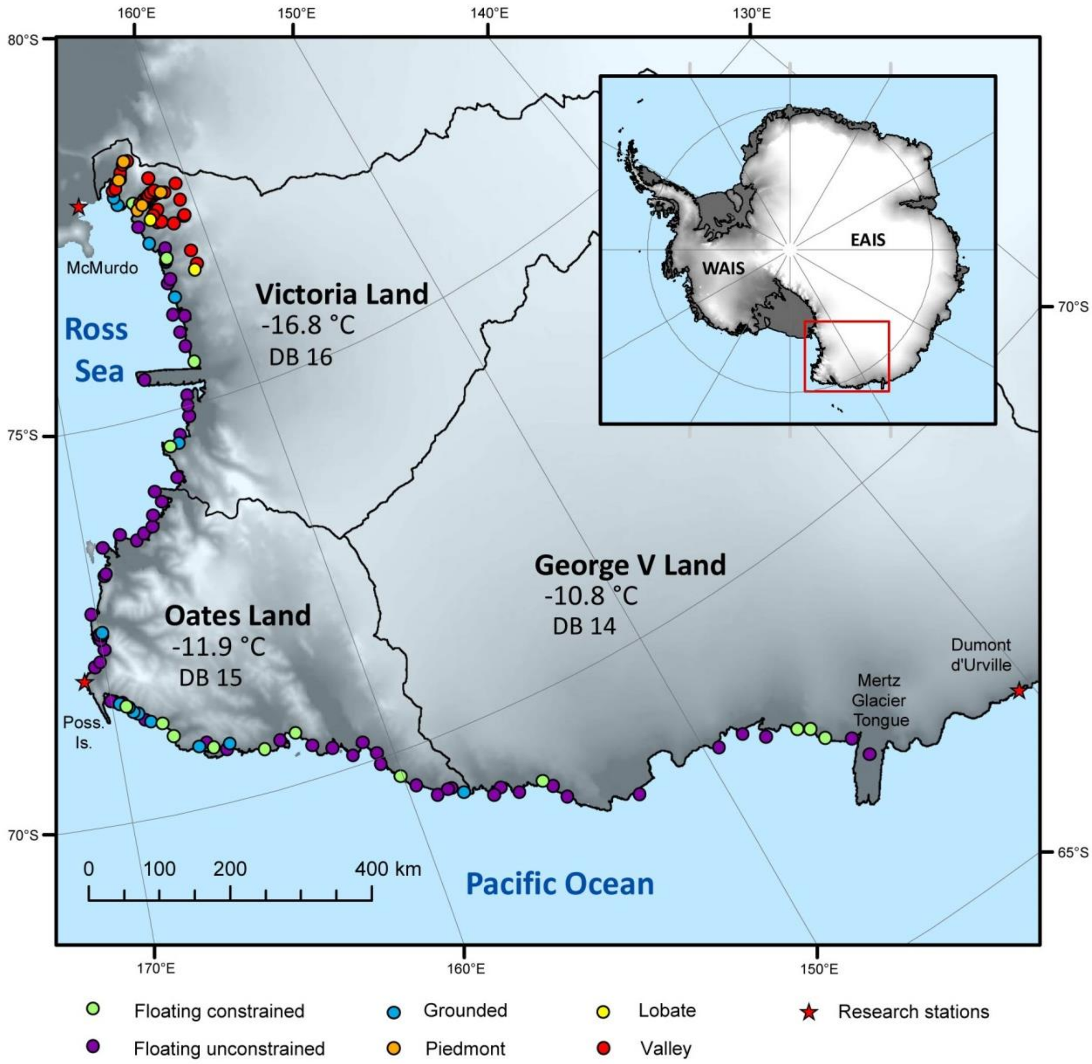


Figure 1.1: Location of the study area showing the positions of the different types of glaciers that were measured, the meteorological stations (red stars) and the mean annual temperature of the three drainage basins. Background image: Bedmap 2 ice-surface elevation grid (Fretwell et al., 2013). Glacier types are represented by coloured circles.

1.2.3 Research questions

The research questions that will be addressed in this study are as follows:

1. Are there differences between the behaviour of outlet glaciers in the three areas that span a latitudinal and climate gradient from colder to warmer?
2. Can atmospheric or oceanic forcing explain any of the observed inter-annual trends in glacier behaviour in each study area?
3. To what extent is glacier behaviour modulated by glacier-specific factors such as glacier width and terminus type (e.g. land-terminating versus marine-terminating glaciers; those with floating tongues versus those without)?

1.3 Thesis structure

Chapter 2 begins with a review of the literature about recent mass changes in the GrIS, WAIS and EAIS. This is followed by an analysis of the current knowledge of the external and internal drivers of outlet glacier change. This chapter ends with a review of the existing literature on outlet glacier change in the EAIS. Chapter 3 describes the study area of this investigation, focusing on the geographic location and climate, the types of glaciers to be found in the region, and previous work undertaken on outlet glaciers in the specific study area. Chapter 4 describes the methods used in this study, including a brief outline of the approach used and the acquisition of glacier change data, and data on external and internal glacier controls. Chapter 5 presents the results of this study, including glacier terminus change, climate and sea-ice data, and terminus type data. Chapter 6 discusses the results and includes some recommendations for further research in this field of study and Chapter 7 summarises the conclusions of this research project. Statistical test results are included in an appendix (Appendix A) at the end of the thesis.

Chapter 2: A REVIEW OF RECENT ICE SHEET MASS LOSS AND OUTLET GLACIER BEHAVIOUR

2.1 Introduction

Recent observations have shown that ice mass loss from the margins of the Greenland and Antarctic ice sheets has accelerated over the last 10 to 20 years (Van den Broeke et al., 2009; Joughin and Alley, 2011; Rignot et al., 2011b; McMillan et al., 2014) (Fig. 2.1). Current mass balance estimates for the period 1992 to 2011 for the Greenland ice sheet (GrIS) and West Antarctic ice sheet (WAIS) are -142 ± 49 and -65 ± 26 Gt yr^{-1}, respectively (Shepherd et al., 2012). A significant portion of this mass is lost via marine-terminating outlet glaciers on the margins of the ice sheets (Bevan et al., 2012; Depoorter et al., 2013; Rignot et al., 2013; Joughin et al., 2014), which have undergone rapid thinning, acceleration and retreat throughout the same time period (Moon and Joughin, 2008; Pritchard et al., 2009; Carr et al., 2013b; Cook et al., 2014).

The predominant mechanisms of mass loss from outlet glaciers are melting and terminus calving. Melting can be separated into two types: 1) melting beneath the base of the ice shelf (basal), which is predominantly controlled by the temperature of the ocean water and the local circulation conditions (Pritchard et al., 2012); and 2) melting on the ice surface which is predominantly controlled by atmospheric temperatures (Scambos et al., 2000). Calving is the mechanical process whereby sections of an outlet glacier terminus break off into icebergs, as a result of crevasse formation, and are transported away from the calving front (Benn et al., 2007). Following some form of trigger, calving glaciers have been known to retreat very rapidly. As such, it is important to understand what drives their behaviour. Due to the complexity and heterogeneity of calving events, there is no agreement on a unifying theory that satisfactorily explains all types of calving (Benn et al., 2007; Bassis, 2011; Bassis and Jacobs, 2013). However, Benn et al. (2007) proposed a hierarchy of controls on iceberg calving. The first-order control determines the position and depth of ice fractures in the glacier via the strain rate caused by spatial variations in ice velocity. This is followed by a series of second- and third-order controls including fracture propagation and undercutting of the glacier terminus.

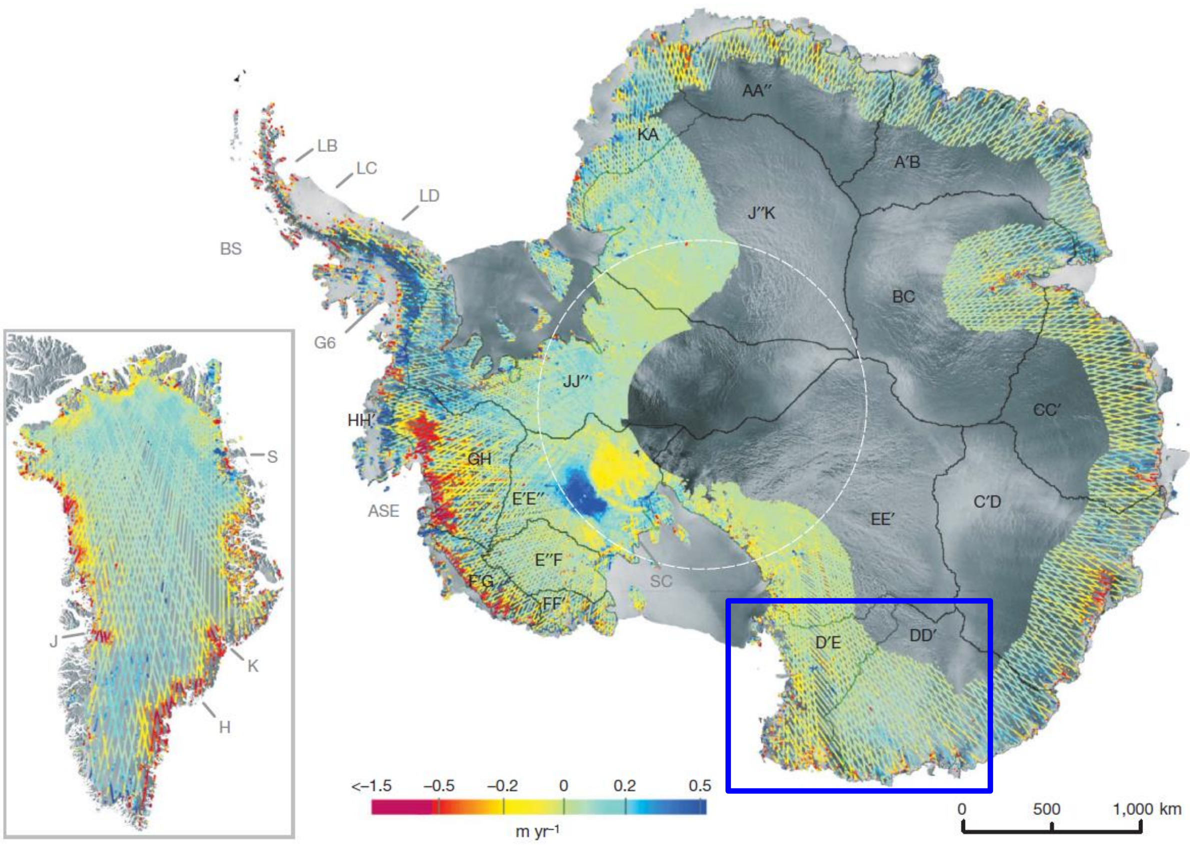


Figure 2.1: Rate of change of surface elevation for the GrIS, WAIS and EAIS (from Pritchard et al., 2009). There are small hints of mass loss (areas in red) along the margin of Victoria Land, Oates Land and George V Land which are located in the study area of this investigation (blue box).

It is important to acknowledge that the GrIS and AIS have very different climatic and topographic conditions and are therefore subject to different drivers and lose mass in different ways with varying magnitude. For example, air temperatures play a more important role in the mass losses occurring in the GrIS (Van den Broeke et al., 2009), than in the AIS, where air temperatures are generally much cooler and mass loss is dominated by oceanic-driven basal melting (Rignot et al., 2013). Due to these hemispheric differences, this thesis will mostly focus on the Antarctic ice sheets.

In this chapter, the literature on the drivers of mass loss and outlet glacier change will be reviewed and analysed separately for the WAIS, Antarctic Peninsula ice sheet (APIS) and EAIS. The first section of this chapter reviews the current research on the drivers of recent mass loss in the WAIS (Section 2.2). The second section reviews the research on the drivers of mass loss in the APIS (Section 2.3). This is followed by a section which focuses on mass balance and outlet glacier terminus change in the EAIS (Section 2.4). The final section reviews the current understanding of the influence of glacier terminus type and fjord width on the response of outlet glaciers to external forcings (Section 2.5).

2.2 The drivers of recent mass loss and glacier retreat in the West Antarctic ice sheet

Glacier change in the predominantly marine-based WAIS has corresponded closely with warming trends in air and ocean temperatures (Pritchard et al., 2009; Joughin and Alley, 2011; Pritchard et al., 2012). This raises concerns about the stability of the WAIS (Pritchard et al., 2009; Favier et al., 2014; Joughin et al., 2014; Mouginot et al., 2014) and its future contribution to global sea-level rise, which, between 1992 and 2011, was estimated to be -65 ± 26 Gt yr^{-1} (West Antarctica) (Shepherd et al., 2012). In particular, there are concerns that the WAIS, which is known to have collapsed during previous interglacials, could be vulnerable to future collapse, potentially contributing up to 3.3 m to global sea level (Mercer, 1978; Thomas, 1979; Joughin and Alley, 2011).

2.2.1 Climatic and oceanic drivers of the WAIS

Although air temperatures do not have a direct impact on outlet glacier change in the WAIS, which experiences very little surface melting in comparison with the GrIS (Zwally et al., 2002; Meierbachtol et al., 2013; Leeson et al., 2014), recent research suggests that the behaviour of marine-terminating glaciers in the WAIS is heavily influenced by oceanic forcing. Ocean-driven mass loss is predominantly caused by basal melting beneath the glacier tongue or ice shelf. Basal melting is most active in the grounding zones and calving fronts of large outlet glaciers and ice shelves (Rignot et al.,

2013) and is predominantly caused by three ocean forcing mechanisms: (i) brine rejection from the development of sea ice near the terminus, leading to denser, more saline water entering the sub ice shelf/tongue cavity, (ii) intrusion of warm circumpolar deep water, and (iii) ocean mixing driven by the tides or atmospheric circulation (Depoorter et al., 2013). The recent acceleration, thinning and rapid grounding line retreat of some of the major outlet glaciers in the Amundsen Sea embayment of the WAIS (Rignot et al., 2014), such as Pine Island Glacier, which has the highest basal melt rate of all the glaciers in Antarctica (Pritchard et al., 2012) and retreated 31 km between 1992 and 2011 (Rignot et al., 2014), and Thwaites Glacier, which retreated 14 km during the same period (Rignot et al., 2014), has been attributed to changes in Circumpolar Deep Water (CDW) circulation bringing warmer waters into contact with the glaciers and enhancing sub-shelf melt and grounding line retreat (Favier et al., 2014; Joughin et al., 2014).

2.2.2 Internal dynamic drivers of the WAIS

Outlet glacier changes and mass loss in the WAIS have also been driven by internal dynamic controls leading to often rapid and non-linear responses. One of these is the acceleration of marine-terminating outlet glaciers in response to the removal of ice shelves as a result of Circumpolar Deep Water-induced basal melting (Favier et al., 2014). Ice shelves act as a buttress on outlet glaciers, controlling the rate of glacier flow into the oceans (Hanna et al., 2013). When the ice shelf thins or collapses, this restraining force disappears, leading to an increase in glacier acceleration and thinning, known as dynamic thinning (Pritchard et al., 2009). Debuttressing of the marginal ice shelves in the Amundsen Sea embayment has been observed to result in the acceleration and dynamic thinning of the majority of outlet glaciers in the region, including Pine Island, Thwaites, Haynes and Smith ice streams (Pritchard et al., 2009; Macgregor et al., 2012; Rignot et al., 2014).

Another topographic control on marine-terminating outlet glacier behaviour that is of growing concern in the WAIS is the influence of bed-slope on glacier retreat. Large parts of the WAIS sit on submarine bedrock that slopes towards the interior of the continent (Fretwell et al., 2013). If an ice sheet retreats on a reverse slope, it becomes grounded in deeper water and ice thickness at the grounding line (the contact between the ice sheet and the ocean where the ice sheet begins to float) increases. Ice flux across the grounding line increases with ice thickness, leading to increased thinning of the ice and increased retreat of the grounding line into even deeper water where the ice sheet is thicker (Weertman, 1974; Schoof, 2007; Joughin and Alley, 2011; Hanna et al., 2013). This positive feedback triggers a process of runaway glacier retreat called marine ice-sheet instability which is, theoretically, maintained until the ice sheet retreats onto bedrock sloping away from the interior and re-stabilises (Joughin and Alley, 2011). However, through numerical modelling, Jamieson et al. (2012) revealed that the Marguerite Bay ice stream, which also sat on an inland-sloping bed, demonstrated unusual behaviour during its retreat since the Last Glacial Maximum, by stabilising several times on the reverse bed slope. The model suggested that these stabilisations occurred as a result of the narrowing of the ice stream which increased lateral drag and it was argued that bed slope is not the only control on marine ice-sheet instability. Marine ice sheet instability is thought to be driving the rapid retreat of some of the major outlet glaciers in the Amundsen Sea sector of the WAIS, including Pine Island and Thwaites glaciers (Favier et al., 2014; Rignot et al., 2014).

Topographic pinning points on the glacier bed (e.g. bumps on the sea floor) have also been highlighted as important controls on outlet glacier terminus behaviour in the WAIS. It has been observed that the grounding line of Pine Island Glacier, was recently resting on a bedrock ridge, acting as a topographic pinning point (Jenkins et al., 2010). However, the grounding line has since retreated past this threshold and is predicted to experience continued unstable retreat inland due to the lack of obstacles on the bed up-glacier to stabilise this retreat (Jenkins et al., 2010; Rignot et al., 2014).

2.3 The drivers of recent mass loss and glacier retreat in the Antarctic Peninsula ice sheet

The APIS contains considerably less ice than the larger Antarctic ice sheets, with a relatively small sea-level rise equivalent of 0.2 m (Fretwell et al., 2013). However, it was reported to have a negative mass balance of -20 ± 14 Gt yr^{-1} between 1992 and 2011 (Shepherd et al., 2012), and it has received a substantial amount of research attention due to rapidly warming air temperatures, which have risen by

~2 °C over the past 50 years, warming oceanic temperatures, recent ice shelf collapse and glacier acceleration and retreat (Doake and Vaughan, 1991; Scambos et al., 2000; Cook et al., 2005; Davies et al., 2012; Cook et al., 2014).

2.3.1 Climatic and oceanic drivers of the APIS

The dramatic collapse of several of the ice shelves on the APIS over the last 30 to 40 years (Doake and Vaughan, 1991; Scambos et al., 2000; Glasser et al., 2011; Banwell et al., 2013), which has amounted to a decrease in ice shelf area in the APIS of approximately 13,500 km^2 (Scambos et al., 2004), has been attributed to a combination of oceanic and climatic drivers (Shepherd et al., 2003; Banwell et al., 2013). Particular attention has been paid to the triggers of the rapid and catastrophic collapse of the Larsen B ice shelf in March 2002 (Rignot et al., 2004; Scambos et al., 2004; Rebesco et al., 2014) which occurred over just a few days (Banwell et al., 2013). Between 1992 and 2001, the ice shelf had steadily thinned by 0.17 ± 0.11 m yr^{-1} (Shepherd et al., 2003), however, just prior to its collapse, the number of supraglacial meltwater pools on the ice shelf, caused by record warming air temperatures (Scambos et al., 2004), increased rapidly and then drained abruptly (Banwell et al., 2013). This suggests that supraglacial meltwater pools, caused by warming air temperatures, were a possible trigger of the disintegration of the Larsen B ice shelf through surface meltwater pool-induced hydrofracture in combination with long-term basal melt-induced thinning (Scambos et al., 2000; Shepherd et al., 2003; Banwell et al., 2013).

2.3.2 Internal dynamic drivers of the APIS

Ice shelf debuttressing has also been observed as a driver of dynamic thinning, acceleration and retreat of tributary outlet glaciers in the APIS (Pritchard et al., 2009; Rott et al., 2014). Glasser et al. (2011) observed that the Röhss Glacier, a tributary of the Prince Gustav ice shelf (PGIS), located north of the Larsen A and B ice shelves, thinned and retreated rapidly and eventually transformed into a tidewater glacier after the PGIS collapsed in 1995. Several of the Larsen B ice shelf tributary glaciers were also reported to thin, accelerate and retreat rapidly after its collapse (Scambos et al., 2004).

2.4 The drivers of recent mass loss and glacier retreat in the East Antarctic ice sheet

2.4.1 Existing literature on mass balance in the East Antarctic ice sheet

In contrast to the WAIS, the EAIS is generally thought to be gaining mass (Zwally and Giovinetto, 2011; Shepherd et al., 2012) and to be relatively stable, perhaps explaining why it has received much less research attention. However, due to the use of numerous different estimation techniques, e.g. radar or laser altimetry (measuring elevation change), gravimetric techniques (measuring gravity changes) and mass budget techniques (the difference between estimated ice mass loss and estimated net accumulation) (Rignot and Thomas, 2002; Hanna et al., 2013), 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) (Table 2.1) and there is still a lack of agreement about whether the ice sheet's

Table 2.1: Published estimates of the mass balance of the EAIS based on varying techniques (radar altimetry, gravimetry and mass budget methods).

Study	Time period	Mass balance estimation method	Mass balance estimate (Gt yr-1)
McMillan et al. 2014 Geophysical Research Letters	2010-2013	Radar altimetry	-3 ± 36
King et al. 2012 Nature	2002-2010	Gravimetry	+60 ± 13
Zwally et al. 2005 Journal of Glaciology	1992-2001	Radar altimetry	+16 ± 11
Shepherd et al. 2012 Science	1992-2011	Altimetry, mass budget and gravimetry	+14 ± 43
Rignot et al. 2008 Nature Geoscience	1992-2006	Mass budget	-4 ± 61

mass balance is actually positive or negative (Hanna et al., 2013). For example, for the period 1992-2006, Rignot et al. (2008) estimated the mass balance for the EAIS to be -4 ± 61 Gt yr^{-1} using mass budget techniques, whereas King et al. (2012) estimated the mass balance to be +60 ± 13 Gt yr^{-1} for a similar time period (1992-2010) based on satellite gravimetry techniques.

Radar altimetry data has shown that between 1992 and 2003, the interior of the EAIS steadily gained elevation (approximately 2 to 4 cm yr^{-1}) (Fig. 2.2a) (Davis, 2005; Wingham et al., 2006). This growth has been linked to increased precipitation trends (Fig. 2.2b) and has been estimated to equal a global sea-level lowering of between 0.12 mm yr^{-1} (Davis, 2005) and 0.8 mm yr^{-1} (Wingham et al., 2006). Climate models have suggested that future global climate changes may lead to increased snowfall on the AIS by the end of the 21st century (Winkelmann et al., 2012; Lenaerts et al., 2013). The long-term effects of this are uncertain. While some studies predict that this could lead to a negative effect on global sea-level rise (Lenaerts et al., 2013), others suggest that it may enhance the contribution of the ice sheet to sea level through increased, dynamically-driven ice discharge (Winkelmann et al., 2012). A study by Zwally et al. (2015), which also used altimetry data, reported that between 1992 and 2008, mass gains from the EAIS (of 136 Gt yr^{-1}) and parts of the WAIS were large enough to offset the mass losses from the AIS, leaving the entire ice sheet with a total positive mass balance of 112 ± 61 Gt yr^{-1} from 1992 to 2002 and 82 ± 25 Gt yr^{-1} from 2003 to 2008. However, there is a general consensus among most other studies that the overall mass balance of the AIS is negative (Zwally et al., 2005; Rignot et al., 2008; King et al., 2012; Shepherd et al., 2012; McMillan et al., 2014).

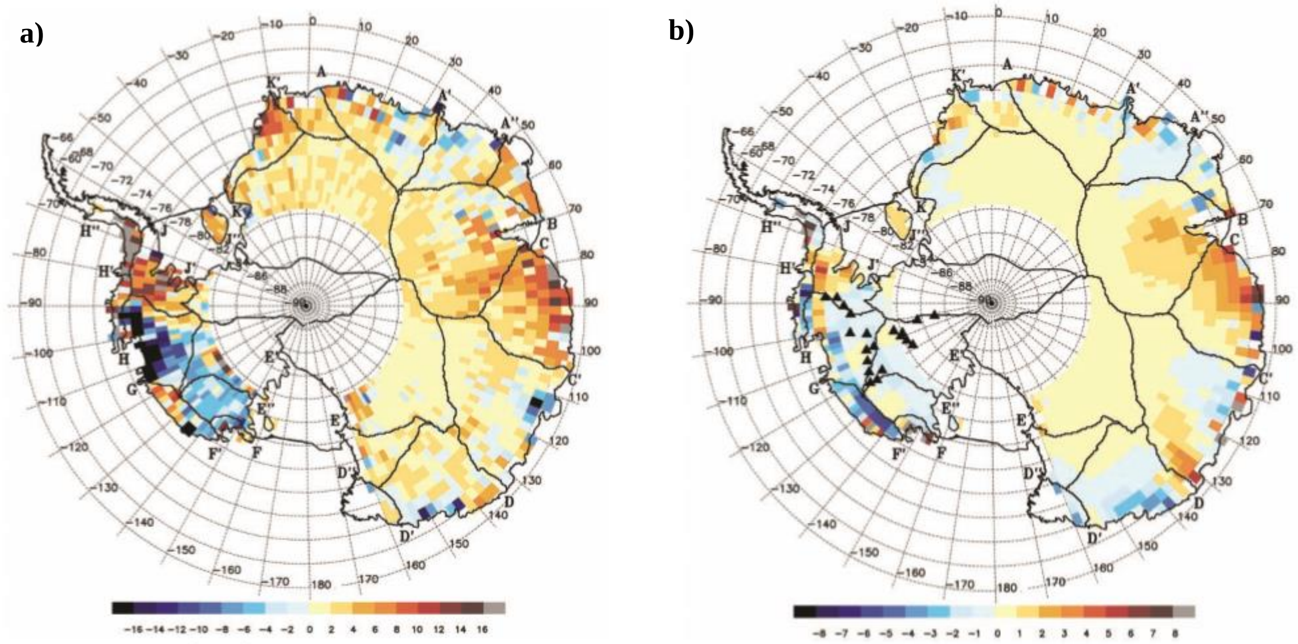


Figure 2.2: a) Elevation change (cm yr^{-1}) between 1992 and 2003 for the AIS and b) precipitation change (cm of snow yr^{-1}) between 1992 and 2003 for the AIS (from Davis, 2005).

Despite steady gains in elevation in the interior of the EAIS, altimetry data has also revealed interesting variations in elevation change across the ice sheet, in particular, large elevation losses along sections of the ice sheet margin (Davis, 2005). This mass loss in coastal areas of the EAIS (e.g. Wilkes Land and Oates Land) has also been highlighted in other recent mass balance studies (Rignot et al., 2008; King et al., 2012) (Fig. 2.3). Using ICESat laser altimetry, Pritchard et al. (2009) observed that while large parts of the EAIS margin were either stable or thickening from 2003 to 2007, several glaciers and ice shelves were thinning by between 0.5 and 1.5 m yr^{-1}. Totten Glacier in Wilkes Land, one of the fastest thinning outlet glaciers in the EAIS, in particular, was revealed to be thinning at a much faster rate than previously established. This shows that much uncertainty remains about the stability of the EAIS and its future contributions to sea level, in particular, the balance between mass gain in the interior and mass loss at the margins of the EAIS (Davis, 2005), and highlights the need for a better understanding of the dynamics of the EAIS. This is especially important because the EAIS is the largest of the three Antarctic ice sheets, and contains the equivalent of 53.3 m of global sea-level rise (Fretwell et al., 2013).

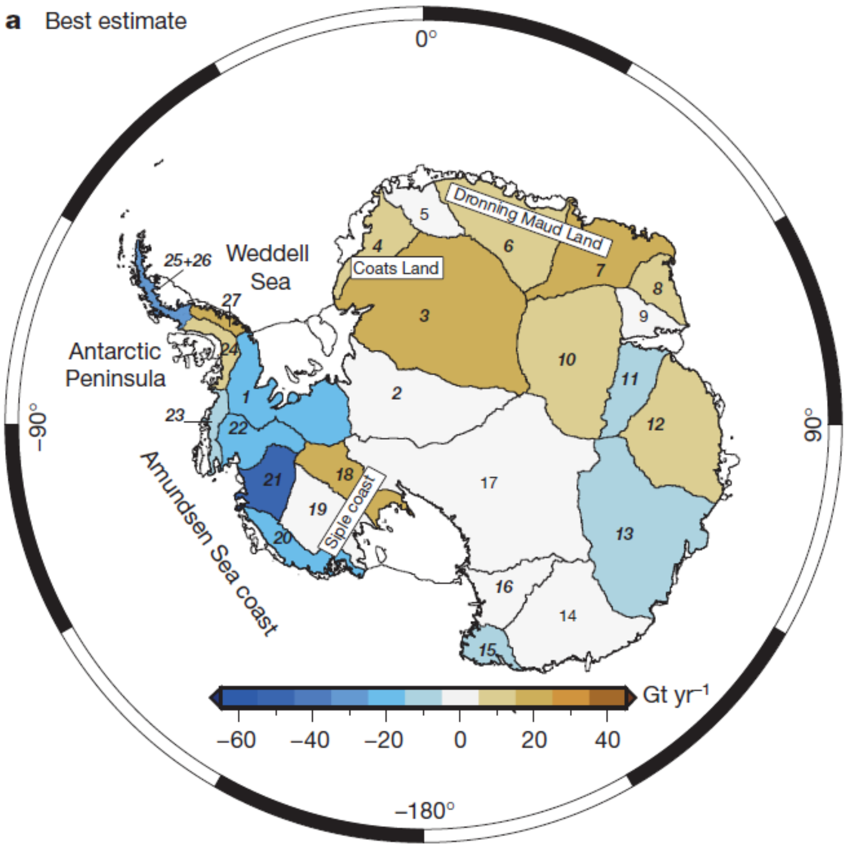


Figure 2.3: Estimated mass-change rates by drainage basin in West (basins 1, 18-27) and East (basins 2-17) Antarctica based on gravimetric techniques. Oates Land (15), Wilkes Land (13) and Princes Elizabeth Land (11) have been identified as areas of mass loss (King et al., 2012).

2.4.2 The drivers of outlet glacier behaviour in the East Antarctic ice sheet

Compared with the GrIS and WAIS, research on the drivers of outlet glacier terminus change and mass balance in the EAIS has been relatively limited. Results from a number of studies focusing on individual glaciers located all over the EAIS (glacier sites shown in Fig. 2.4) suggest that, over the last 20 to 30 years, the glaciers have exhibited no strong signs of retreat or have had only very minor mass imbalances. Fukuda et al. (2014) investigated recent (2000-2012) velocity, surface elevation and terminus changes of the Langhovde Glacier on the Sôya Coast, using satellite imagery and field measurements, and found it to be largely stable during the study period. Zhou et al. (2014) studied velocities changes of Polar Record Glacier on the Ingrid Christensen Coast from 1996 to 2008 using D-InSAR and intensity tracking and although they observed that glacier velocity varied on seasonal time-scales, possibly as a result of changes in sea-ice concentrations, they found no significant changes in glacier velocity on inter-annual timescales. Golledge and Levy (2011) conducted a modelling study on Ferrar Glacier in Victoria Land, testing its behaviour under present and past climatic regimes and concluded that it currently has the characteristics of a cold-based glacier, flowing via internal deformation but may have been warm-based and more dynamic during warmer past climates such as the mid-Pliocene. Mass balance studies have been conducted on a handful of glaciers located in the Ross Sea embayment (David, Mulock, Byrd and Nimrod glaciers) (Stearns, 2011) and along the entire coastline of the EAIS (David, Ninnis, Mertz, Totten, Scott, Denman, Lambert, Shirase and Stancomb-Wills) (Rignot, 2002) using the mass budget method. These studies found that the glaciers under investigation had relatively small mass imbalances, apart from Byrd Glacier, which had a large positive imbalance that was attributed to inaccuracies in the estimation of the glacier's accumulation (Stearns, 2011). Particular attention has also been paid to some of the larger glaciers in the EAIS such as David (Frezzotti and Mabin, 1994), Mertz and Ninnis Glaciers (Massom et al., 2001; Massom, 2003; Massom et al., 2015), which have all experienced major calving events in the last 50 years but which appear to be part of cyclic calving cycles. A limited number of studies of multiple glaciers were conducted in the EAIS, describing glacier change along small sections of the EAIS coast over the last 50-100 years, and identified cyclic glacier fluctuations, with no overall trend (Frezzotti, 1997; Frezzotti et al., 1998; Frezzotti and Polizzi, 2002).

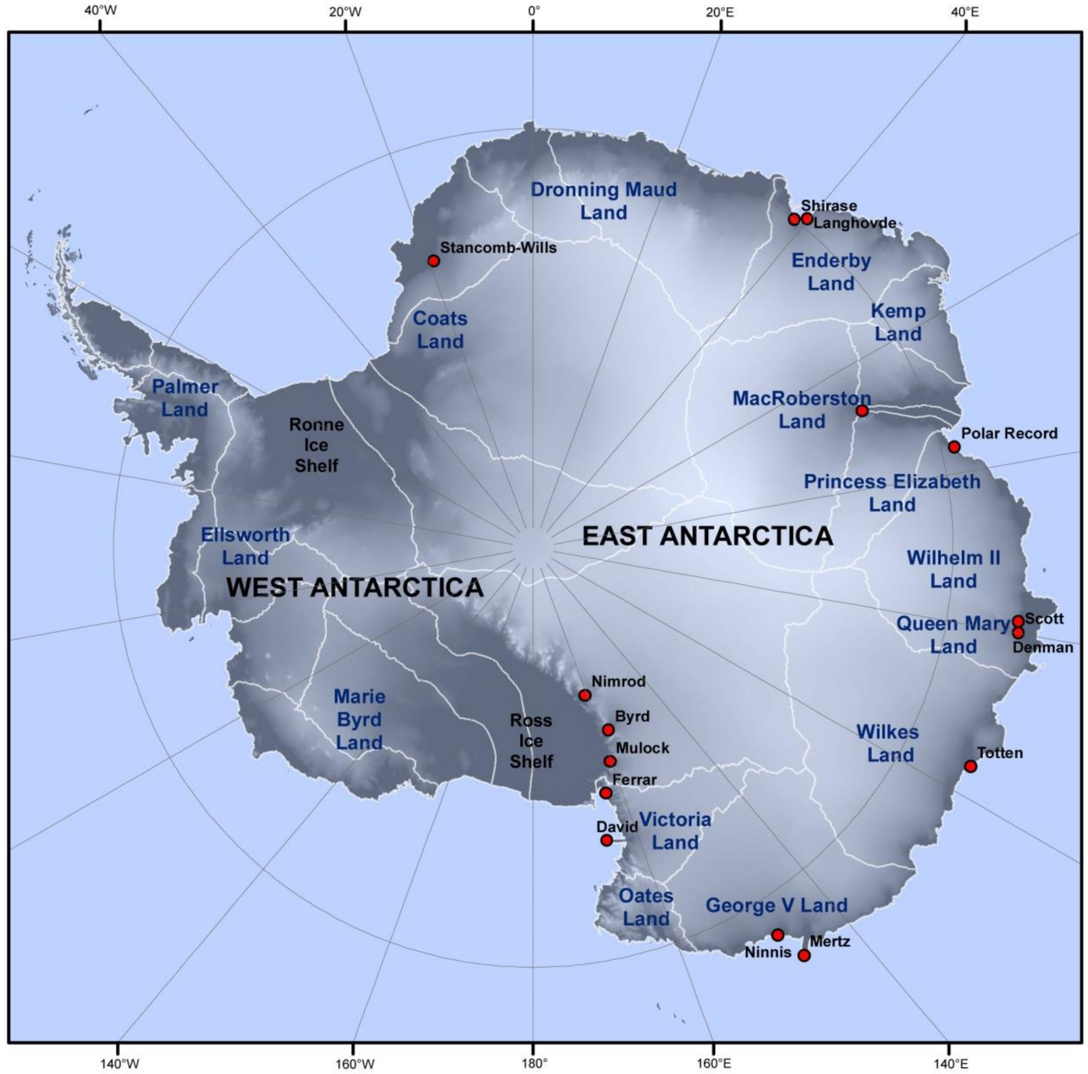


Figure 2.4: Map showing the locations of East Antarctic outlet glaciers that have been previously studied. Background image: Bedmap 2 ice-surface elevation grid (Fretwell et al., 2013).

However, a recent study, which mapped the terminus positions of 175 marine-terminating glaciers using a multi-decadal time-scale (1974-2010) on a large section of the coast (5,400 km) from Victoria Land to Queen Mary Land, observed widespread and synchronous fluctuations in glacier terminus positions which corresponded with changes in air temperature and sea-ice concentrations, suggesting that these outlet glaciers are more sensitive to external forcing than previously thought (Miles et al., 2013). In particular, Miles et al. (2013) noted that glaciers in the Ross Sea region (Victoria Land), which is south of the Antarctic circle and has colder temperatures, showed small changes and no overall trend, whereas glacier fluctuations on the Pacific coast (George V Land and Wilkes Land), which is further north and approximately 9-12 °C warmer, were much more pronounced, highlighting hitherto unrecorded regional variation in glacier behaviour and the possibility of climatic forcing (Miles et al., 2013). However, much less is known about the behaviour of outlet glaciers in the area at sub-decadal intervals and an investigation into the specific mechanisms driving outlet glacier behaviour in this area has not yet been conducted.

2.4.2.1 Climatic and oceanic drivers of the EAIS

Despite some of the studies of outlet glacier change, mentioned above, suggesting that the margin of the EAIS is relatively stable, evidence of climatic and oceanic driven glacier changes has been observed in several sections of the EAIS margin. Similarly to the WAIS, air temperatures have a relatively small direct role to play in outlet glacier change in the EAIS (in comparison with the GrIS or APIS), due to temperatures being too cold for substantial surface meltwater to occur. However, recent observations of surface melting and pooling have been made on the margins of the EAIS at Langhovde Glacier (Langley et al. In prep.) and on Nivlisen ice shelf, Dronning Maud Land (Kingslake et al., 2015) showing that some parts of the EAIS are warm enough for surface melting to occur. This suggests that although air temperatures are not yet high enough for large-scale processes arising from increases in air temperature to occur, such as hydrofracture-triggered ice shelf collapse observed in the APIS, these processes may become more relevant in parts of the EAIS in the future if atmospheric warming leads to increased surface melting and pooling in the ice sheet. As previously mentioned (in Section 2.4.1), it has also been suggested that air temperatures in the EAIS may have an impact on the ice sheet's mass balance by increasing precipitation over the ice sheet and potentially resulting in a positive ice sheet mass balance (Davis, 2005; Wingham et al., 2006).

Oceanic drivers have also been identified as important controls on glacier behaviour in the EAIS. Studies on Totten Glacier have reported that the glacier, which transports ~70 $km^3 yr^{-1}$ of ice to the ocean (Khazendar et al., 2013) and has undergone recent rapid thinning, looks to be potentially vulnerable to warm Circumpolar Deep Water (CDW) intrusion (Gwyther et al., 2014; Greenbaum et al., 2015). Another oceanic control that has been reported to have an influence on outlet glacier behaviour in the EAIS is sea ice, which is thought to inhibit calving at the terminus and promote glacier advance (Carr et al., 2013a; Fukuda et al., 2014). Correlations between sea-ice reduction and glacier retreat have been observed in the EAIS (Miles et al., 2013; Fukuda et al., 2014). Similar relationships have also been observed in the GrIS (Carr et al., 2013b) and the Russian Arctic (Carr et al., 2014). It has also been suggested that sea ice has an influence on regional precipitation patterns in the Arctic where an increase in open water due to a decrease in sea ice has led to enhanced surface evaporation and intensified precipitation (Bintanja and Selten, 2014). However, this is not expected to be an important influence on outlet glaciers in the EAIS due to a general increasing trend in sea-ice concentrations being observed around Antarctica, in contrast to sea-ice reductions witnessed in the Arctic (Bintanja et al., 2013).

Wind forcing is thought to influence both the climatic and oceanic drivers of outlet glacier mass loss in the EAIS and the WAIS (Pritchard et al., 2012). Evidence suggests that Southern Hemisphere westerlies have recently intensified (Böning et al., 2008) leading to increased surface melt, Southern Ocean warming, and basal melt associated with increased intrusions of CDW along the Antarctic ice-sheet margin (Pritchard et al., 2012). Wind forcing has also been observed to be responsible for changes in sea-ice extent in both the Antarctic (Holland and Kwok, 2012) and the Arctic (Serreze et al., 2007); and katabatic winds play a vital role in the formation and maintenance of sea ice-free polynyas in the EAIS (e.g. Mertz Glacier polynya and Terra Nova Bay polynya) (Frezzotti and Mabin, 1994; Massom et al., 2001; Stearns, 2011).

2.4.2.2 Internal dynamic drivers of the EAIS

As well as climatic and oceanic forcing, internal dynamic controls are predicted to be important drivers of glacier behaviour and mass loss in the EAIS. Dynamic thinning has now been observed in several parts of the EAIS margin (Davis, 2005; Pritchard et al., 2009) including Totten glacier, which contains an estimated global sea-level rise equivalent of 3.5 m (Greenbaum et al., 2015). While no sections of the EAIS margin are undergoing unstable retreat in the same manner as the outlet glaciers in the Amundsen Sea embayment, marine ice-sheet instability has been highlighted as a potential future mechanism for significant and unstable ice mass loss from the subglacial Wilkes Basin in George V Land (Fig. 2.5), which contains the largest volume of ice sitting on a submarine bed in the EAIS, if the ice shelves buttressing the basin are removed by external forcing. This could lead to a possible 3-4 m of global sea-level rise (Mengel and Levermann, 2014). This shows that a better understanding of the dynamic drivers of mass loss from the EAIS is critical in order to assess future contributions of this ice sheet to global sea-level rise.

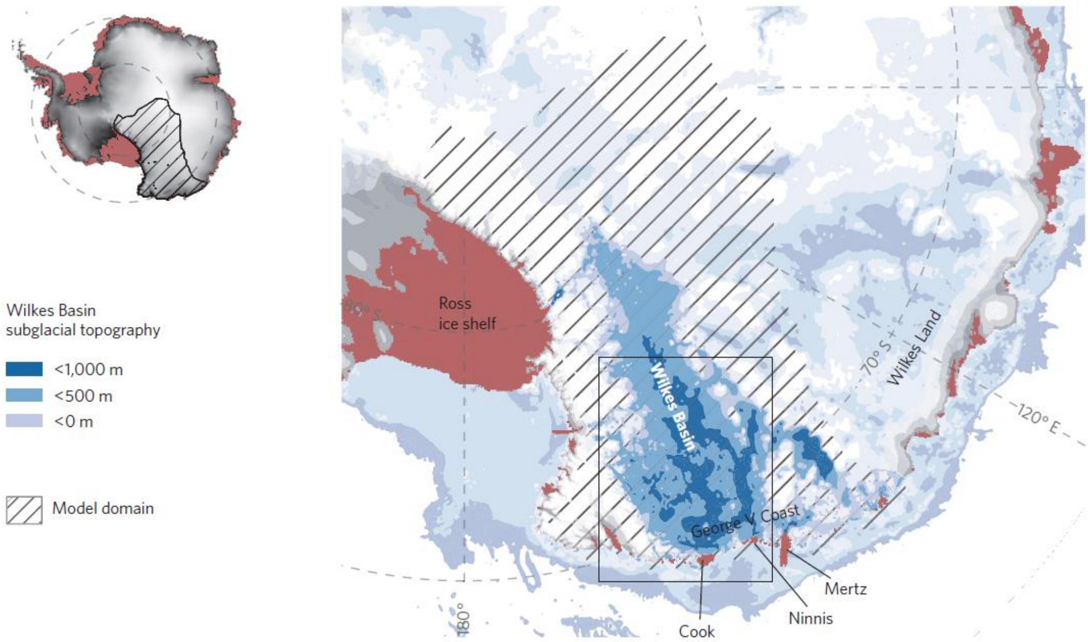


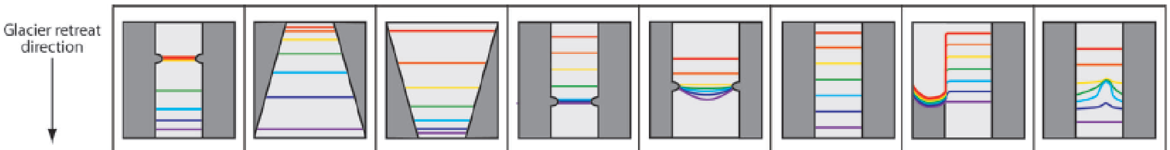
Figure 2.5: Topography of Wilkes subglacial basin in George V Land (Mengel and Levermann, 2014).

2.5 Glacier terminus type and fjord width

Other important non-climatic, internal drivers of glacier behaviour that have received little research attention in any of the Antarctic ice sheets are glacier terminus type and fjord width. Research conducted by Carr et al. (2013b) on marine-terminating glaciers on the north-west coast of Greenland indicated that while glaciers were retreating due to warming air and ocean temperatures, glacier-specific factors such as terminus type also had an important influence on their behaviour. Recent studies have also reported differences in the behaviour of marine- and land-terminating glaciers in response to climatic forcing in other parts of the Arctic (Moon and Joughin, 2008; Mernild et al., 2012; Carr et al., 2014). Marine-terminating glaciers have an ice-sea interface at their termini whereas the termini of land-terminating glaciers only have direct contact with land. Therefore, marine-terminating glaciers are subject to additional ocean-related controls such as ocean temperatures and the presence/absence of sea ice. Carr et al. (2014) observed that glacier change for land-terminating glaciers in the Russian Arctic was significantly smaller than for marine-terminating glaciers in the same area. Similar differences in behaviour were also observed in glaciers in south-east Greenland (Mernild et al., 2012).

The variation in behaviour of different types of marine-terminating glacier (e.g. those with an unconstrained floating ice tongue compared with those with a constrained ice shelf compared with those without an ice shelf) is also poorly understood in the AIS, although it has recently become an area of focus in Greenland. Moon et al. (2012) reported behavioural differences between land-terminating glaciers (which had the slowest velocities), ice shelf-terminating glaciers (which had faster but steady velocities) and fast-flowing marine-terminating glaciers (which experienced the most rapid accelerations) in Greenland. Carr et al. (2013b) suggested that the more rapid retreat of Alison Glacier in northwest Greenland, compared with other marine-terminating glaciers in the area, may have been due to the presence of a floating ice tongue. However, McFadden et al. (2011) investigated marine-terminating glacier dynamics in a similar area (west coast of Greenland) and noted that both glaciers with a floating ice tongue and glaciers with a grounded terminus were capable of large and rapid retreats, suggesting that a floating ice tongue was not a requirement for large retreats in glacier termini. This uncertainty highlights the need for more research on the controls of glacier terminus type, particularly in the AIS which has few, if any, studies of this type.

Glacier trough width has also been identified as a controlling factor on glacier terminus retreat rates. Jamieson et al. (2012) modelled ice-stream retreat in Antarctica using high-resolution topographic data and observed that the retreat rate decelerated when the glacier receded into a narrower trough section. They suggested that the decreased width of a glacier trough increased both lateral resistance and ice-stream surface steepening and acted as lateral pinning points for the ice-stream, reducing its retreat rate. Glacier retreat has also been observed to slow down as glacier termini retreat into narrower sections of a fjord in Greenland (Carr et al., 2013b) and at Columbia Glacier, in Alaska (O'Neel et al., 2005). Similarly, in a study in Novaya Zemlya, in the Russian Arctic, glacier retreat tended to accelerate in fjords that widened up-glacier and decelerate in fjords that narrowed up-glacier. However, acceleration or deceleration of retreat was enhanced in fjords that contained pinning points compared with those that widened or narrowed more gradually (Carr et al., 2014) (Fig. 2.6). A further influence on terminus behaviour is glacier geometry. For example, ice thickness at the grounding line has been hypothesised as a control on the style of calving that occurs at the glacier terminus (Bassis and Jacobs, 2013).



Glacier name	Coast	Retreat rate (m a^{-1}) (1992 – 2010)	(i) Retreat from pinning point	(ii) Widening fjord	(iii) Narrowing fjord	(iv) Retreat onto pinning point	(v) Central retreat/ lateral pinning points	(vi) Minimal width change	(vii) Percentage land-terminating	(viii) Bathymetric pinning points?
VIS	West	-190.63	X	X					0	
INO	West	-140.77	X	X	X				0	
KRO	East	-98.30	X	X					65	
KRI	West	-84.34	X	X					0	
VIJ	West	-82.95	X	X					30	X
MAK	West	-77.27	X	X		X			0	
CHA	West	-75.85	X	X		X			0	
VEL	West	-70.70		X		X			0	
CHE	West	-66.45	X	X					0	X
ROZE	East	-65.98		X	X	X	X		0	X
KRA1	West	-64.93	X	X					65	
TAI1	West	-63.32			X	X			0	
TAI2	West	-62.55	X			X			45	X
SH	West	-54.86	X	X	X	X			0	
ROZH	East	-46.67			X	X	X		0	
VER	East	-44.33				X	X		35	
MG	East	-44.15					X		25	X
SHU1	East	-31.35				X	X		0	
VOE	West	-25.08		X					0	X
RYK	West	-23.55					X		0	X
SHU2	East	-22.47			X		X		0	X
VIZ	West	-20.46		X			X		0	X
VYL2	East	-19.23					X		60	
SRE	East	-18.13				X	X	X	55	
VYL1	East	-17.05					X	X	30	X
KRA2	West	-13.32					X	X	0	X
ANU	West	-11.59		X			X	X	0	X
BRO	West	4.14						X	0	

Figure 2.6: Fjord width change categorisation proposed by (Carr et al., 2014) relative to the 1992-2010 glacier retreat rate (from highest to lowest) of retreating glaciers in Novaya Zemlya in the Russian Arctic. Each column represents an idealised retreat of glacier terminus position in relation to variations in fjord width. Each row shows the retreat rate of an actual glacier (from highest retreat rate to lowest) and an 'x' marks the types of width variation observed during the glacier's retreat. Column vii includes the percentage of the glacier that that is land-terminating.

2.6 Summary

To summarise, surface and basal melting and calving all contribute varyingly to mass loss in the GrIS, WAIS and EAIS. In the GrIS, mass is lost predominantly via calving and surface runoff (Rignot and Thomas, 2002). However, in Antarctica, basal melt is now thought to have overtaken calving processes as the most dominant cause of mass loss (Pritchard et al., 2012; Depoorter et al., 2013; Rignot et al., 2013). Outlet glacier dynamics are complex and may be influenced by a mixture of external forcing and non-climatic internal controls. The implications of this are that outlet glaciers may change quickly or slowly depending on the combination of local and regional factors and that neighbouring glaciers may not behave in a similar fashion in response to a given ocean-climate forcing. In order to understand the behaviour of ice sheets, a better understanding of the complexities driving outlet glacier fluctuation is required and this is particularly relevant to the EAIS where there have been few systematic studies of glaciers at inter-annual time-scales. Although in this chapter, literature on the WAIS and APIS were reviewed separately, from this point forward, it should be assumed that the APIS will be included in any further discussion of the WAIS unless otherwise specified.

Chapter 3: STUDY AREA

3.1 Geographical setting and climate

The study area (Fig. 1.1) encompasses ~1,000 km of the East Antarctic coastline from the McMurdo station located on the Ross Sea ice shelf in southern Victoria Land to the Ninnis and Mertz glacier tongues in George V Land. This study area was selected because it spans three regions with distinct ocean-climatic characteristics and includes three major drainage basins (DBs) (Zwally et al., 2012). Victoria Land (DB 16) is the furthest south, bordering the Ross Sea. It has the coldest mean annual air temperatures (-16.8 °C) and mean summer air temperatures (-4.8 °C), and according to Gravity Recovery and Climate Experiment (GRACE) mission estimates, was reportedly in balance or maybe slightly gaining mass between 2002 and 2010 (King et al., 2012). However, altimetry data from McMillan et al. (2014) indicate that it was slightly losing mass from 2010 to 2013. Oates Land (DB 15) is the smallest of the drainage basins and borders both the Ross Sea and the Pacific Ocean. It has warmer mean annual air temperatures (-11.9 °C) than Victoria Land and the warmest mean summer air temperatures (-0.3 °C) of the three regions under investigation which exceeded 0 °C during 21 of the last 22 years, suggesting that surface melting in this region is likely to occur in the summer. It has been identified as an area of mass loss (-5 to -15 Gt yr^{-1}), albeit with high uncertainty which ranges from -15 to + 5 Gt yr^{-1} (King et al., 2012). George V Land (DB 14) is the largest drainage basin and the furthest north, bordering the western Pacific Ocean. It has the warmest mean annual temperatures (-10.8 °C) but cooler mean summer air temperatures (-2.3 °C) than Oates Land and has been reported to both be losing mass (Rignot et al., 2008) and to be in balance or slightly gaining mass (King et al., 2012). According to McMillan et al. (2014), it was in balance between 2010 and 2013. George V Land also contains the large Wilkes subglacial basin which has been identified in various modelling studies as an area potentially vulnerable to future marine ice-sheet instability (Mengel and Levermann, 2014; Gasson et al., 2015; Pollard et al., 2015). Therefore, understanding the drivers of outlet glacier terminus change in this region could be critical to predicting how it will behave in the future. The distinct characteristics of the three drainage basins makes the study area ideal for investigating if climatic and oceanic variations are influencing glacier behaviour and, if so, why.

3.2 Glacier types

In addition to the ocean-climate variability, the study area contains a variety of different glacier types. Victoria Land, which is dominated by the Transantarctic mountain range, hosts both land-terminating glaciers, such as small cirques and valley glaciers, and large marine-terminating glaciers. In contrast, Oates and George V contain no land-terminating glaciers, but host a wide variety of marine-terminating glaciers (ranging in width from <1 km to >60 km). Glaciers in the study area were divided into six terminus types (summarised in Table 3.1) based on the standard classification outlined in the GLIMS Illustrated Glacier Classification Manual (Rau et al., 2005). Marine-terminating glaciers were categorised into: 1) glaciers with a floating ice-shelf terminus that was constrained by the glacier fjord walls and did not extend out beyond them (FC) e.g. Shipley Glacier

Table 3.1: Summary of glacier terminus type in each region of the study area.

	Victoria Land	Oates Land	George V Land
All Glacier Types	70	50	15
Floating Constrained (FC)	4	7	4
Floating Uncontrained (FU)	17	34	11
Grounded (G)	5	9	0
Valley (V)	37	0	0
Piedmont (P)	5	0	0
Lobate (L)	2	0	0

(Fig 3.1a), 2) glaciers with a floating unconstrained tongue that extended out beyond the glacier fjord (FU) e.g. David Glacier (Fig 3.1c), and 3) grounded glaciers which do not have a floating terminus e.g. Oates Piedmont Glacier (Fig 3.1b) (Table 3.1). Marine-terminating glaciers with grounded

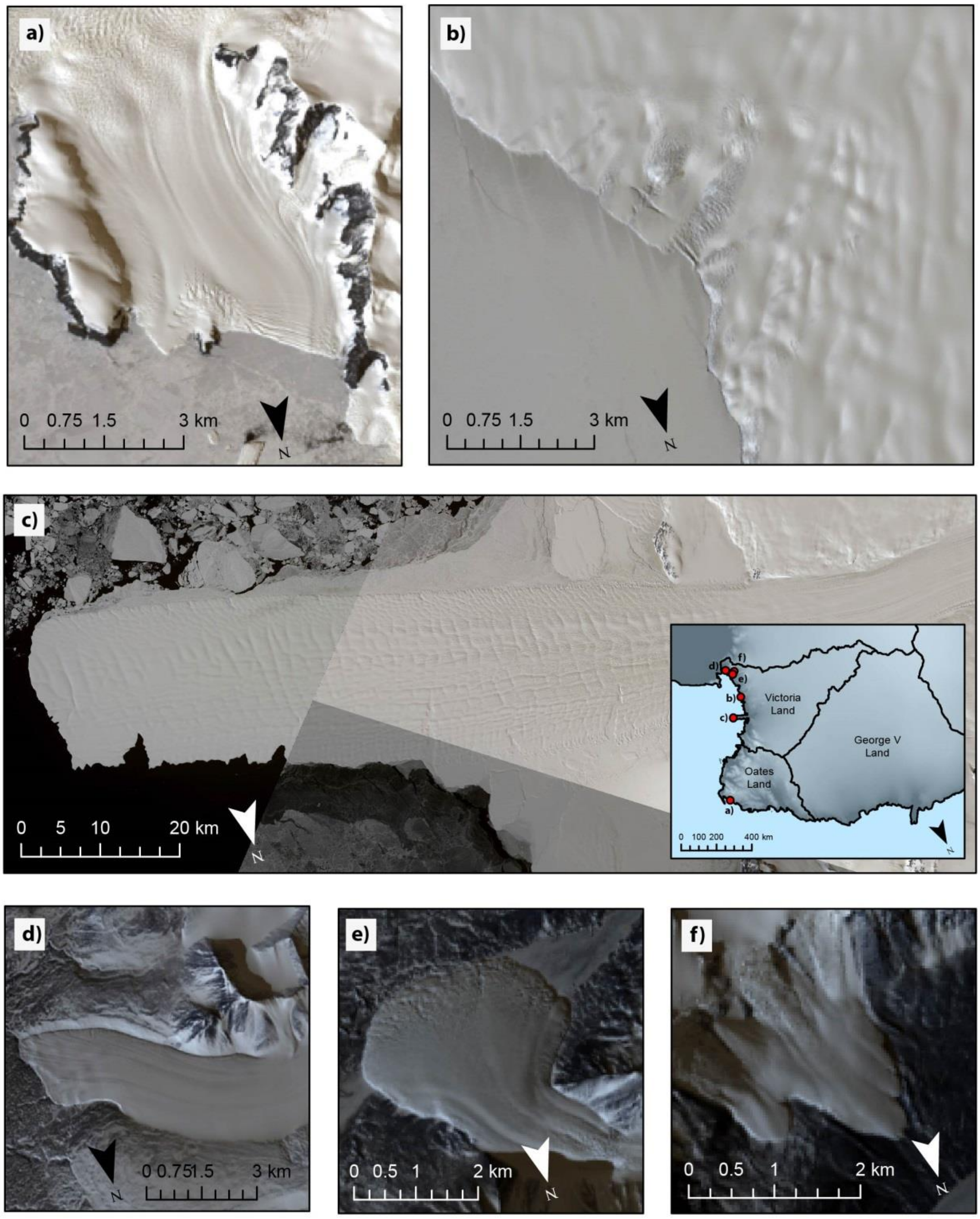


Figure 3.1: Examples of different types of marine-terminating glacier termini: a) floating constrained (FC) terminus (Shipley Glacier), b) grounded (G) glacier terminus (Oates Piedmont Glacier), c) floating unconstrained (FU) tongue (David Glacier); and land-terminating glacier termini: d) valley (V) glacier terminus (Hobbs Glacier), e) piedmont (P) glacier terminus (Canada Glacier) and f) lobate (L) glacier terminus (Hughes Glacier). Inset map shows locations of the different glaciers (red circles).

termini were identified using Bedmap 2 grounding line data (Fretwell et al., 2013) which predominantly consisted of the recent dataset derived from differential satellite synthetic aperture radar interferometry (DInSAR) data (Rignot et al., 2011b). Land-terminating glaciers were divided into: 1) valley glacier termini (V) (Fig 3.1d), 2) piedmont termini (P) (Fig 3.1e) and 3) lobate termini (L) (Fig 3.1f). This variation in glacier size, shape and type makes it a suitable area for investigating the influence of glacier-specific factors on terminus behaviour.

3.3 Previous work on glacier change in the study area

Previous studies on outlet glaciers in this area have primarily focused on individual or small numbers of glaciers with most attention paid to the mechanisms of large calving events on individual ice tongues such as Drygalski (Frezzotti and Mabin, 1994), Ninnis (Massom, 2003) and Mertz (Massom et al., 2015). Another study investigating the mass balance of four glaciers (David, Mulock, Byrd and Nimrod Glaciers) in the Ross Sea region revealed that these glaciers were all slightly gaining mass (Stearns, 2011). Larger-scale studies of terminus change in the area have tended to focus on the long-term (decadal) trends of marine-terminating glacier change. While early studies did not find any strong trends in outlet glacier terminus change (Frezzotti, 1997; Frezzotti et al., 1998; Frezzotti and Polizzi, 2002), a recent study by Miles et al. (2013) suggested that changes in glacier termini along the Pacific coast were linked to variations in air temperature and sea-ice concentrations. They observed that a period of general retreat (63% of glaciers) along the western South Pacific coast between 1974 and 1990 corresponded with warmer than usual air temperatures and reduced sea-ice concentrations. This was followed by two epochs of general glacier advance (72% of glaciers between 1990 and 2000 and 58% between 2000 and 2010) which corresponded with cooler air temperatures and increasing sea-ice concentrations. However, there is a clear need to focus on sub-decadal changes in glacier terminus positions and to take into account glacier-specific characteristics in order to gain insight into the inter-annual controls on glacier terminus position across these ocean-climate gradients.

3.4 Summary

The study area for this investigation encompasses three regions with distinct climatic and oceanic characteristics. It also contains a variety of different glacier types including marine- and land-terminating glaciers. This makes the area ideal for investigating regional variations in glacier behaviour and the potential influence of internal, glacier-specific controls. While some research has been conducted on multi-decadal changes in marine-terminating outlet glaciers in the area, much less is known about the drivers of shorter-term fluctuations and the relative influence of non-climatic, internal controls.

Chapter 4: METHODS

4.1 Introduction

This chapter provides a detailed outline of the methods used in this investigation. The first section focuses on the general remote sensing approach of the study (Section 4.2). This is followed by sections detailing the methods of satellite image acquisition (Section 4.3), glacier terminus digitisation (Section 4.4) and the measurement of glacier change (Section 4.5). The final three sections describe the methods of acquiring other glacier attribute data (Section 4.6) and air temperature and sea-ice data (Section 4.7) and a description of the statistical tests used in the analysis of the results (Section 4.8).

4.2 Remote sensing approach

Technological developments have enhanced the use of remote sensing (the art of investigating a phenomenon on the Earth's surface using satellite imagery or aerial photography (Lillesand et al., 2004)) in polar research. This has aided research in remote and hostile environments, such as Antarctica, where fieldwork is expensive, time consuming and, at times, potentially dangerous. The overarching approach of this study was to use a range of satellite data to map glacier terminus positions in different years to investigate glacier terminus change through time. The predominant satellite data type used was multispectral imagery from the Landsat satellites, which has been used in many outlet glacier studies conducted in both the Arctic and Antarctic (Frezzotti, 1997; Cook et al., 2005; Moon and Joughin, 2008; Miles et al., 2013; Carr et al., 2014; Fukuda et al., 2014). Landsat satellite imagery is popular because it is free, widely available and of relatively high spatial resolution (~30 m). However, because it is multispectral, it can be affected by cloud cover. Synthetic Aperture Radar (SAR) data, which create an image from the echo of radar pulses emitted from the satellite towards the Earth's surface (Pope et al., 2014), are not affected by this problem and are also regularly used in glacier change studies (Carr et al., 2013b; Rignot et al., 2014; Massom et al., 2015). SAR scenes (spatial resolution: 25 to 100 m) were used in this study to fill gaps where Landsat data were not available.

This study investigated outlet glacier terminus change covering approximately 1,000 km of coastline and >130 glaciers of varying size. This was to enable comparisons between expansive regions with varying climatic and oceanic characteristics and it required satellite imagery of sufficient resolution to be able to map small as well as large glaciers. The temporal resolution of this study was approximately 4 year intervals. This time-scale was chosen to capture inter-annual variations in glacier terminus change, which have not yet been investigated in this area and may shed light on shorter-term controls on glacier behaviour. Although the intention was to obtain imagery for 4-5 yr intervals, image availability dictated the precise dates at which glaciers were measured.

4.3 Image acquisition

4.3.1 Satellite data sources

Satellite imagery was acquired from the US Geological Survey (USGS: http://landsat.usgs.gov/) and the European Space Agency (ESA: http://www.esa.int/ESA) from 1972 to 2013 at the following dates: 1972, 1988, 1997, 2001, 2005, 2009 and 2013. The first date in the study was 1972 because it was the earliest date for which Landsat imagery was available and the coverage of other satellite imagery in the study area for the years prior to this date were relatively limited (Frezzotti et al., 1998; Miles et al., 2013). From 1972 to 1999, Landsat imagery for the study area was limited and there were not enough images to cover every study glacier during the years of 1972 and 1988. Therefore, for the 1972 time step, imagery was acquired between 1972 and 1974 and for the 1988 time step, imagery was acquired between 1988 and 1991. However, for simplicity's sake, these time steps will always be referred to in this study as "1972" and "1988".

The primary source of imagery used for this study was from the Landsat 1, 2 and 3 Multispectral Scanner (MSS), 4 and 5 Thematic Mapper (TM), 7 Enhanced TM and 8 Operational Land Imager

(OLI) Thermal Infrared Sensor (TIRS) satellites (Fig.4.1a), courtesy of the US Geological Survey (USGS) (properties of satellite imagery are summarised in Table 4.1). Landsat scenes were downloaded using the USGS Global Visualization (GLOVIS) and Earth Explorer viewers. Landsat images were chosen for their accessibility, high resolution (~30 m) and coverage across the study area. Landsat scenes with more than 25% cloud cover were rejected. SAR and Advanced SAR imagery, acquired from the European Space Agency's ERS and ENVISAT satellites (Fig.4.1b and 4.1c), were used where Landsat data were not available. Approximately 120 Landsat, 8 SAR and 6 ASAR scenes were used to cover all seven times slices.

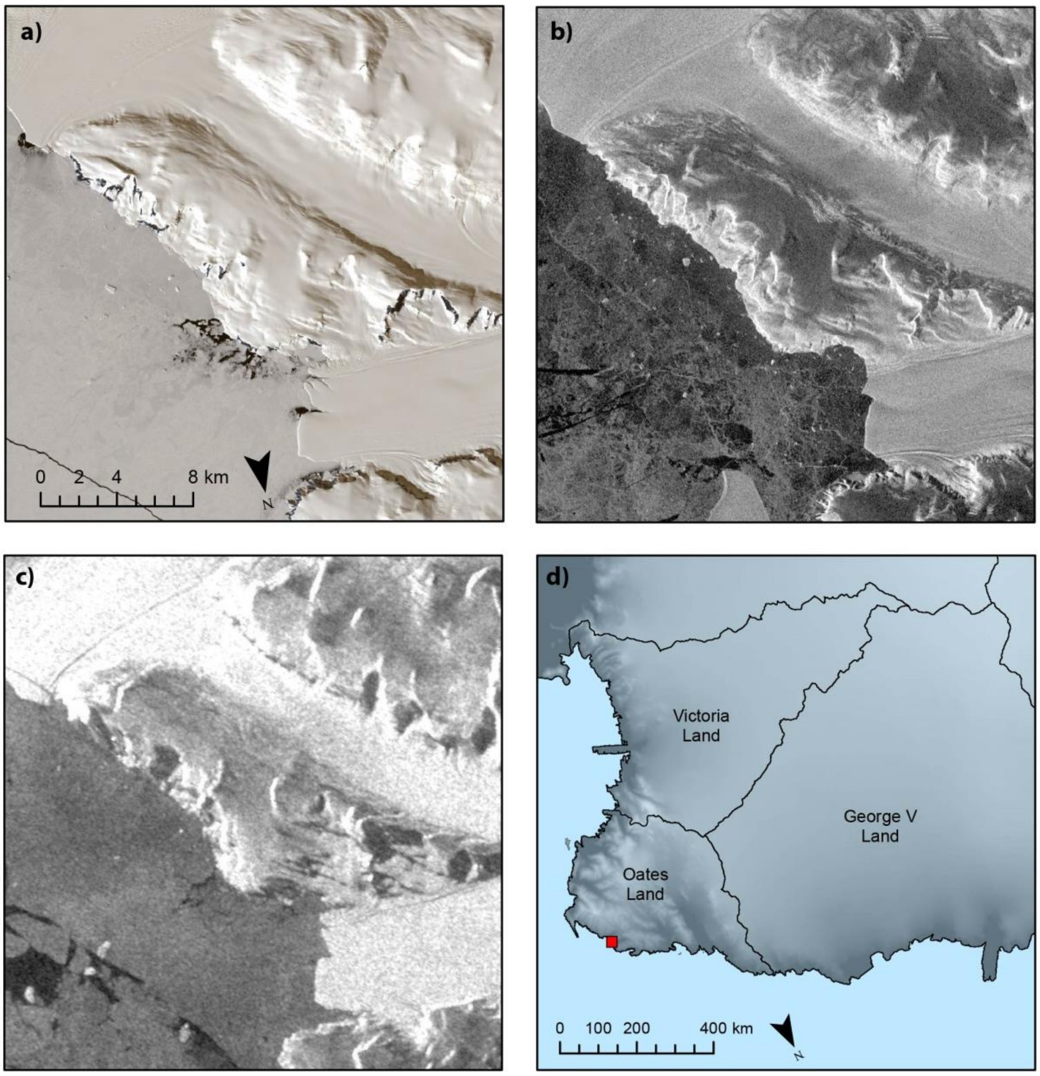


Figure 4.1: Examples of a) Landsat, b) ERS and c) ENVISAT satellite imagery and (d) location map.

Table 4.1: Summary of satellite imagery properties.

Year	Satellite	Sensor	Resolution	Launch year	Extra information	Source
1972	Landsat 1-3	Multispectral Scanner (MSS)	80 m	1972		US Geological Survey (USGS)
1988	Landsat 4-5	Thematic Mapper (TM)	30 m	1982		USGS
1997	ERS-1	Synthetic Aperture Radar data-SAR	25 m	1991	1997 mosaic accessed from Byrd Polar Research Centre http://research.bpcrc.osu.edu/rsl/	European Space Agency (ESA)
2001	Landsat 7	Enhanced Thematic Mapper Plus-ETM+	30 m	1999		USGS
2005	ENVISAT	Advanced Synthetic Aperture Radar-ASAR	100 m	2002		ESA
2009	Landsat 7	Enhanced Thematic Mapper Plus-ETM+	30 m	1999	Failure of Scan Line Corrector (SLC) from 2003 onwards affects this dataset	USGS
2013	Landsat 8	Operational Land Imager-OLI; Thermal Infrared Sensor-TIRS	30 m	2013		USGS

To minimise the effects of any seasonal cycles in advance and retreat, imagery was selected at the end of the austral summer (mid-January to mid-February). However, where imagery was not available, imagery was selected from as early as December. Landsat imagery used for the year 2009 was captured by the Landsat 7 +ETM satellite which experienced a failure of the Scanner Line Corrector (SLC). This means that the edges of each scene used during this year are covered in lines of no data and only ~20 km width strip down the centre of each scene is completely unaffected (Fig. 4.2). However, only ~22% of each scene is lost (USGS, 2013) and because the effect is systematic it was still possible to map most glacier termini using this imagery.

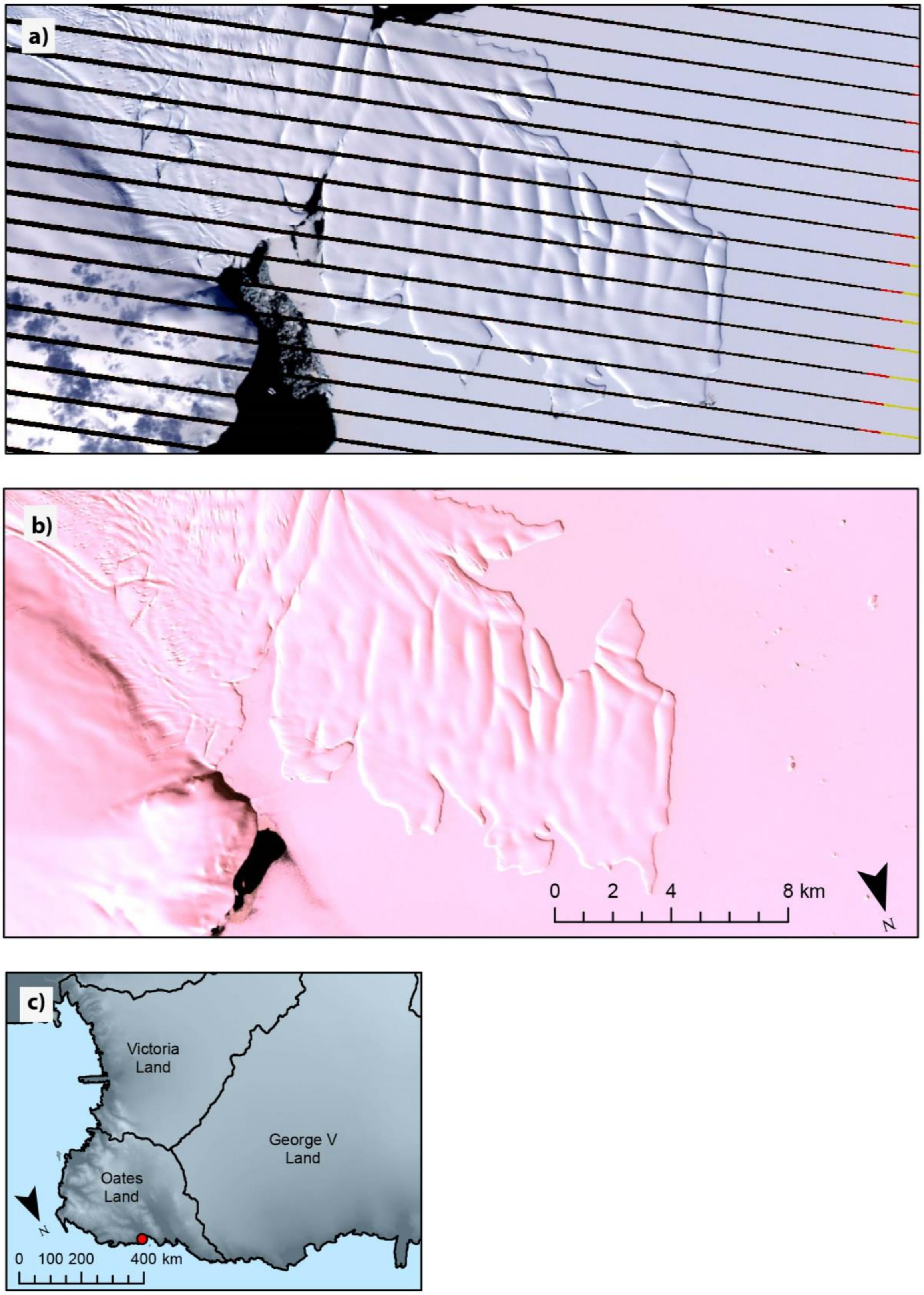


Figure 4.2: Examples of Landsat 7 ETM+ imagery with SLC failure (2009) (a) and without SLC failure (2001) (b) on Lillie Glacier, Oates Land. Location of glacier shown on map (c). Note the complex patterns on the glacier surface which most likely reflect the transition from grounded ice to floating ice.

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 Landsat imagery from 2006 instead. The number of glaciers per time slice that could not be mapped due to cloud cover, or the inability to distinguish them from the surrounding sea ice, is listed in Table 4.2.

Table 4.2: Number and percentage of glaciers that were and were not mapped during each time step.

Year	Number of glaciers mapped	Number of glaciers not mapped	% mapped
1972	130	5	96.3
1988	134	1	99.26
1997	130	6	96.3
2001	129	6	95.6
2005	74	61	54.8
2009	124	11	91.9
2013	135	0	100

4.3.2 Satellite data processing and error

The images, which were already georectified, were co-registered to the Polar Stereographic projection in ESRI ArcGIS using the most recent year (2013) as a base image, which has a geometric error of 12 m. Each image was co-registered using a series of control points to match recognisable and non-moving landmarks from the image being co-registered to the base image. The accuracy of the co-registration was verified by overlaying the image that was being co-registered over the base image to check that there was no shift in the recognisable features from one layer to the other.

The co-registration error for each type of imagery was estimated by digitising 16 points across the study area on easily recognisable 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 was calculated as the co-registration error. The upper limit of the error calculated for different satellite imagery types was the following: Landsat (±37-65 m), ERS SAR (±139 m) and ENVISAT ASAR (±215 m). While the co-registration error between different sets of Landsat imagery was relatively low, the error between the Landsat imagery and the ERS and ENVISAT data was higher. The co-registration error of the ENVISAT data was particularly high because it had a lower resolution (100 m) than the Landsat data, making it more difficult to identify recognisable landmarks in the ENVISAT imagery.

The digitisation error was also determined by repeatedly digitising twelve 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 4.3). The error is quoted alongside the glacier terminus position changes in the Results chapter of this study and any terminus changes that are less than the error per year are classified as 'no change'. The error calculated in this study is in line with the error calculated in other glacier terminus mapping studies using similar remote sensing methods (Howat et al., 2008; Howat and Eddy, 2011; Miles et al., 2013).

Table 4.3: Error per year (m yr^{-1}) for each epoch, including the 1972-2013 long-term epoch and the 2001-2006, 2006-2009 epochs for Victoria Land glaciers.

Epoch	Epoch duration (years)	Satellite imagery	Coregistration error (m)	Error per year (m yr^{-1})
1972-1988	16	Landsat MSS	65	4.1
1988-1997	9	ERS SAR	139	15.4
1997-2001	4	ERS SAR	139	34.8
2001-2005	4	Envisat ASAR	215	53.8
2005-2009	4	Envisat ASAR	215	53.8
2009-2013	4	Landsat ETM	37	9.3
1972-2013	41	Landsat MSS	65	1.6
2001-2006	5	Landsat ETM	37	7.4
2006-2009	3	Landsat ETM	37	12.3

4.4 Digitising glacier termini

Glacier termini were manually digitised for ~135 glaciers in the study area, from the McMurdo Dry Valleys in Victoria Land to Mertz Glacier Tongue in George V Land, for each time step using ESRI ArcGIS (Fig. 4.3). In order to investigate a broad spread of glaciers over a large area, the study focused on glaciers with widths > 0.5 km. This represents ~85% of the total population of glaciers in the study area. A total of 28 marine- and 46 land-terminating glaciers were mapped in Victoria Land, 50 marine-terminating glaciers were mapped in Oates Land and 15 marine-terminating glaciers were mapped in George V Land (Table 3.1). Glacier termini that were obscured by cloud cover, or where the glacier tongue could not be clearly discerned from sea ice for a particular time step, were not mapped in that time step.

For Landsat imagery with 30 m pixel resolution, glacier terminus digitisation was predominantly conducted at a scale of 1:15,000. This was chosen because it was at a small enough scale to digitise the glaciers with sufficient accuracy, but did not make the image appear too pixelated. Glacier termini on the SAR imagery, with a pixel resolution of 25 m, were also mapped at a scale of 1:15,000. Terminus digitisation on the Landsat 1-3 MSS data was conducted at a scale of 1:20,000 because it had a lower resolution (80 m) and termini on ENVISAT SAR data, which had the lowest resolution (100 m) were mapped at scales of 1:20,000 to 1:25,000. False-colour composites were generated from the Landsat imagery by stacking the multispectral bands in one of the following RGB orders: 321, 432 or 543. This helped to increase the contrast between glacier ice and sea ice to make identifying glacier termini easier (Paul et al., 2015).

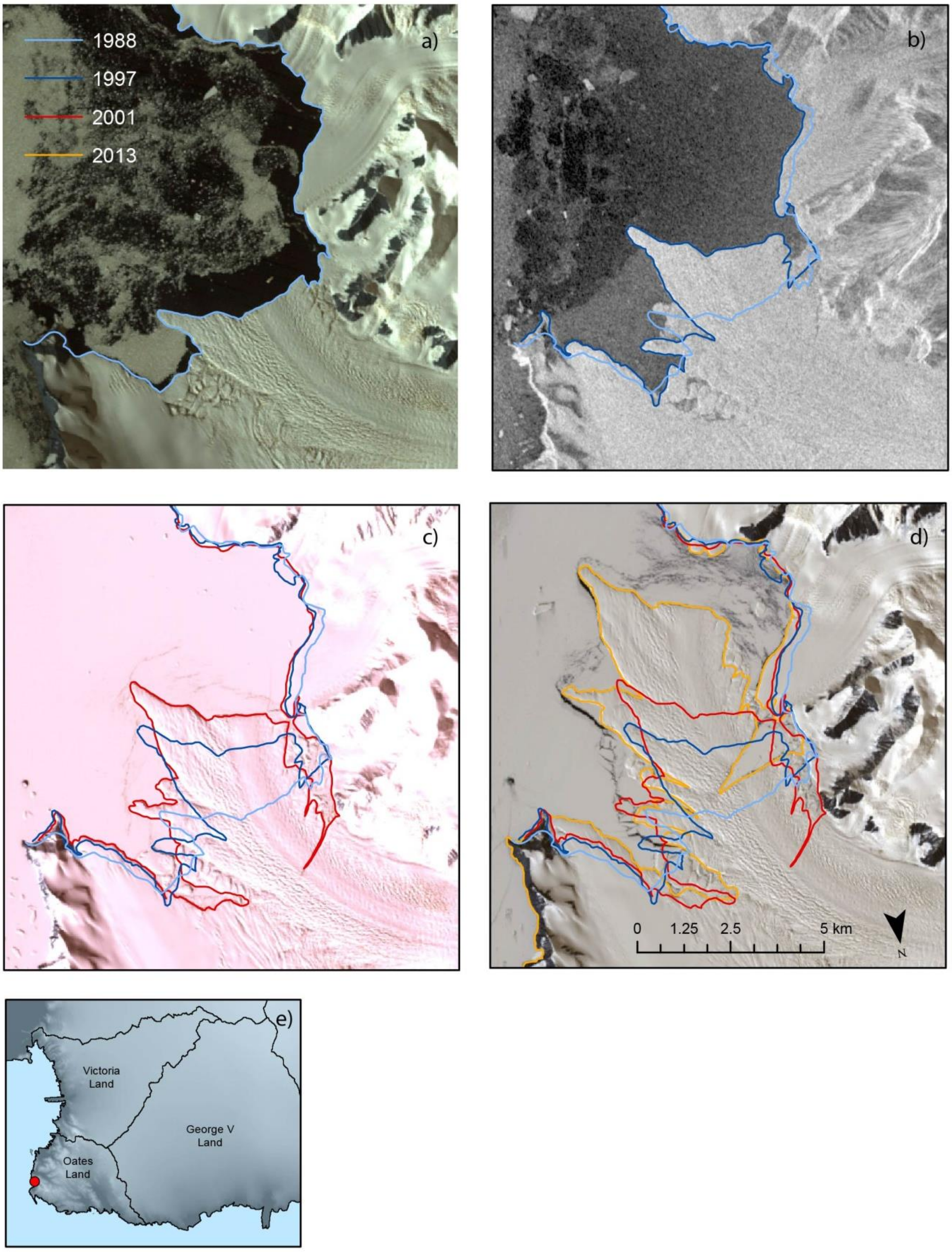


Figure 4.3: Examples of terminus digitisation on Ironside Glacier using imagery from different years a) Landsat TM: 1988, b) ERS SAR: 1997, c) Landsat ETM+: 2001, d) Landsat OLI TIRS: 2013 and e) location map.

4.5 Measuring glacier change

Glacier change in the study area was assessed through changes in glacier terminus position rather than glacier changes across the entire drainage basin. This was due to having imagery that was limited to the margins of this part of the ice sheet. A disadvantage of this is that it precludes the assessment of changes in total glacier area and changes occurring in the accumulation zones of these marginal glaciers as has been achieved by Jiskoot et al. (2012) in central East Greenland. This means that changes will be emphasised in larger glaciers relative to smaller ones and therefore the potentially more dynamical responses of smaller outlet glaciers to external forcings may be missed. Despite this, glacier terminus position changes are accepted as an important indicator of outlet glacier health and have been used in many studies on recent changes in outlet glacier behaviour in both Greenland and Antarctica (Moon and Joughin, 2008; Howat and Eddy, 2011; Carr et al., 2013b; Miles et al., 2013). Measuring glacier terminus positions is also a relatively quick and easy method to collect data on outlet glacier behaviour making it an appropriate method for studying changes in large numbers of glaciers such as is the case in this study.

There are several established methods to quantify the change between mapped terminus positions (Lea et al., 2014). One of the most simple is the centre-line method, which calculates the change in distance between the midpoints of sequential ice fronts along the direction of ice flow (Cook et al., 2005; Bevan et al., 2012). Although this allows for quick quantification of terminus change, it does not allow for uneven variation along the terminus (Carr et al., 2013b; Lea et al., 2014). In this study, the well-established rectilinear box method (Moon and Joughin, 2008) was used, which has been employed in a wide range of glacier terminus change studies in several different areas (Carr et al., 2013b; Miles et al., 2013; Muto and Furuya, 2013; Carr et al., 2014; Fukuda et al., 2014; McNabb and Hock, 2014). The box method has the advantage over other glacier terminus position change measurement methods because it allows for uneven variation along the terminus and it is relatively quick and simple to use (Lea et al., 2014). A rectilinear box of a fixed width was drawn over the glacier terminus, the long sides of which were drawn approximately parallel to the glacier sides (Fig.4.4b). The area of the glacier termini was measured within the box for each time slice using the

Spatial Analyst tool in ArcGIS (Fig.4.4c). The width-averaged change between time slices was then calculated for each glacier by dividing the areal difference between two dates by the width of the glacier. Glacier terminus change is given as a rate (m yr^{-1}) in order to account for time steps of varying duration. The mean and median rate of glacier terminus change were calculated for each region and for all glaciers for all time steps. However, the median was chosen as the main summary statistic for the glacier change rate rather than the mean because the mean is more easily influenced by outliers, such as a major calving event on a single glacier. The occurrence of major calving events on all glaciers was recorded. A major calving event is defined here as being when the length of an iceberg calved in a given time step > glacier width.

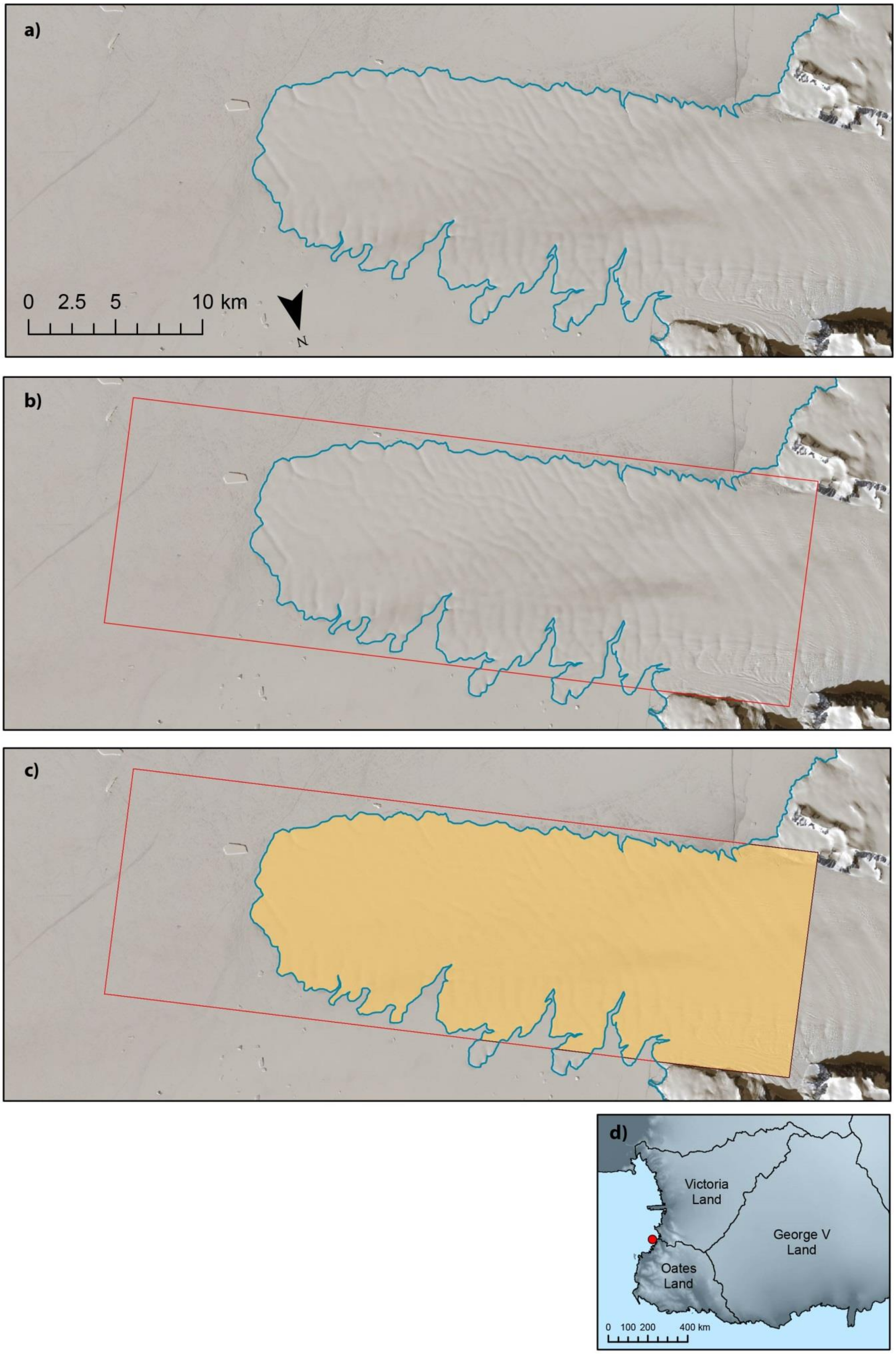


Figure 4.4: Rectilinear box method: a) terminus was manually digitised for a given year (2013 in this example), b) a rectilinear box was drawn over the terminus and c) the area within that box was extracted using the Spatial Analyst toolbox in ArcGIS. Background image is Aviator Glacier (location shown in map (d)).

4.6 Other glacier attributes

The classification of different glacier terminus types was based on the GLIMS Illustrated Glacier Classification Manual (Rau et al., 2005) (Table 3.1). Other glacier attribute data that were acquired included initial terminus width (measured parallel to the calving front on the 1972 Landsat imagery), glacier length which was measured from the terminus to the headwall of each glacier (and rounded up to the nearest 5 km), ice velocity data from Rignot et al. (2011a) and glacier thinning data from Pritchard et al. (2009). A measure of ice thickness was derived from Bedmap 2 (Fretwell et al., 2013) and maximum ice thickness was sampled for each glacier using a point shapefile at the intersection of the glacier centre-line and the grounding line. It was not always possible to identify the grounding line on all glaciers in the study area using optical imagery. For simplicity's sake, therefore, grounding line data was also derived from Bedmap 2 (Fretwell et al., 2013).

Data on fjord shape was collected for all marine-terminating glaciers to assess along-flow variation in fjord width using a simplified version of shape criteria proposed in Carr et al. (2014). Four categories of fjord geometry were used: Convergent (narrowing down-glacier (C)) (Fig 4.5a), Divergent (widening down-glacier (D)) (Fig. 4.5b) Parallel (P) (Fig. 4.5c) and None (glaciers not within a fjord (N)). For the marine-terminating glaciers, it was also noted whether they terminated in the Ross Sea or the Pacific Ocean, whether the glaciers portrayed any signs of cyclic behaviour (experiencing a calving event followed by a period of advance) and whether their termini maintained the same shape throughout the study period (an indication that no calving occurred).

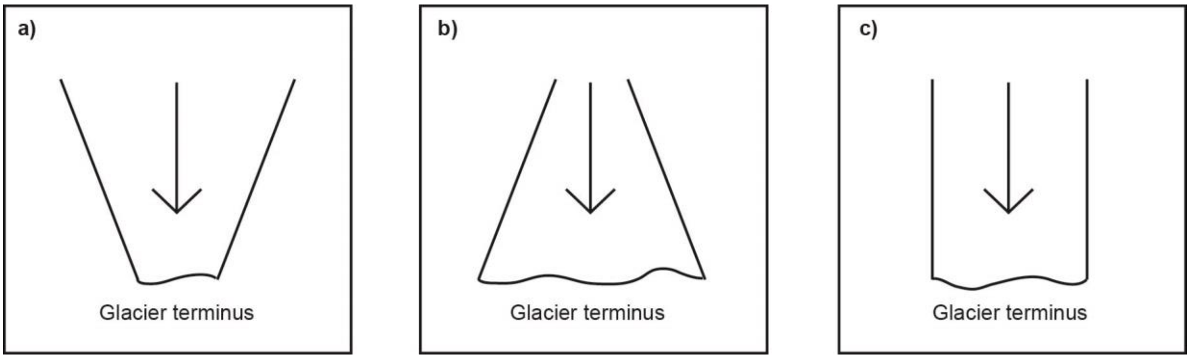


Figure 4.5: Diagrams depicting different classifications of fjord shape, simplified from criteria proposed by Carr et al. (2014), a) convergent (narrowing down-glacier), b) divergent (widening down-glacier) and c) parallel. Arrows represent glacier flow direction at the centre-line.

4.7 Air temperature and sea-ice data

Monthly air temperature data were collected from three stations in the three regions of the study area: McMurdo station (Victoria Land: 77.9°S, 166.7°E), Possession Island automatic weather station (Oates Land: 71.9°S, 171.2°E) and Dumont d'Urville station (George V Land: 66.7°S, 140.0°E) (locations shown in Fig. 1.1). All temperature data covered the period from 1952 (earliest measurement date) to 2013, except for Possession Island which only started recording air temperatures in 1993. All data were accessed from the Scientific Committee on Antarctic Research (SCAR) Met Reference Antarctic Data for Environmental Research Project (Turner et al., 2004). Time series of mean annual and mean austral summer (December, January and February) temperatures were plotted and mean summer air temperature anomalies were calculated for each region.

Monthly sea-ice data were obtained from the Sea-Ice Concentrations from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) and SSMI Sounder Passive Microwave dataset from the National Snow and Ice Data Center (NSIDC) (Cavalieri et al., 1996). Mean monthly sea-ice data were extracted for each region in ArcGIS using sample polygon areas that stretched along the coastline of each region, ~50 km offshore, and extended ~200 km seaward (Fig. 4.6). Average annual sea-ice concentrations for each region were calculated from the monthly mean data. Ocean temperature data were not readily available for the study area and therefore were not used in this investigation, however it is acknowledged that ocean temperatures are closely related to sea-ice behaviour.

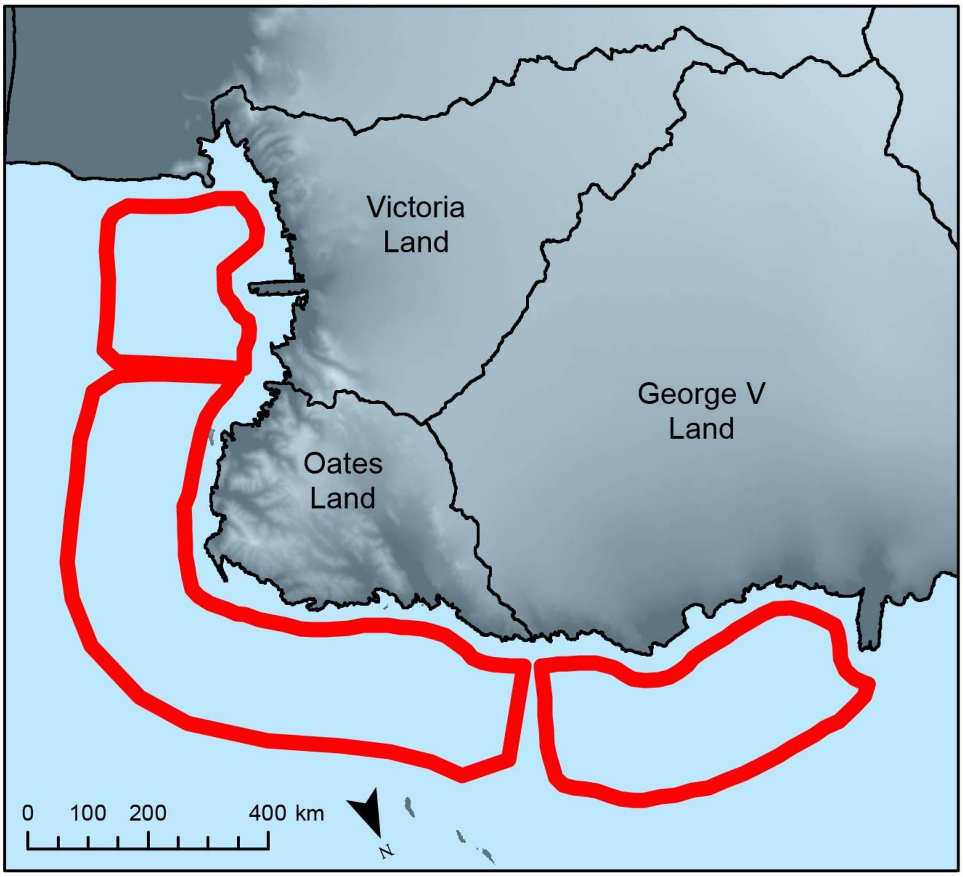


Figure 4.6: Sampling area polygons for mean monthly sea-ice concentrations off the coast of Victoria Land, Oates Land and George V Land.

4.8 Statistical analysis

The relationships between terminus change and possible drivers were analysed using statistical tests. The Wilcoxon rank sum test (Schuenemeyer and Drew, 2011) was used to test the significance of observed epochal differences within terminus position change and the differences in the long-term terminus changes of marine- and land-terminating glaciers (see Appendix A). The Student *t* test (Schuenemeyer and Drew, 2011) was used to test the significance of observed epochal differences in mean annual and summer air temperatures and mean sea-ice concentrations. The Kruskal-Wallis test (Schuenemeyer and Drew, 2011) was used to test the differences between the three marine-terminating glacier terminus types (floating constrained, floating unconstrained and grounded) and to test the differences between marine-terminating glaciers with different fjord shapes (converging, diverging, parallel or no fjord). Linear regression analyses were used to test the correlations between long-term (1972-2013) glacier terminus change and glacier width, glacier length, ice velocity and ice thickness and to test long-term trends in sea-ice concentrations in the three regions.

4.9 Summary

This investigation has been undertaken using remote sensing techniques, allowing the examination of 135 glaciers spread over a large area. Satellite imagery was acquired from the Landsat satellite suite, supplemented by SAR data from the ERS and ENVISAT satellites. Glacier terminus change was measured by manually digitising glacier termini for the following years: 1972, 1988, 1997, 2001, 2005, 2009 and 2013 and using the rectilinear box method to calculate area change per time step. External forcing data used in this investigation consisted of air temperature and sea-ice data. Other glacier-specific data included glacier width, terminus type, ice velocity and ice thickness.

Chapter 5: RESULTS

5.1 Introduction

The results of this investigation are presented in this chapter. The first part of this chapter (Section 5.2) focuses on the overall glacier terminus change within the entire study area from 1972 to 2013, then the inter-annual terminus position fluctuations, and then the variations in terminus behaviour between the three regions of Victoria Land, Oates Land and George V Land. The second part of this chapter (Section 5.3) examines trends in climatic (air temperature) and oceanic (sea ice) data in the region. This is followed by an investigation of the influence of glacier specific factors such as terminus type, glacier width, length, and velocity, and fjord shape, in order to identify potential internal controls on terminus positions (Sections 5.4 and 5.5). The final section focuses on major calving events and potential cyclical behaviour of glacier termini (Section 5.6). Note that statistical analyses are used to test the significance of glacier terminus change, air temperature and sea-ice trends and the influence of these drivers on glacier behaviour, but only relationships that are significant are mentioned in this results section.

5.2 Time-series of glacier change

5.2.1 Long-term glacier terminus change from 1972 to 2013

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 long-term measurement error (± 65 m or ± 1.6 m yr^{-1}) and classified as 'no change' (Fig. 5.1). The median terminus position change for all glaciers between 1972 and 2013 was just 0.2 ± 1.6 m yr^{-1}. Over the same time period, 16% of glaciers in Victoria Land advanced, 19% retreated and 65% exhibited no change, with an overall median terminus 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 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 change rate: 2.9 ± 1.6 m yr^{-1}).

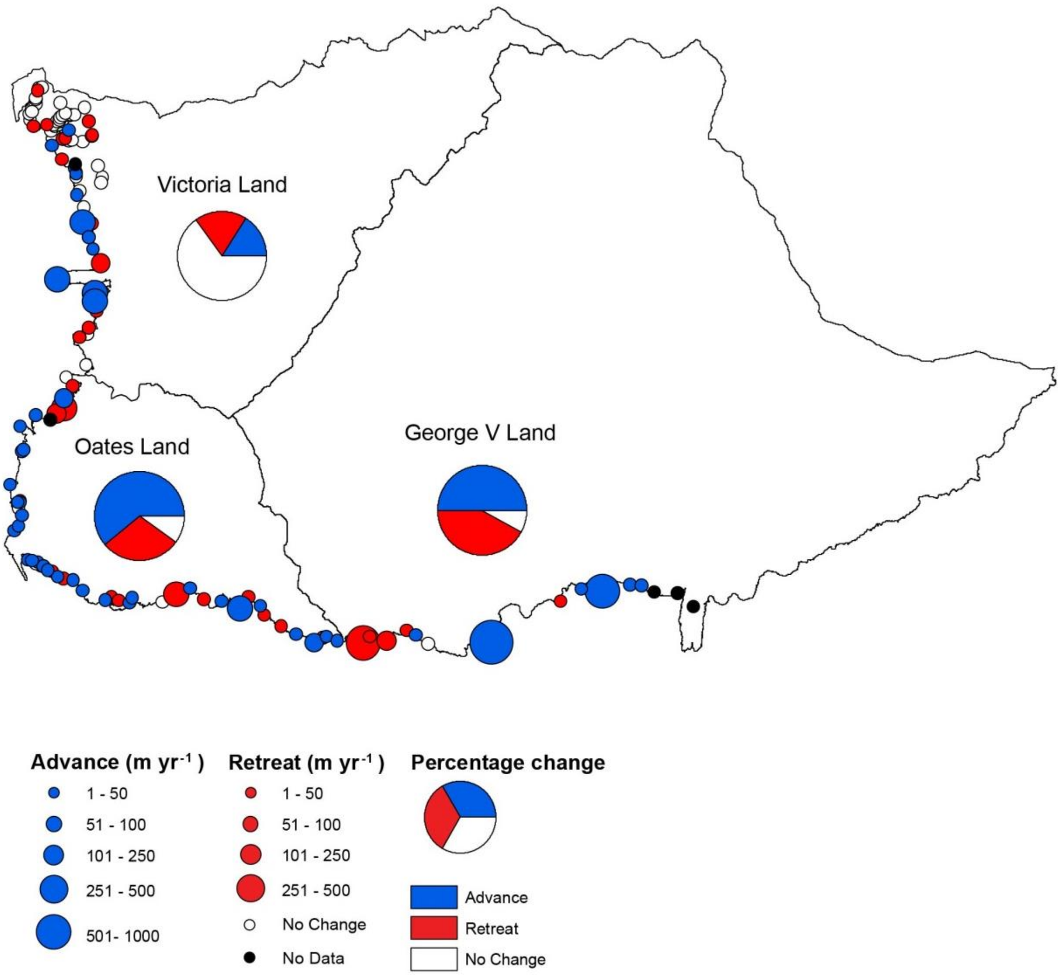


Figure 5.1: Long-term glacier terminus change (1972-2013) within each region.

5.2.2 Inter-annual fluctuations in glacier terminus positions

There were no clear trends (outside of the measurement error) in glacier terminus position changes of the entire glacier population between epochs. While Figure 5.2a suggests that there was a slight advance in all glaciers during the 2001-2005 and 2005-2009 epochs, the median terminus change rates remained within the error margin for each epoch and, therefore, this cannot be considered a trend (Table 5.1).

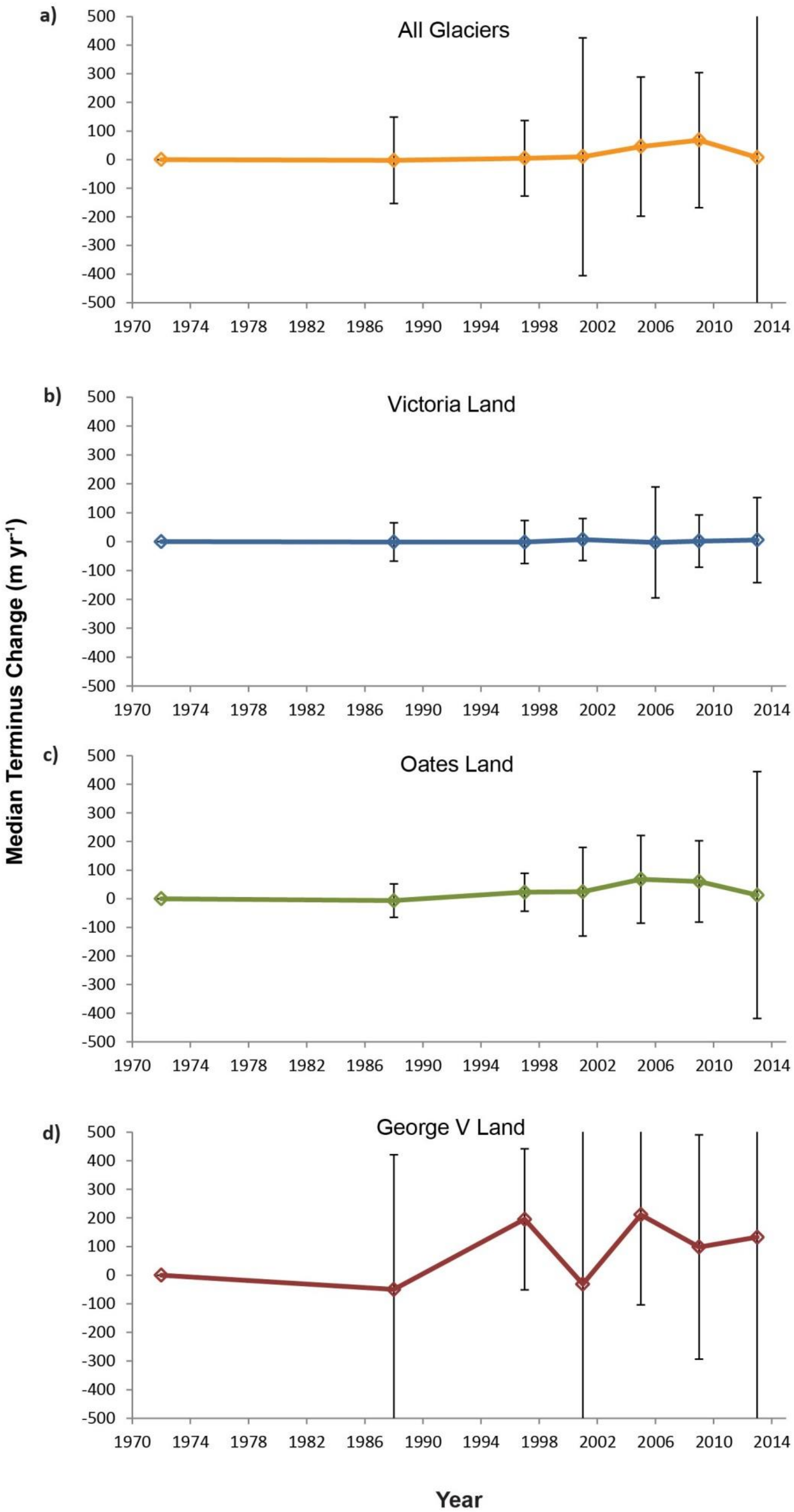


Figure 5.2: Median terminus change (m yr^{-1}) per epoch for a) the whole study area, b) Victoria Land, c) Oates Land and d) George V Land. 1 standard deviation error bars are shown as black lines. Note that some error bars extend beyond the graph.

When glacier change patterns are examined in each region for each separate epoch, some differences in behaviour emerge. The glacier termini in Victoria Land (Fig. 5.2b) experienced the least variation of the three regions with a standard deviation (s.d.) for the longest time step (1972 to 2013) of only 42.7 m yr^{-1} (Table 5.1). Median glacier terminus change values were within the error margins for each epoch and therefore it is concluded that there were no significant epochal trends of advance or retreat in this region. Glacier terminus changes in Oates Land were slightly larger than in Victoria Land (s.d. from 1972 to 2013 of 47.6 m yr^{-1}). After a period of minor retreat during the 1972-1988 epoch (median terminus change: -6.7 ± 4.1 m yr^{-1}), the termini of glaciers in Oates Land (Fig. 5.2c) experienced a significant switch ($p < 0.05$) to a period of advance (median terminus change: 22.7 ± 15.4 m yr^{-1}). This advance continued to increase until the 2009-2013 epoch, when median terminus change fell from 60.3 ± 53.8 to 12.8 ± 7.5 m yr^{-1}, but this decrease was not significant due to the large spread of advance and retreat in the most recent epoch.

Glaciers in George V Land (Fig. 5.2d) underwent the most extreme changes in each epoch, experiencing both the largest advance (maximum: 1,101 m yr^{-1} between 1972 and 1988) and the largest retreat distances (minimum: -14,177 m yr^{-1} between 2009 and 2013) of all three regions in the study area (s.d. from 1972 to 2013 of 228.7 m yr^{-1}). During the 1972-1988 epoch, glaciers in George V Land generally retreated (median terminus change: -49.8 ± 4.1 m yr^{-1}). From 1988 onwards, however, there was a significant switch ($p < 0.05$) to a period of advance (median terminus change: 195.3 ± 15.4 m yr^{-1}). This advance was followed by a period between 1997 to 2001 when there was no strong trend (median terminus change: -31.5 ± 34.8 m yr^{-1}) but 54% of the glaciers retreated. Glaciers then returned to a period of advance during the 2001-2005 epoch (median terminus change: 211.2 ± 53.8 m yr^{-1}). This was maintained until the end of the study time period, although the median terminus change rate was reduced to 98.5 ± 53.8 m yr^{-1} and 132.7 ± 7.5 m yr^{-1} for the 2005-2009 and 2009-2013 epochs, respectively.

Table 5.1: Summary statistics of glacier change for all glaciers, Victoria Land, Oates Land, and George V Land with uncertainties derived from the co-registration error. Uncertainties are in m yr^{-1} and vary according to the number of years in each epoch and the satellite imagery used. Refer back to table 4.3.

Summary statistics (m yr^{-1})	1972-1988	1988-1997	1997-2001	2001-2005	2005-2009	2009-2013	Long-term: 1972-2013
All Glaciers							
Median	-2.5 ± 4.1	4.5 ± 15.4	9.9 ± 34.8	45.8 ± 53.8	68.1 ± 53.8	7.2 ± 9.3	0.2 ± 1.6
Mean	0.2 ± 4.1	48.4 ± 15.4	-25.3 ± 34.8	47.4 ± 53.8	81.1 ± 53.8	-135.3 ± 9.3	8.8 ± 1.6
S.D.	150.7 ± 4.1	131.8 ± 15.4	415.2 ± 34.8	243.0 ± 53.8	235.9 ± 53.8	1307.1 ± 9.3	80.1 ± 1.6
Min.	-758 ± 4.1	-159 ± 15.4	-4200 ± 34.8	-939 ± 53.8	-536 ± 53.8	-14177 ± 9.3	-343 ± 1.6
Max.	1101± 4.1	854 ± 15.4	602 ± 34.8	1008 ± 53.8	1022 ± 53.8	743 ± 9.3	574 ± 1.6
	1972-1988	**1988-1997**	**1997-2001**	**2001-2006**	**2006-2009**	**2009-2013**	**Long-term: 1972-2013**
Victoria Land							
Median	-1.1 ± 4.1	-1.8 ± 15.4	7.0 ± 34.8	-2.9 ± 7.4	1.6 ± 12.3	5.4 ± 9.3	-0.5 ± 1.6
Mean	11.0 ± 4.1	11.4 ± 15.4	16.2 ± 34.8	-17.7 ± 7.4	28.3 ± 12.3	-10.1 ± 9.3	7.3 ± 1.6
S.D.	66.2 ± 4.1	74.3 ± 15.4	72.6 ± 34.8	192.1 ± 7.4	90.5 ± 12.3	147.4 ± 9.3	42.8 ± 1.6
Min.	-86 ± 4.1	-91 ± 15.4	-133 ± 34.8	-1481 ± 7.4	-60 ± 12.3	-1045 ± 9.3	-75 ± 1.6
Max.	471 ± 4.1	451 ± 15.4	467 ± 34.8	188 ± 7.4	502 ± 12.3	343 ± 9.3	218 ± 1.6
	1972-1988	**1988-1997**	**1997-2001**	**2001-2005**	**2005-2009**	**2009-2013**	**Long-term: 1972-2013**
Oates Land							
Median	-6.7 ± 4.1	22.7 ± 15.4	24.4 ± 34.8	68.0 ± 53.8	60.3 ± 53.8	12.8 ± 9.3	5.4 ± 1.6
Mean	-10.9 ± 4.1	32.0 ± 15.4	2.8 ± 34.8	33.6 ± 53.8	37 ± 53.8	-100.1 ± 9.3	1.9 ± 1.6
S.D.	58.2 ± 4.1	66.4 ± 15.4	154.9 ± 34.8	153.0 ± 53.8	141.9 ± 53.8	431.2 ± 9.3	47.6 ± 1.6
Min.	-263 ± 4.1	-159 ± 15.4	-601 ± 34.8	-464 ± 53.8	-317 ± 53.8	-2306 ± 9.3	-242 ± 1.6
Max.	108 ± 4.1	193 ± 15.4	210 ± 34.8	276 ± 53.8	415 ± 53.8	266 ± 9.3	129 ± 1.6
George V Land							
Median	-49.8 ± 4.1	195.3 ± 15.4	-31.5 ± 34.8	211.2 ± 53.8	98.5 ± 53.8	132.7 ± 9.3	2.9 ± 1.6
Mean	-17.8 ± 4.1	264.7 ± 15.4	-331.7 ± 34.8	264.6 ± 53.8	258.3 ± 53.8	-899.8 ± 9.3	45.6 ± 1.6
S.D.	470.2 ± 4.1	246.6 ± 15.4	1238.9 ± 34.8	314.9 ± 53.8	391.7 ± 53.8	4000.2 ± 9.3	228.7 ± 1.6
Min.	-758 ± 4.1	-18 ± 15.4	-4200 ± 34.8	-89 ± 53.8	-258 ± 53.8	-14177 ± 9.3	-343 ± 1.6
Max.	1101 ± 4.1	854 ± 15.4	602 ± 34.8	1008 ± 53.8	1022 ± 53.8	743 ± 9.3	574 ± 1.6

5.3 Climate and sea-ice trends

5.3.1 Air temperatures

Victoria Land had the coolest mean annual air temperatures of the three regions (-16.8 °C between 1957 and 2014), approximately 5 and 6 °C cooler than Oates and George V Land, respectively (Fig. 5.3); and exhibited a warming trend of approximately 2 °C for the same time period. Since records began in 1993, mean annual air temperatures in Oates Land experienced ~1 °C of warming, but the measurement record is, perhaps, too short to be considered a long-term trend. Since the early 1980s, mean annual temperatures in George V Land experienced a slight cooling trend of 1-2 °C.

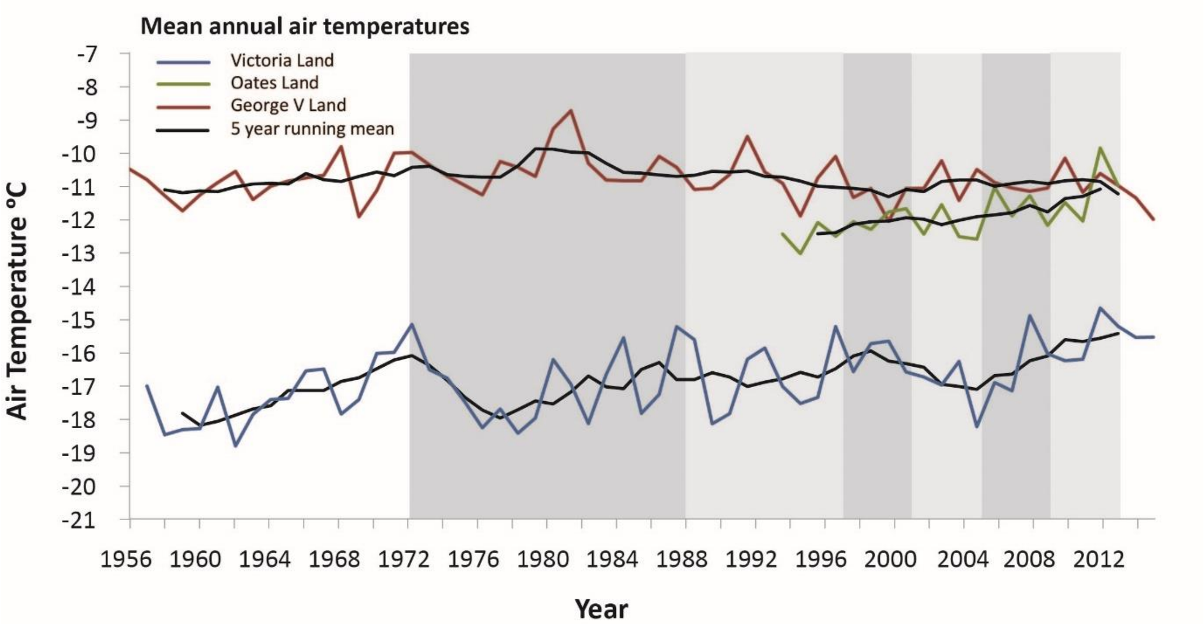


Figure 5.3: Mean annual air temperatures from the Antarctic stations. The black line represents the 5 year running mean. Epochs where glacier changes were measured are shaded in background.

Victoria Land also had the coolest mean austral summer (December, January, February) air temperature out of the three regions (-5 °C between 1957 and 2015) which exhibited a slight warming trend of approximately 1 °C during the same time period (Fig. 5.4). Oates Land had the warmest mean summer temperatures (-0.3 °C between 1993 and 2015), exceeding 0 °C during 21 of the past 22 years and exhibited a warming trend of ~1 °C during that time. George V Land had cooler mean summer temperatures (-2.3 °C between 1957 and 2015) than Oates Land, but exhibited no obvious long-term trends. Figure 5.5 plots summer temperature anomalies alongside the terminus position data for each region and shows that Victoria Land had cooler than average mean summer temperatures during the early 1960s, and from 1973 to 1995 (Fig. 5.5a). George V Land experienced a period of generally above average summer air temperatures from 1972 to 1994 (Fig. 5.5c). This was followed by a sequence of cooler than average summer temperatures up until 2001.

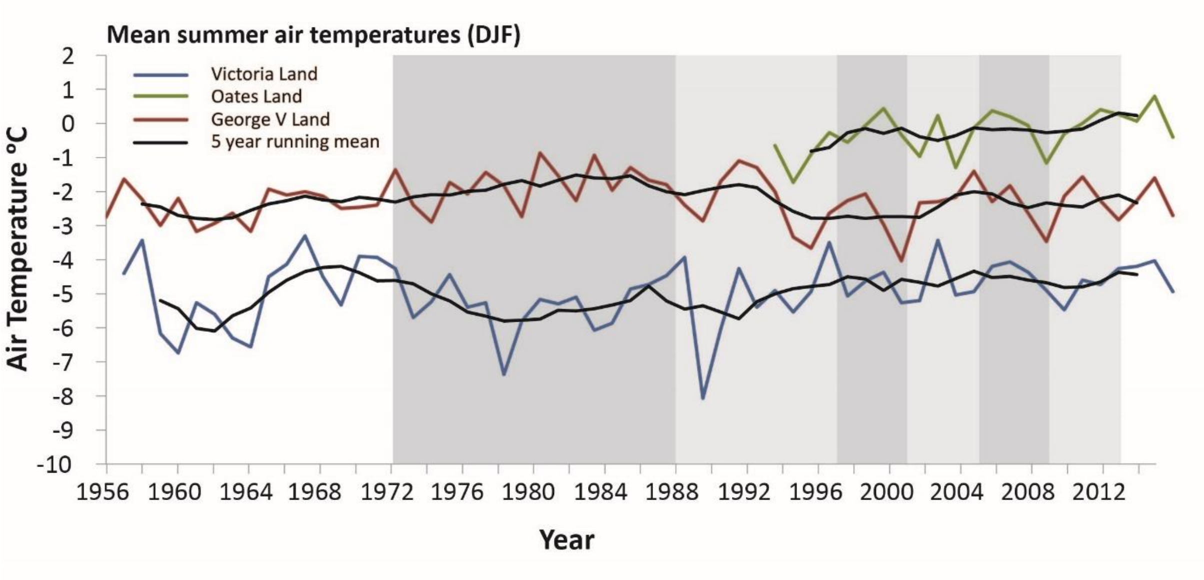


Figure 5.4: Mean austral summer air temperatures from the Antarctic stations. The black line represents the 5 year running mean. Epochs where glacier changes were measured are shaded in background.

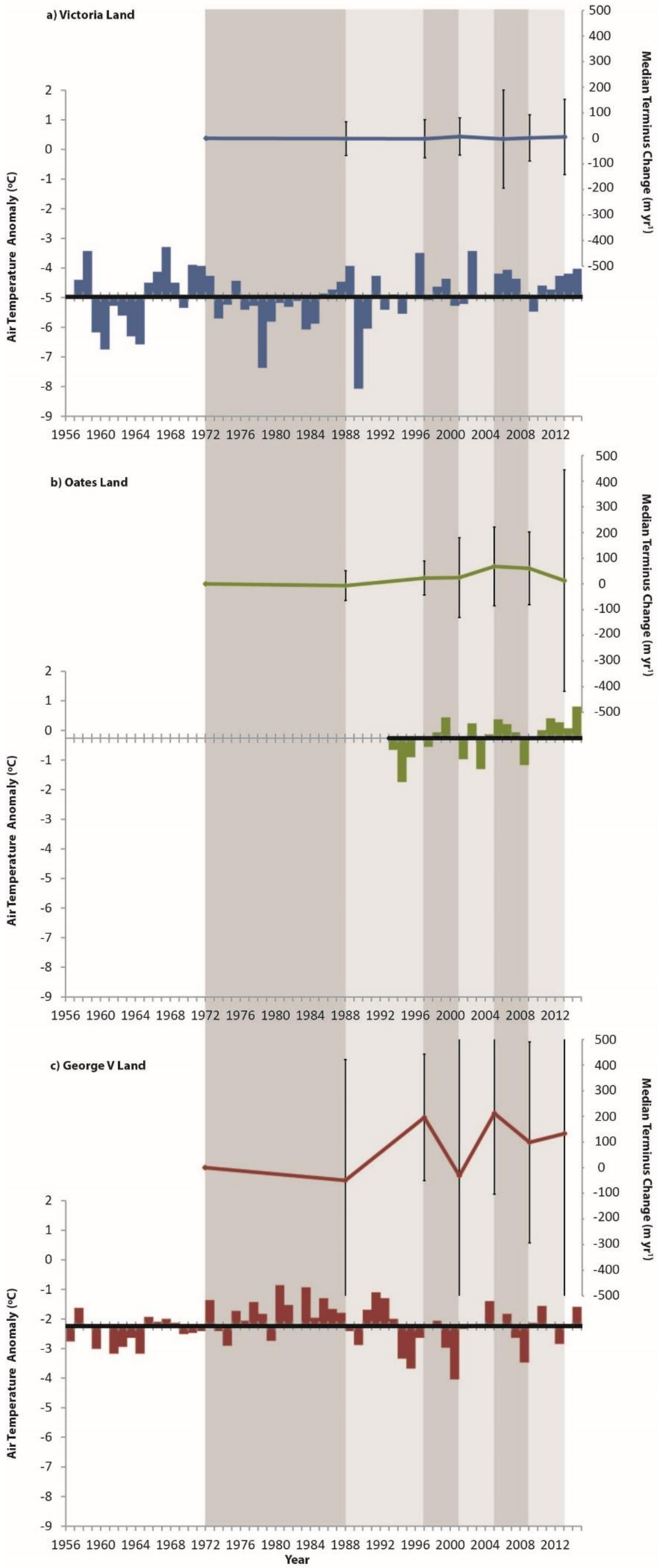


Figure 5.5: Mean summer air temperature anomalies and median terminus change (m yr^{-1}) for a) Victoria Land, b) Oates Land and c) George V Land. 1 standard deviation error bars are shown as black lines. Note that some error bars extend beyond the graph. Epochs where glacier changes were measured are shaded in background.

5.3.2 Sea ice

Mean long-term (1979 to 2014) annual sea-ice concentrations in the study area were 62% in Victoria Land, 71% in Oates Land and 81% in George V Land. There were no significant long-term trends in mean annual sea-ice concentrations in Victoria Land or George V Land (Fig. 5.6). However, there was a relatively strong trend of increasing sea-ice concentrations ($R^2 = 0.54$; $p < 0.05$) in Oates Land throughout the time period of this study with mean annual sea-ice concentrations increasing from 64% during the 1972-1988 epoch to 77% in the 2009-2013 epoch. Mean annual sea-ice concentrations exhibited the highest variability in George V Land and experienced a noticeable decrease during the epoch 1972-1988 (marked with a red arrow in Fig. 5.6), with a minimum averaged annual sea-ice concentration of 58%. A smaller decrease in sea-ice concentrations was experienced in both George V Land and Oates Land during the 2001-2005 epoch, with minimum annual sea-ice concentrations dropping ~10 and ~6 % below average, respectively.

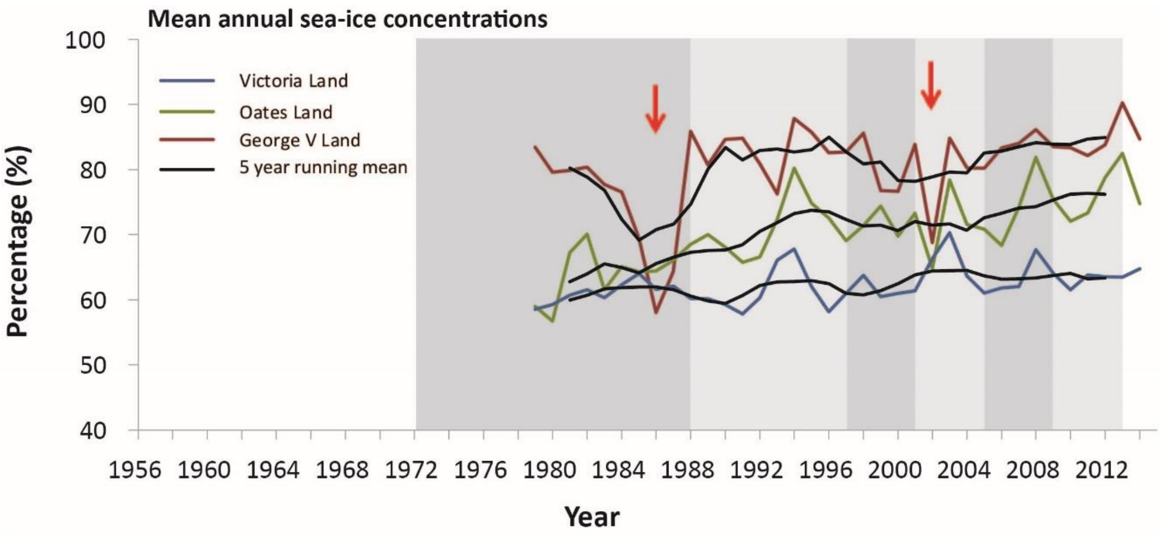


Figure 5.6: Mean annual sea-ice concentrations. The black line represents the 5 year running mean. Red arrows mark the decreases in sea ice in George V Land. Epochs where glacier changes were measured are shaded in background.

The differences in mean annual sea-ice concentrations between epochs reveal some inter-annual variation (Fig. 5.7). Between the 1972-1988 and 1988-1997 epochs, there was a general increase in mean annual sea ice along the Pacific Ocean coastline of Oates Land and George V Land (Fig. 5.7a).

Between the 1988-1997 and 1997-2001 epochs, there was a decrease in sea ice along the Pacific coastline and sea-ice concentrations generally stayed the same or increased slightly along the Ross Sea coastline (Fig. 5.7b). Between the 1997-2001 and 2001-2005 epochs, sea-ice concentrations along the coastline of Oates Land and George V Land generally stayed the same or decreased slightly, but along the southern section of Victoria Land's coast there was an increase in sea ice (Fig. 5.7c). Sea-ice concentrations increased again along the coastlines of Oates Land and most of George V Land between the 2001-2005 and 2005-2009 epochs (Fig. 5.7d). However, around Mertz Glacier Tongue in George V Land, and in the southern part of Victoria Land, there were localised reductions in sea ice in 2005-2009 compared to the 2001-2005 epoch (Fig. 5.7e). Between the 2005-2009 and 2009-2013 epochs, there was a reduction in sea-ice coverage in Victoria Land, and along the coastline between Oates Land and George V Land (Fig. 5.7f). However, sea-ice concentrations around Mertz Glacier Tongue increased again during the 2009-2013 epoch compared to the 2005-2009 epoch.

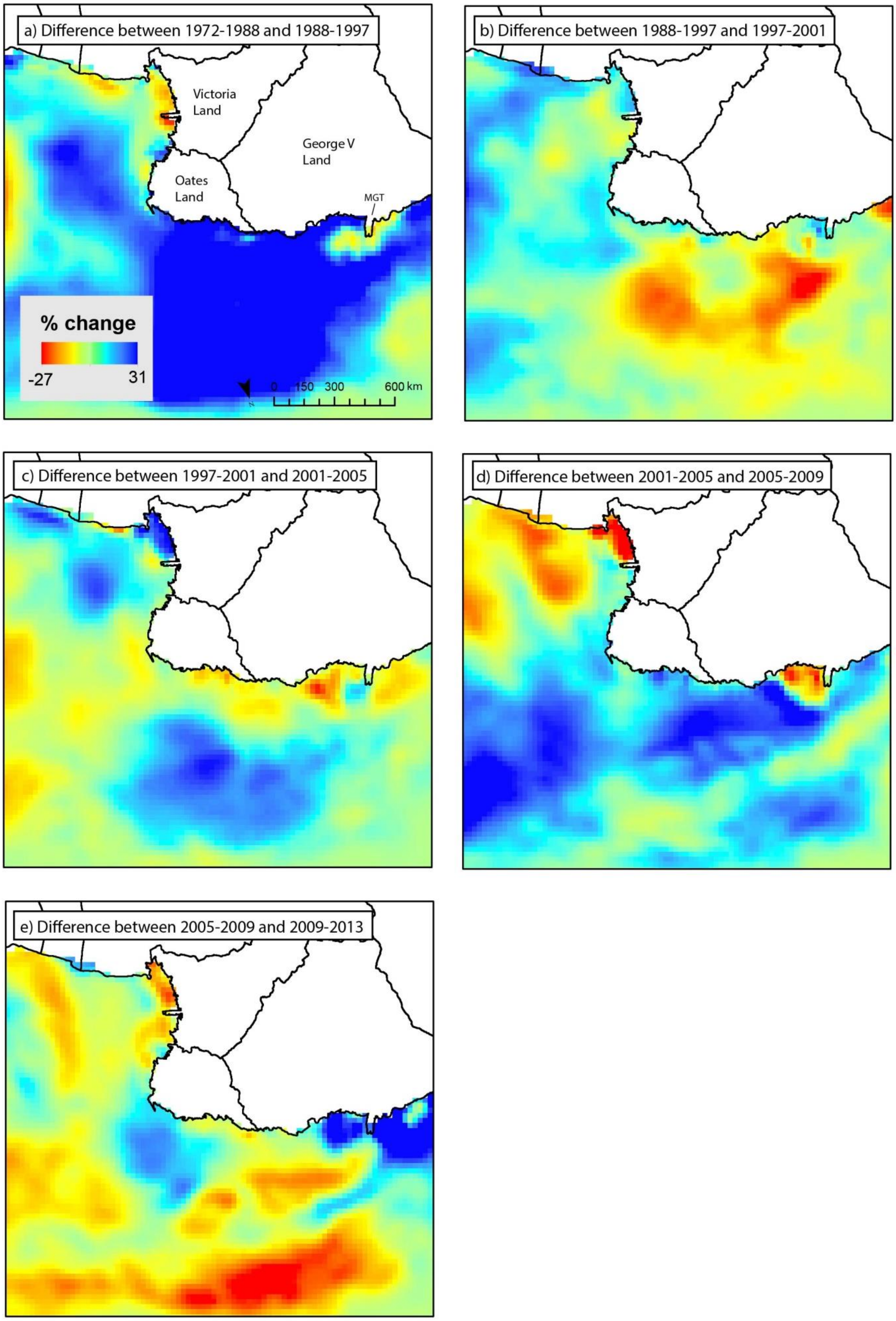


Figure 5.7: Differences in mean sea-ice concentrations (as a percentage) between epochs, e.g. a) difference in mean sea-ice concentrations between the 1972-1988 epoch and the 1988-1997 epoch. MGT = Mertz Glacier Tongue.

5.4. Influence of terminus type on terminus change

5.4.1 Marine- vs land-terminating glaciers

The entire study area contains 91 marine- and 44 land-terminating glaciers (which are all located in Victoria Land) (Table 3.1). Only the marine-terminating glaciers in Victoria Land were compared to the land-terminating glaciers in Victoria Land to tease out the influence of terminus type from other possible controls such as region-specific differences. Over the longest time step (1972-2013), there were no significant differences between marine- and land-terminating glaciers in Victoria Land in terms of their advance or retreat (i.e. both exhibited very little change) (Fig. 5.8). The median terminus 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 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}). This pattern was consistent for all of the epochs in the study time period (Fig. 5.9).

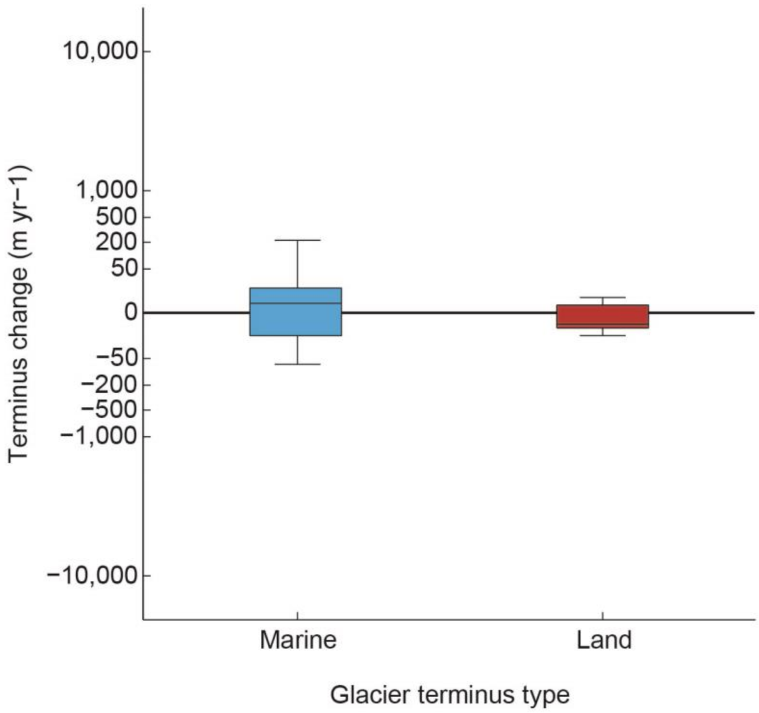


Figure 5.8: Long-term (1972-2013) terminus change of marine- and land-terminating glaciers in Victoria Land. Blue = marine-terminating glaciers, Red = land-terminating glaciers. All boxplots show median, 25th and 75th percentiles and maximum and minimum whiskers on a cube-root scale (y axis). Note that all land-terminating glaciers are only in Victoria Land.

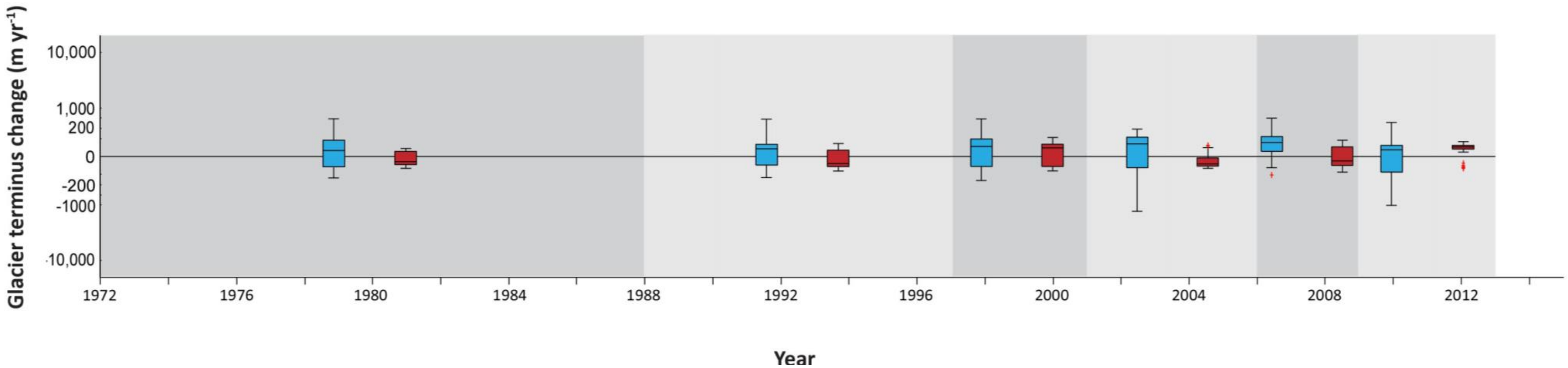


Figure 5.9: Terminus change of marine- and land-terminating glaciers in Victoria Land per epoch. Blue = marine-terminating glaciers, Red = land-terminating glaciers. All boxplots show median, 25th and 75th percentiles and maximum and minimum whiskers on a cube-root scale (y axis). Note that all land-terminating glaciers are only in Victoria Land. Epochs where glacier changes were measured are shaded in background.

It should be noted that comparing the absolute glacier terminus position change between marine- and land-terminating glaciers is problematic due to the likelihood of the glacier types being different sizes and that comparing relative percentage changes would be more suitable. This was not possible in this study due to the lack of data on the total areas of the study glaciers. However, it should be an important consideration for further research

5.4.2 Marine-terminating glacier terminus types

Differences in glacier behaviour were also found within the marine-terminating glaciers throughout the study area (Fig. 5.10a). Although there were no long-term (1972-2013) significant differences between each class of marine-terminating glacier in terms of advance or retreat, those with floating unconstrained (FU) termini experienced the largest variation with a range of 918 m yr^{-1}, followed by glaciers with floating constrained termini (FC) (range: 106 m yr^{-1}). Marine-terminating glaciers that were grounded (G) had the smallest terminus changes (range: 37 m yr^{-1}). Even between epochs and within the three different regions, FU glaciers had a tendency to experience more variation compared to FC or G glaciers (Fig. 5.11 a-x).

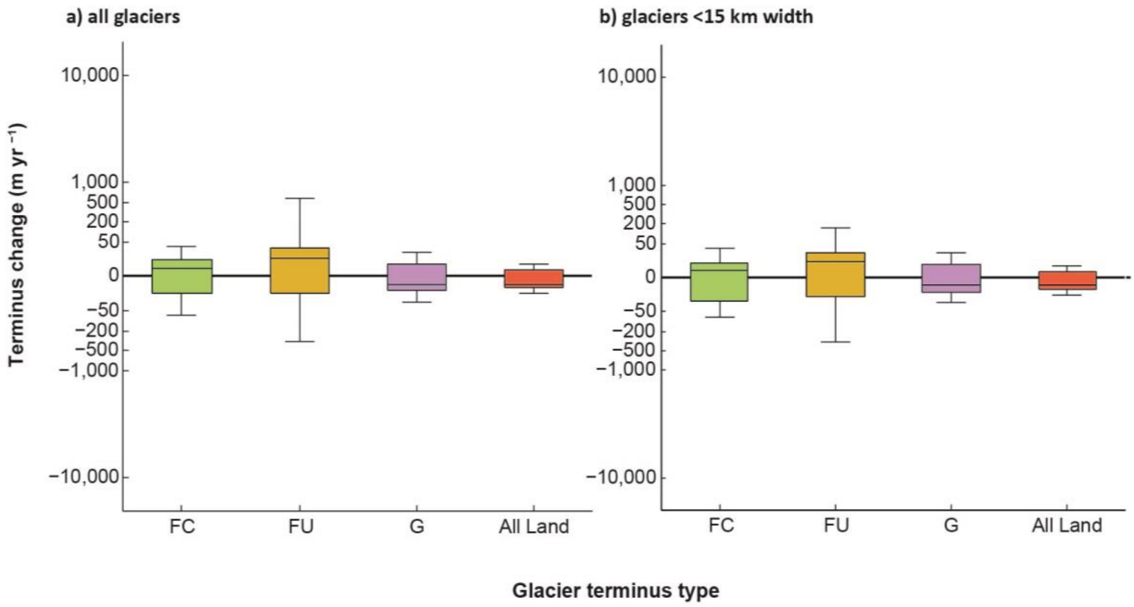


Figure 5.10: a) Long-term (1972-2013) terminus change of different marine-terminating terminus types, b) terminus change of marine-terminating terminus types for glaciers <15 km width. FC = floating constrained, FU = floating unconstrained, G = grounded. All boxplots show median, 25th and 75th percentiles and maximum and minimum whiskers on a cube-root scale (y axis). Note that all land-terminating glaciers are only in Victoria Land.

Figure 5.11: Terminus change of different marine-terminating terminus types 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 maximum and minimum whiskers on a cube-root scale (y axis).

5.5 Influence of other glacier characteristics on terminus change

5.5.1 Glacier size, ice velocity and glacier terminus change

The influence on terminus change of glacier size attributes (width, length and ice thickness) was tested. Scatterplots hint at a relationship between glacier width and long-term glacier terminus change (showing glacier change in advance or retreat on the y-axis) (Fig. 5.12) and between glacier length and long-term terminus change (Fig. 5.13). That is, that glaciers that are wider and longer experienced larger variations. This is expected and, as mentioned in the previous section (5.4.1), for further work, comparing relative percentage changes would be an interesting development. However, the relationships between glacier terminus change and width and length are not particularly strong (R^2 = 0.23 for glacier width and terminus change and R^2 = 0.25 for glacier length and terminus change).

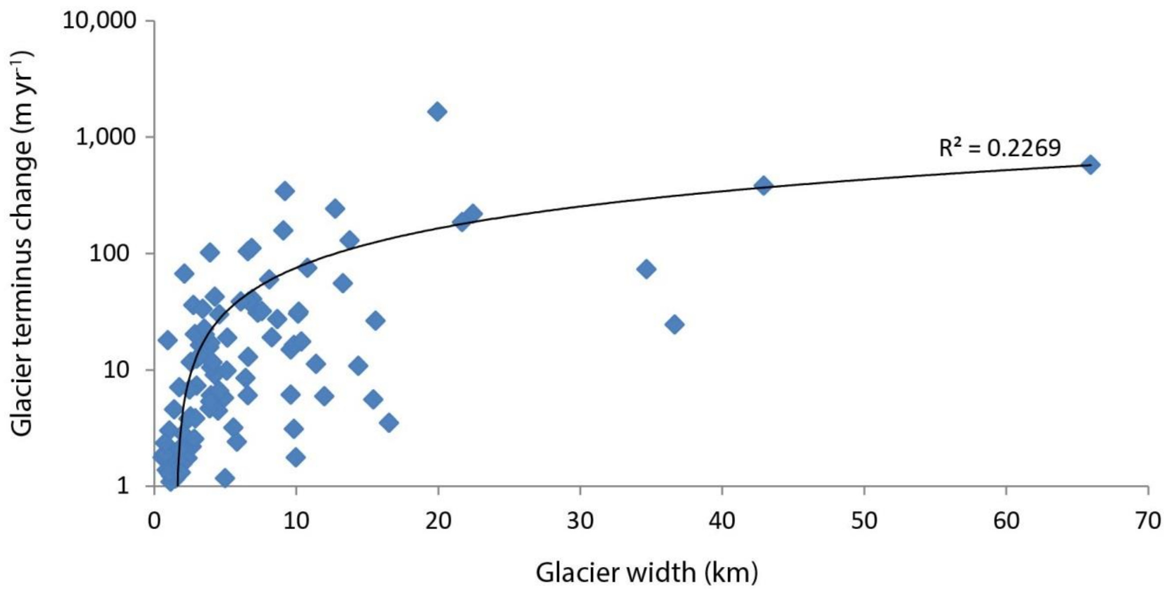


Figure 5.12: Linear regression showing weak relationship between glacier width and long-term (1972 to 2013) glacier terminus change (on a logarithmic scale) and R-squared value of relationship. The y-axis represents glacier change rate in advance or retreat.

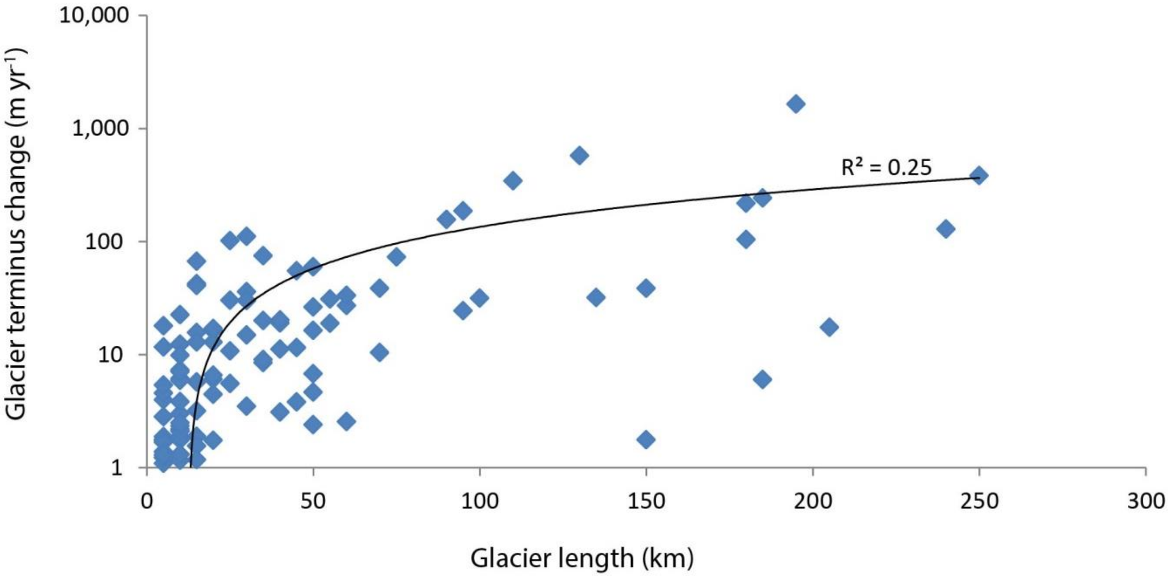


Figure 5.13: Linear regression showing weak relationship between glacier length and long-term (1972 to 2013) glacier terminus change (on a logarithmic scale) and R-squared value of relationship. The y-axis represents glacier change rate in advance or retreat.

Figure 5.14 also suggests that a relationship may exist between ice thickness at the grounding line and long-term glacier terminus change, where glaciers with greater ice thicknesses experienced greater terminus position changes. This is to be expected as ice thickness at the terminus is a key control on a glacier's response time via the equation: $T_v = H/(-b_t)$, where H is ice thickness and b_t is the balance rate at the terminus (Johannesson et al., 1989). However, this relationship was not particularly strong ($R^2 = 0.3$). The relationship between ice velocity and terminus change was slightly stronger ($R^2 = 0.49$) (Fig. 5.15). This is also to be expected as glaciers with higher velocities tend to have a more rapid response time due to having a steeper mass balance gradient (Benn and Evans, 2010).

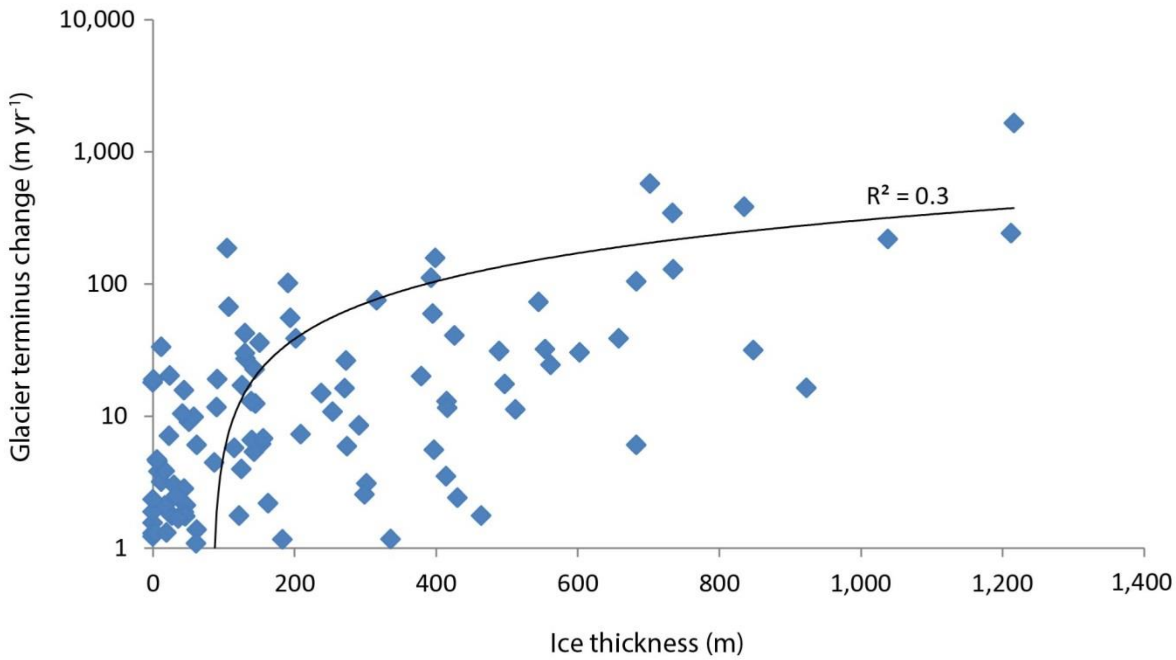


Figure 5.14: Linear regression showing weak relationship between ice thickness and long-term (1972 to 2013) glacier terminus change (on a logarithmic scale) and R-squared value of relationship. The y-axis represents glacier change rate in advance or retreat.

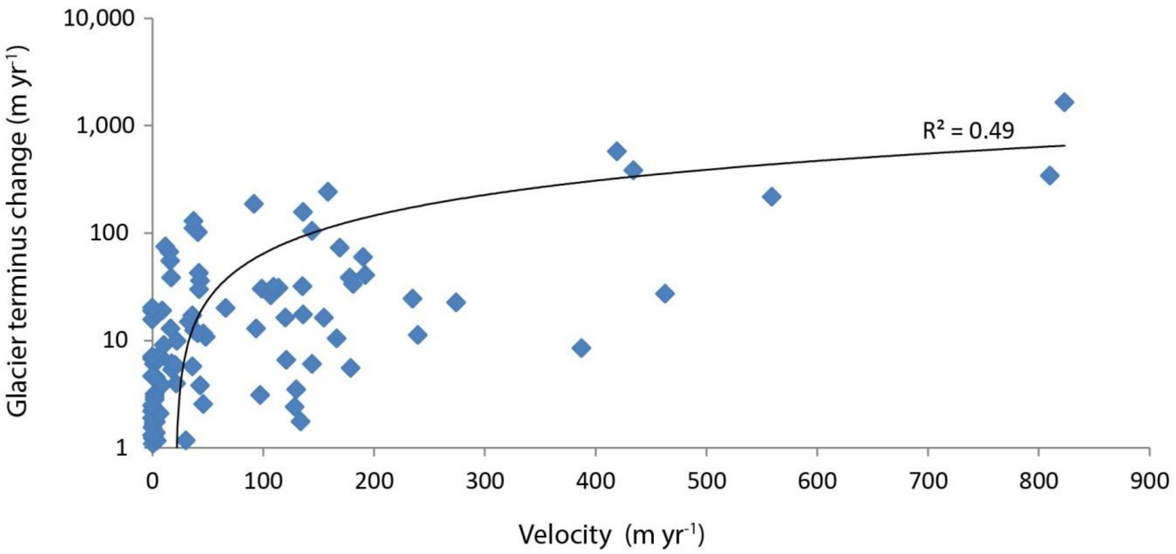


Figure 5.15: Linear regression showing relatively strong relationship between ice velocity and long-term (1972 to 2013) glacier terminus change (on a logarithmic scale) and R-squared value of relationship. The y-axis represents glacier change rate in advance or retreat.

5.5.2 Fjord shape and glacier terminus change

There were no statistically significant differences, in terms of advance and retreat, between the long-term terminus changes of all glaciers in the study area with different fjord shapes or for glaciers not in a fjord (Fig. 5.16). There were also no obvious differences in terminus change between different fjord types between epochs (Fig. 5.17).

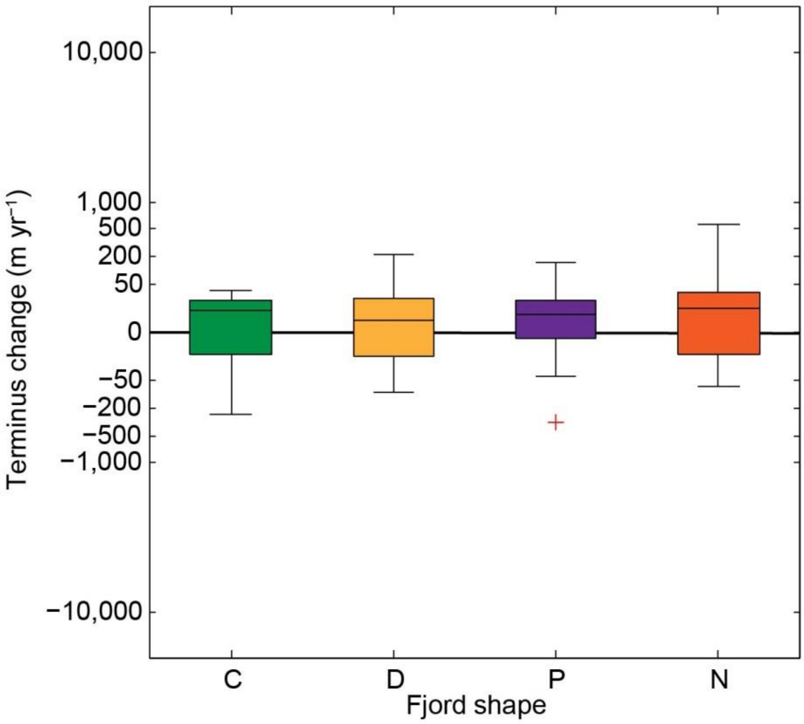


Figure 5.16: Long-term (1972-2013) terminus change of marine-terminating glaciers with different fjord shapes. C = converging (narrowing down-glacier), D = diverging (widening down-glacier), P = parallel and N = no fjord. All boxplots show median, 25th and 75th percentiles and maximum and minimum whiskers on a cube-root scale (y axis).

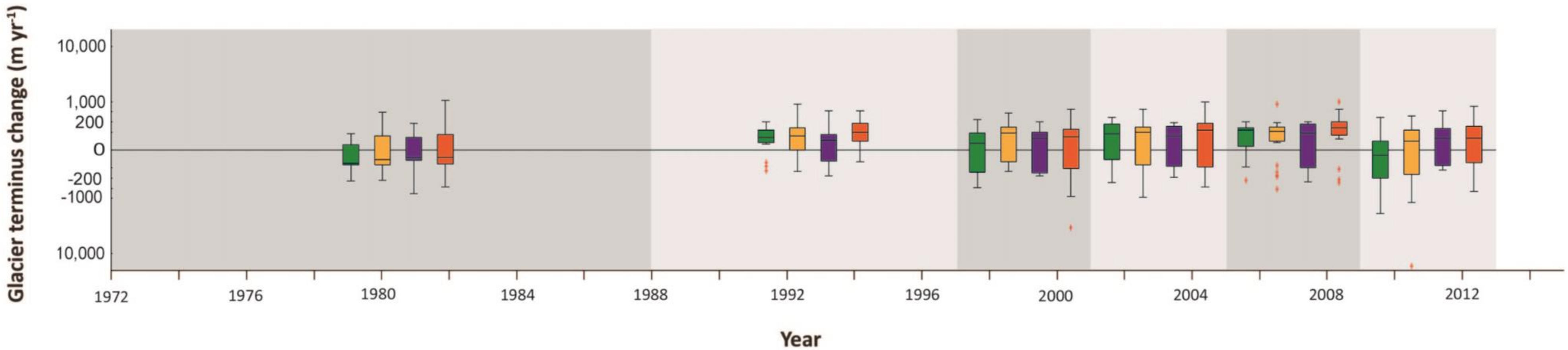


Figure 5.17: Terminus change of marine-terminating glaciers with different fjord shapes per epoch. C = converging (narrowing down-glacier), D = diverging (widening down-glacier), P = parallel and N = no fjord. All boxplots show median, 25th and 75th percentiles and maximum and minimum whiskers on a cube-root scale (y axis).

5.6 Major calving events and cyclical behaviour

It is worth noting that several glaciers (n = 16: Fig 5.18) experienced one or more major calving events (a major calving event is defined as being when the length of iceberg calved is greater than the glacier width close to the terminus). There was at least one of these major calving events in every epoch, but nine of these events (56%) occurred between 2009 and 2013, the majority of them (n = 6) taking place in Oates Land. Major calving events occurred in glaciers of varying size (3-40 km width) and in all three regions. All but one major calving event occurred on glaciers with floating unconstrained termini.

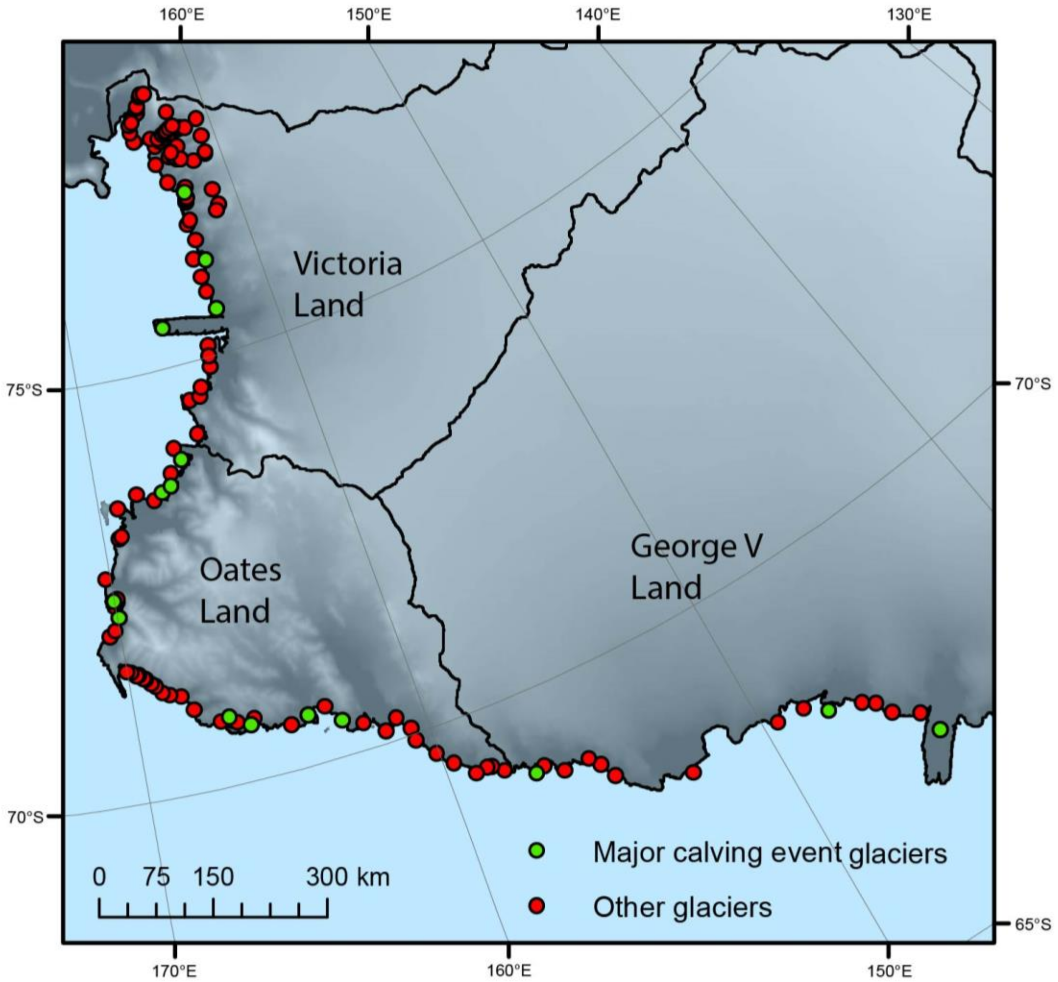


Figure 5.18: The location of the marine-terminating glaciers that experienced major calving events during the study time period.

Two glaciers, Matusevich Glacier (9 km wide, 69°S, 157.2°E) and Lillie Glacier (12 km wide, 70.6°S, 163.9°E) (Lillie Glacier shown in Fig. 5.19a), experienced more than one major calving event during the study period, separated by a period of advance. They both first calved in the 1972-1988 epoch and then Matusevich Glacier calved a second time in the 1997-2001 epoch, and Lillie Glacier calved in the 2009-2013 epoch. This hints that the glaciers were calving and advancing in a cyclic manner with a calving cycle length of approximately 10-30 years and 20-40 years for Matusevich Glacier and Lillie Glaciers, respectively.

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 the 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 calving events during the ~40 years of the study time period (e.g. Mawson Glacier (76.1°S, 163.1°E), Fig. 5.19b). These were all located only in Oates Land and Victoria Land, but were spread out among the two regions.

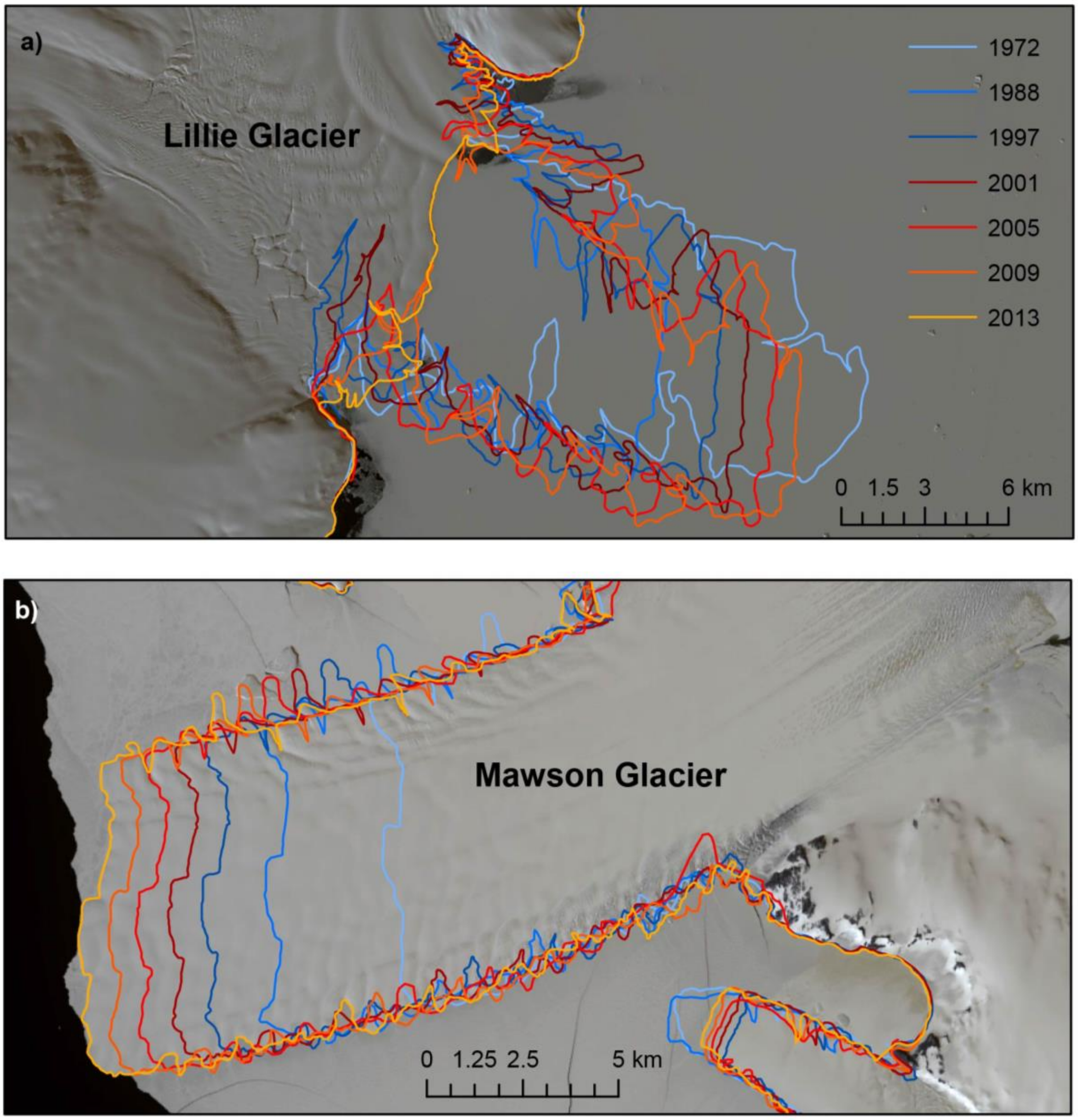


Figure 5.19: Digitised terminus changes for a) Lillie Glacier, Oates Land an example of a glacier that has experienced a major calving event and b) Mawson Glacier, Victoria Land, an example of a glacier which has maintained the same terminus shape throughout the study period. The background images are from February 2014 for Lillie Glacier and December 2013 for Mawson Glacier, taken by the Landsat 8 satellite.

5.7 Summary

Although overall terminus change in the entire study area between 1972 and 2013 was small (median terminus change: 0.2 m yr^{-1}), there was a trend of glacier advance in all glaciers from 1997 until 2009 and there were variations in the magnitude of glacier change between Victoria Land, Oates Land and George V Land. The three regions also had differing air temperature and sea-ice characteristics. Victoria Land had the coolest mean annual temperatures and the lowest mean annual sea-ice concentrations and George V Land had the warmest mean annual air temperatures and the highest mean annual sea-ice concentrations. While glacier terminus type did not seem to influence whether glaciers advanced or retreated, marine-terminating glaciers exhibited more variation than land-terminating glaciers and, within marine-terminating glaciers, floating unconstrained glaciers exhibited the most variation. A small number of marine-terminating glaciers in the study area experienced major calving events and these glaciers were located in all three regions. At least one of these calving events occurred in every epoch.

Chapter 6: DISCUSSION

6.1 Introduction

In this chapter, the results are discussed in the context of the existing literature to assess trends in glacier behaviour and the drivers of terminus position change in this study area. The chapter begins with an exploration of the regional trends in glacier behaviour and the possible drivers behind them (Section 6.2). This is followed by a discussion of the inter-annual behaviour of glaciers in the study area in the context of air temperature and sea-ice data (Section 6.3). The fourth part of this chapter focuses on the links between glacier terminus change and mass loss (Section 6.4). This is then followed by a section focussing on the internal drivers of terminus change such as terminus type, glacier width, ice thickness and fjord shape (Section 6.5). The sixth part focuses on individual major calving events (Section 6.6) and this chapter finishes with some suggestions for further work in this field of study (Section 6.7).

6.2 Spatial trends in glacier behaviour between the three regions (1972-2012)

The results show that between 1972 and 2013, overall glacier terminus change in this study area was almost negligible (median: 0.2 ± 1.6 m yr^{-1}). Out of all of the glaciers in the study area, 36%, advanced, 25% retreated and 39% exhibited no change. This indicates that, in contrast to well-documented widespread outlet glacier retreat over the last several decades in large parts of the GrIS (Moon and Joughin, 2008; Mernild et al., 2012; Carr et al., 2013b) and the WAIS (Favier et al., 2014; Rignot et al., 2014) including the Antarctic Peninsula (Cook et al., 2005), relatively few glaciers in this section of the EAIS have retreated. This is consistent with research conducted by Rignot (2002) who revealed minor positive mass balances throughout the 1990s on several large marine-terminating glaciers in East Antarctica; David (1 ± 4 km^3 yr^{-1}), Ninnis (3 ± 3 km^3 ice yr^{-1}), Mertz (1.5 ± 3 km^3 ice yr^{-1}) and Stancomb-Wills (0.9 ± 3 km^3 ice yr^{-1}) using the mass-budget technique based on interferometric synthetic aperture radar (InSAR) data from RADARSAT-1 and the European Remote-sensing satellites (ERS-1 and 2). Stearns (2011) also revealed small positive balances on Mulock (1.9 ± 0.8 Gt yr^{-1}) and Nimrod (0.9 ± 0.4 Gt yr^{-1}) glaciers in the Ross Sea sector of the EAIS between 1990 and 2007 using the mass budget method. The results of this study are also consistent with a study by Miles et al. (2013) on multi-decadal terminus changes of marine-terminating glaciers which showed minimal overall change (median: 0.7 m yr^{-1}) between 1974 and 2010 in the area under investigation in the present study.

Despite very little overall terminus change for the study area as a whole, the data reveal clear differences in the magnitude of outlet glacier behaviour in the drainage basins of Victoria Land, Oates Land and George V Land over the past forty years. Victoria Land glaciers exhibited relatively little glacier terminus position variation (long-term s.d. 42.7 m yr^{-1} for the period 1972-2013) and showed no obvious trends of advance or retreat (Fig. 5.2). Oates Land glaciers exhibited slightly larger variations (s.d. 47.6 m yr^{-1}) and experienced an advancing trend in the second half of the study period. George V Land glaciers exhibited the largest terminus position variations of the three regions (s.d. 228.7 m yr^{-1}), fluctuating between advancing and retreating trends but with glaciers predominantly advancing during the last three epochs (2001-2013).

Miles et al. (2013) observed that decadal glacier terminus changes on the Western South Pacific coast of East Antarctica (incorporating the westernmost part of George V Land of the present study) fluctuated significantly between a general retreat from 1974 to 1990 to an advance from 1990 to 2000 and back to a retreat from 2000 to 2010, and attributed this to a response to significant decadal-scale changes in mean summer air temperatures. However, for the same time periods, they found that glacier terminus changes in the Ross Sea area (Victoria Land), which had ~9 to 12 °C cooler air temperatures than along the Pacific coast, did not change significantly between decades. They suggested that these regional differences in terminus behaviour were a result of increased surface melting and reduced sea-ice concentrations in the warmer climate of George V Land. In contrast, they argued that the lack of significant variation in the Ross Sea glaciers were a result of insufficiently warm summer air temperatures to initiate surface melting and enhance glacier calving.

While Miles et al. (2013) observed that there were differences in the magnitude of terminus changes between glaciers on the Ross Sea coast and glaciers on the western South Pacific coast, the present study reveals that differences can also be observed when comparing the three drainage basins of Victoria Land, Oates Land and George V Land. The results from this present study initially suggest that there may be some correspondence between the variations in glacier change within each drainage basin and the gradient in mean annual air temperature between the regions. In general, Victoria Land had the coolest mean annual temperatures and its glaciers experienced the smallest variations in terminus position. Oates Land had warmer mean annual temperatures and had larger variations in glacier terminus change, and George V Land had the warmest mean annual temperatures and also the largest fluctuations in glacier terminus change. However, the warmest mean summer temperatures in the three regions consistently occurred in Oates Land (mean: -0.3 °C) (Fig. 5.4) where they exceeded 0 °C in 21 of the last 22 years compared with George V Land where mean summer air temperatures averaged at -2.2 °C and only exceeded 0 °C in 4 of the last 22 years. This was unexpected because George V Land is actually the furthest north and would therefore be expected to have warmer summer temperatures. However, Oates Land is a mountainous region with large areas of land that exists above the ice sheet, and is therefore likely to have a lower albedo compared with George V Land. The warmer summer air temperatures in Oates Land may also be a result of weaker katabatic winds in the region, due to the high topography acting as an orographic barrier, which would reduce their cooling effect compared with in George V Land (van Lipzig et al., 2004).

In this study, several areas of supraglacial meltwater pooling were observed on some glaciers in Oates Land from Landsat imagery (Fig. 6.1), but no evidence of meltwater pooling was found on glaciers in George V Land or Victoria Land. This indicates that summer air temperatures may have a direct impact on supraglacial meltwater production in Oates Land. However, despite the fact that Oates Land had the warmest summer air temperatures, it did not exhibit the largest fluctuations in advancing or retreating trends (these were in George V Land which had cooler summer temperatures). This implies that the difference in magnitude of glacier terminus change in the three regions is not primarily a function of surface melting caused by warm air temperatures.

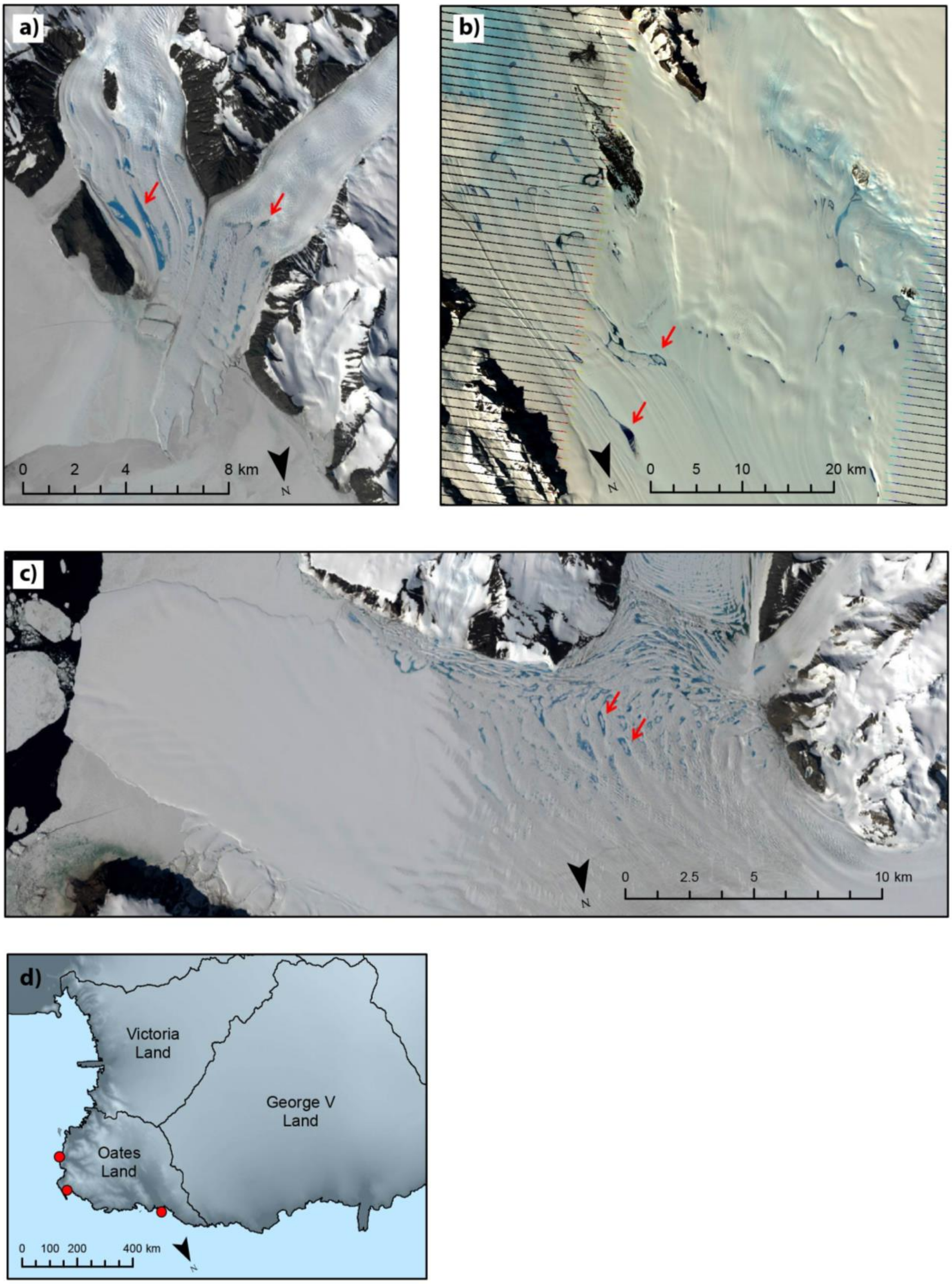


Figure 6.1: Supraglacial meltwater pools (red arrows point to some examples) observed on glaciers in Oates Land on a) Dugdale Glacier, up-glacier of the grounding line according to data provided by Bedmap 2 (Fretwell et al., 2013) (image taken in January 2014), b) Rennick Glacier, up- and down-glacier of the grounding line (image taken in February 2010), and c) Tucker Glacier, down-glacier of the grounding line (image taken in January 2014). d) Map showing location of glaciers.

There were also regional differences in sea-ice concentrations (Fig. 5.6). Mean sea-ice concentrations in the study area were lowest in Victoria Land (62% between 1979 and 2014) and highest in George V Land (81%). However, these differences in sea ice do not appear to correspond with the differences in glacier terminus 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, due to the suppressing effect of sea ice on calving. Glaciers in Victoria Land, with the lowest concentrations of sea ice, would be expected to be less stable due to increased calving (Reeh et al., 2001; Carr et al., 2013a). Thus, no obvious link between regional spatial variations in glacier behaviour and sea ice was detected.

Another possible explanation for the regional variations in the magnitude of changes that would merit further investigation is regional variations in precipitation (see Section 6.7). The Victoria Land drainage basin, as well as being the coldest region, receives the least precipitation out of the three regions (Palerme et al., 2014) and this is consistent with the limited glacier terminus movement compared with Oates Land and George V Land. However, a more likely explanation for the variation in glacier change magnitude between regions is simply the difference in glacier size (expressed in this study as glacier width). Larger glaciers are more likely to have higher velocities than smaller glaciers (Rignot et al., 2011a) and Miles et al. (2013) observed that outlet glacier velocity and the magnitude of glacier change both in terms of advance and retreat were correlated along the East Antarctic coastline (see Supplementary Figure 1 in Miles et al., 2013). There is a clear gradient in glacier size 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. 6.2). Thus, the spatial variations in terminus position behaviour (with increasing variability towards the west) are probably more closely related to glacier size than any spatial gradient in ocean-climatic characteristics.

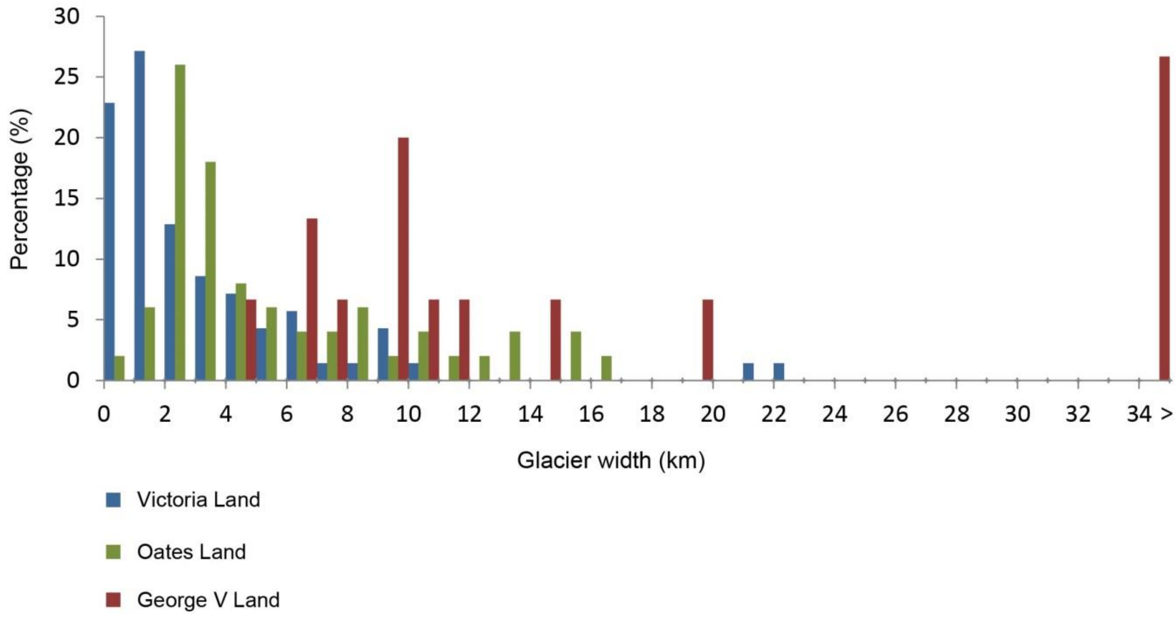


Figure 6.2: Histogram of glacier widths in the three regions of the study area.

6.3 Temporal trends in glacier behaviour and ocean-climatic forcing within each region

6.3.1 Air temperature trends and inter-annual glacier terminus change within each region

Previous work by Miles et al. (2013) suggested a link between warmer regions and glacier sensitivity on decadal time-scales. As previously noted, they observed that the glaciers further north 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 were linked to changes in air temperature and sea ice. In the present study, in Victoria Land, there was no discernible change in glacier terminus positions and this is unsurprising given that air temperatures are well below zero (maximum mean annual and mean summer air temperatures were -14.7 and -3.3 °C, respectively). (Fig. 5.3 and Fig. 5.4).

In Oates Land, despite mean summer air temperatures often exceeding 0 °C and a warming trend of ~1 °C in both mean annual and mean summer air temperatures since records began in 1993 (Fig. 5.3 and Fig. 5.4), glaciers were predominantly advancing from 1988 onwards and it was only during the last epoch (2009-2013) that this glacier advance began to slow down. This suggests that, between 1993 and 2009, air temperature increases do not have much of an influence on inter-annual terminus behaviour, most likely because mean annual summer air temperatures are not warm enough (average summer air temperatures for each epoch between the 1993-1997 epoch and the 2005-2009 epoch range from -0.8 to -0.2 °C). However, the slow-down of glacier advance in Oates Land during the 2009-2013 epoch suggests that glacier terminus positions in the area might have begun responding to warming summer air temperatures that were consistently exceeding 0 °C in both the December and January months (mean summer air temperature for the 2009-2013 epoch was 0.2 °C) and a reversal of the advancing trend during the previous four epochs was beginning to occur. This is supported by the fact that the majority of major calving events that occurred during the 2009-2013 epoch were located in Oates Land, and that supraglacial meltwater pools have been identified on several glaciers in the drainage basin (Fig. 6.1). This implies that although summer air temperatures in Oates Land might not have been warm enough to initiate widespread retreat in the region during the time period of this study, if air temperatures continue to rise to similar levels experienced in the Antarctic Peninsula (Cook et al., 2005), and the ice shelves are subjected to basal melt thinning, this region could potentially be vulnerable to surface and basal melt-induced calving retreat in the future. Along with the mass loss estimates (King et al., 2012), this suggests that Oates Land could be the most vulnerable region in this area to future climate changes.

In George V Land, although warmer than average summer air temperatures (mean summer temperatures between -2 and -1 °C) coincided with a period of glacier retreat during the 1972-1988 epoch, glaciers advanced during the following epoch (1988-1997) despite summer air temperatures continuing to be warmer than average. This was then followed by the retreat of 54% of the glaciers in the region during the epoch 1997-2001, when summer air temperatures were actually cooler than average. Thus, apart from a possible connection between the reversing trend of glacier advance during the 2009-2013 epoch in Oates Land and the warming trend in regional air temperatures, there appears to be no obvious link between inter-annual glacier behaviour and air temperatures in the three regions.

Observed glacier responses to warming air temperatures in the Antarctic ice sheet have predominantly been found in the Antarctic Peninsula, where ice shelf break up has been linked to hydrofracture driven by supraglacial meltwater pools (Scambos et al., 2000; Banwell et al., 2013) in combination with long-term ice shelf thinning caused by basal melting (Shepherd et al., 2003). However, the collapse of ice shelves in this area are associated with a mean annual temperature threshold of -5 °C (Scambos et al., 2000). The mean annual temperatures of Victoria Land, Oates Land and George V Land are much cooler than this and in Victoria Land and George V Land, it is suggested that summer air temperatures are not warm enough to currently have a major impact on inter-annual glacier behaviour. Although the warmer summer air temperatures in Oates Land during the 2009-2013 epoch may be linked to the slow-down of glacier advance (and the six major calving events), there is no obvious evidence that the major calving events are driven by hydrofracture, as will be discussed in section 6.6.

6.3.2 Influence of sea ice on inter-annual glacier terminus change within each region

Some correlation was found between sea-ice concentrations and terminus change on inter-annual time-scales in Oates Land and George V Land. In Oates Land, lower than average sea-ice concentrations (Fig. 5.6) coincided with a period of minor glacier retreat during the 1972-1988 epoch (Fig. 5.2). Following this epoch, there was a significant trend of increasing sea-ice concentrations which coincided with a period of increasing glacier terminus advance. This is consistent with the idea that increased sea ice may suppress calving and promote glacier advance (Carr et al., 2014; Fukuda et al., 2014) via a number of mechanisms including the application of back-stress and the reduction of ocean wave-related bending stress on the glacier terminus (Reeh et al., 2001). However, during the 2009-2013 epoch, mean sea-ice concentrations were the highest experienced in Oates Land throughout the study period and yet, during that epoch, glaciers did not advance as much as in the previous ones.

In George V Land, a period of dramatically lower summer sea-ice concentrations during the 1972-1988 epoch coincided with a general retreat of glaciers in the region. However, a second dramatic decrease in sea ice, during the 2001-2005 epoch, coincided with a general advance in George V Land glaciers. Moreover, no correlation was found between sea-ice change and inter-annual glacier terminus change in Victoria Land. Taken together, while there may be a potential relationship between sea-ice concentrations and glacier calving events in George V Land and Oates Land, sea-ice concentrations do not sufficiently explain all of the inter-annual variation in glacier behaviour in the study area.

The abrupt decrease in sea ice during the 2001-2005 epoch in George V Land also occurred after a period where 54% of glaciers in George V Land retreated (during the 1997-2001 epoch). This suggests that calving events, in turn, may influence the local configuration of sea-ice concentrations, a possibility that has previously been suggested by Massom (2003), who observed that a large iceberg produced during a major calving event on the Ninnis Glacier Tongue acted as a barrier to the advection of sea ice from the east, allowing an ice-free polynya to form on the lee side of the iceberg. However, in the present study, the temporal resolution is not high enough to ascertain whether the increased glacier retreat during the 1997-2001 epoch and the decrease in sea ice in the following (2001-2005) epoch in George V Land are related. The influence of sea ice on glacier change in this area would benefit from a higher resolution study to determine more precisely the timings of changes in sea-ice concentrations and individual calving events.

6.3.3 Other possible influences on glacier terminus position change

It is acknowledged that the direct attribution of glacier changes to either air temperature or sea ice is challenging without the addition of precipitation and oceanic data, a surface mass balance model, and knowledge of glacier response times, because these glaciers are likely to be influenced by a complex interaction of various different climatic and oceanic drivers, not all of which were in the scope of this investigation. Although no data is available for the response times of the glaciers under investigation, the response times of similar marine-terminating glaciers in the APIS have been very rapid (from sub-annual to decadal timescales) (Glasser et al., 2011). This suggests that the marine-terminating glaciers in this study are also likely to have relatively rapid responses to climatic and non-climatic forcings.

The weak relationship between air temperature and glacier terminus change is perhaps not surprising because mean annual and summer air temperatures, apart from in Oates Land, are well below 0 °C. However, the absence of ocean temperature data in this study, means that the potential influence of warming ocean waters, which has been observed to have an influence on outlet glacier behaviour in other parts of the EAIS, such as Totten glacier (Greenbaum et al., 2015), remains undetected.

Another possible reason for the apparent insensitivity of these glaciers to changing air temperature and sea-ice conditions is that the glacier termini are responding to the recent trend of mass gain in the interior of the EAIS that has occurred since 1992 as a result of increasing precipitation (Davis, 2005; Wingham et al., 2006). This mass gain equates to 45 billion metric tonnes yr^{-1} (Davis, 2005) and could explain why glaciers in this region are not experiencing a trend of retreat despite, in some places, experiencing external forcing that is preferential for retreat. However, the lack of precipitation data in this study has also meant that the influence of snowfall on glacier terminus changes could not be tested.

6.4 Links between mass loss and glacier terminus position changes

Mass loss, albeit with large uncertainties, was detected in Oates Land (-5 to -15 Gt yr^{-1}) for the period 2002 to 2010 using gravimetric techniques and GRACE satellite data (Fig. 2.2) (King et al., 2012) and in Victoria Land (-2 ± 4 Gt yr^{-1}) and Oates Land (-2 ± 5 Gt yr^{-1}) for the period 2010 and 2013 using altimetry techniques and Cryosat-2 data (McMillan et al., 2014). Both studies found George V Land to be predominantly in balance (-5 to 5 Gt yr^{-1} from 2002-2010 according to King et al. (2012) and 1 ± 13 Gt yr^{-1} from 2010 to 2013 according to McMillan et al. (2014)). This is consistent with the results from the present study which show that between 2001 and 2013, glaciers in this drainage basin predominantly advanced (Fig. 5.2). However, it is interesting to note that the results of this study show no signal of retreat coincident with the possible mass loss in Victoria Land or Oates Land. Indeed, from 2001 onwards, glaciers in Oates Land were generally advancing and there is no obvious signal of glacier retreat in Victoria Land during the last epoch (2009-2013). There are two possible explanations. First, the mass losses detected in both studies for Oates Land and in the McMillan et al. (2014) study for Victoria Land were relatively small (-2 to -12 Gt yr^{-1}) and subject to sizeable uncertainties. As such, the signal of mass loss could be negligible. Second, if this mass loss existed, it could have occurred via glacier thinning and basal melt rather than terminus calving. Thus, it might not necessarily be apparent through observations of glacier terminus change (Pritchard et al., 2012). This is supported 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) all predominantly lose mass via basal melting. Moreover, although Rennick Glacier was identified to be thinning between 2003 and 2008, due to increased basal melt (Pritchard et al., 2012), its terminus advanced steadily throughout the duration of this study (Fig.6.3). This highlights the complexities of these systems and how they respond to long-term changes in climatic (and oceanic) conditions.

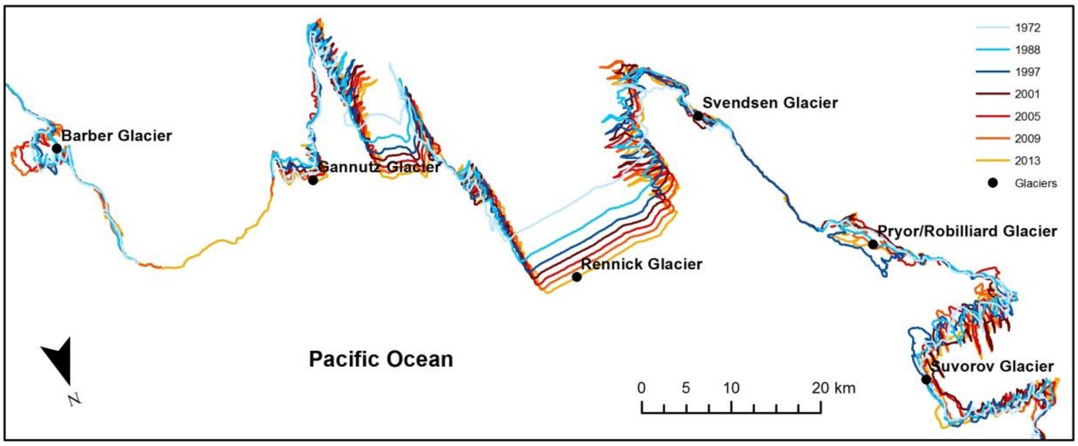


Figure 6.3: A sample of neighbouring glaciers in Oates Land with the digitised positions from each year, revealing asynchronous terminus behaviour of adjacent glaciers.

6.5 Influence of terminus type on terminus change

6.5.1 Marine- vs land-terminating glaciers

The data show that advance and retreat patterns were similar between terminus types across the study area and there were no significant differences between the terminus change rates of marine-terminating (long-term median terminus rate from 1972 to 2013: 0.6 m yr^{-1}) and land-terminating glaciers (median terminus rate: -0.6 m yr^{-1}) (Fig. 5.8). 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). The difference is due to the fact that, in Victoria Land, there was no strong trend of advance or retreat in glacier terminus positions during the time period of this study (median terminus change rate: -0.5 m yr^{-1}). However, the fluctuations of marine-terminating glaciers were consistently of a higher magnitude (long-term range: 292.8 m yr^{-1}) than land-terminating glaciers (range: 8.4 m yr^{-1}) throughout the study period. This is most likely because marine-terminating glaciers are prone to large calving events. Additional mechanisms that may have minor roles in explaining the variation in behaviour between marine- and land-terminating glaciers are that marine-terminating glaciers are subject to the influence of additional ocean-related factors such as changes in ocean circulation, warming ocean temperatures and sea ice. Thus, they are likely to respond more rapidly to external forcings compared to land-terminating glaciers (Carr et al., 2013a). This has been observed along several margins of the Antarctic ice sheet where ice shelf and marine-terminating glacier retreat has been attributed to basal melt driven by the upwelling of warm Circumpolar Deep Water (CDW) (Pritchard et al., 2012), particularly the retreat of large marine-terminating glaciers in the Amundsen Sea sector (e.g. Pine Island, Thwaites and Smith glaciers) (Favier et al., 2014; Rignot et al., 2014). Moreover, marine-terminating glaciers are highly sensitive to changes at their termini (Joughin and Alley, 2011) and debuttressing at the glacier terminus can trigger the rapid propagation of glacier flow acceleration up-glacier via internal responses (Nick et al., 2009). Thus, although there are no obvious trends in the behaviour of marine-terminating glaciers, it is clear that because they are subject to large calving events, they will always tend to show a larger magnitude of terminus change than land-terminating glaciers.

6.5.2 Influence of terminus type within marine-terminating glaciers

The difference in magnitude of glacier change was also evident within the different types of marine-terminating glaciers. Glaciers with a floating unconstrained (FU) tongue had a tendency to experience the most variation in glacier terminus position through time (1972 to 2013 range: 916.7 m yr^{-1}) (Fig. 5.10a and 5.11). Glaciers with a floating but constrained (FC) tongue experienced the second highest amount of variation (range: 105.9 m yr^{-1}), and grounded (G) glaciers experienced the least (range: 36.9 m yr^{-1}). This variation is most likely due to the fact that glaciers that are floating and unconstrained by topography are more likely to experience major, although infrequent, calving events due to the exposed nature of their termini (Bassis and Jacobs, 2013). These glaciers also tend to be larger and experience higher velocities, suggesting that they will advance more rapidly after a major calving event than glaciers with a 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 the largest glaciers were excluded (> 15 km width) (Fig. 5.10b), the results still revealed that FU glaciers experienced more variation than FC glaciers.

Similar differences in behaviour between marine-terminating glacier types have been observed in Greenland, where glaciers with a floating tongue were more likely to produce large tabular icebergs (Moon and Joughin, 2008) and more likely to be vulnerable to dynamic thinning and crevassing than other types of marine-terminating glaciers (Carr et al., 2013b). Very little research has been conducted on variations in the behaviour of different terminus types in Antarctica but a study conducted by Rau et al. (2004) in the Antarctic Peninsula, from 1986 to 2002, noted that glaciers with completely or partially floating ice tongues experienced 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, the data from Victoria Land, Oates Land and George V Land demonstrate the importance of terminus type in controlling the magnitude of outlet glacier change and suggest that it should be taken into consideration when predicting the response of land-terminating and different types of marine-terminating glaciers to climatic and oceanic forcing.

Other glacier-specific characteristics that have previously been identified as controls on glacier terminus change were also tested, such as glacier width, glacier length, ice thickness at the grounding line, fjord width, and ice velocity but no strong correlations emerged, simply because there were no obvious and strong trends in glacier behaviour.

6.6 Major calving events and asynchronous terminus change behaviour

The results show that major calving events occurred in glaciers of varying size and throughout the Victoria Land, Oates Land and George V Land regions. All but one of the glaciers that experienced a major calving event had an unconstrained floating terminus and just over half (56%, n = 9) of these events occurred during the 2009-2013 epoch. The glaciers that calved in this final epoch were a variety of sizes and were also situated in all three regions of the study area. Although the majority of them (n = 6) were located in Oates Land, they do not appear to be linked to changes in sea ice because sea-ice concentrations were relatively high in all regions for that period and therefore would be expected to restrict calving (Carr et al., 2014; Fukuda et al., 2014). Moreover, despite the major calving events during this most recent 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, thus suggesting that supraglacial melting was not an important driver of these events. Two glaciers, Matusevich and Lillie Glaciers, experienced more than one calving events during the study period. Their first major calving event occurred during the 1972-1988 epoch. This was then followed by a period of advance for both glaciers before they calved a second time during the 1997-2001 (Matusevich Glacier) and 2009-2013 (Lillie Glacier) epochs. This suggests that both glaciers were behaving in a cyclic manner. Many other glaciers in the study area also showed signs of cyclic calving behaviour, but the temporal resolution of this study is not high enough to observe the exact timings of calving cycles.

There were also several marine-terminating glaciers (n = 10) that maintained their terminus shape and continuously advanced, implying that they experienced no major calving events e.g. Mawson glacier (Fig. 5.19b). These glaciers were all located in Oates Land and Victoria Land, but were spread out among these two regions. However, a number of these glaciers (e.g. Rennick, Mariner, Tucker) were recorded to have experienced a major calving event during the 1960s (Frezzotti, 1997), which implies that they have longer calving periods than were recorded in the scope of this study.

Rather than revealing any trends in the behaviour of glaciers in the study area, the results show that there were no regional patterns in major calving events that occurred in the study area and that glacier calving behaviour often varied between neighbouring glaciers. This is illustrated by a case study of a group of six neighbouring marine-terminating glaciers in Oates Land (from Suvorov Glacier to Barber Glacier) (Fig. 6.3) where there were asynchronous patterns in terminus change behaviour. Barber Glacier (70.4°S, 162.8°E) experienced a slight retreat from 1972 to 1997, 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.

The asynchronous behaviour of neighbouring glaciers and the lack of regional patterns in the locations of these glaciers suggests that marine-terminating glaciers were more strongly controlled by a combination of internal characteristics specific to each glacier such as terminus type, terminus size and calving cycle rather than external forcing. Therefore, understanding the drivers of these calving events may well benefit from a case-specific approach. This has been proposed by Massom et al. (2015) who argued that the major calving event of Mertz glacier tongue in 2010 was the culmination of a collection of drivers including the interaction with a large iceberg that calved from the neighbouring Ninnis Glacier approximately 10 years previously. Similar asynchronous behaviour among neighbouring outlet glaciers has also been observed in parts of Greenland and is thought to be modulated by glacier-specific factors (Carr et al., 2013a).

6.7 Further research

There is opportunity for further research on outlet glacier terminus change in this study area which was not within the scope of this investigation.

1. **Ocean temperature**

   Investigating the influence of ocean temperature on outlet glacier terminus change is complex due to the difficulty of acquiring accurate ocean temperature data (such as sea-surface and sub-surface ocean temperatures). However, alongside air temperatures and sea ice, oceanic forcing has been identified as an important driver of glacier terminus change in both the WAIS and the EAIS (Jenkins et al., 2010; Khazendar et al., 2013).

2. **Regional precipitation**

   This research would also benefit from the addition of precipitation data to investigate whether regional variations in precipitation influence the differences in glacier change magnitude found in the different regions.

3. **Atmospheric circulation**

   Wind patterns are thought to have an important influence on ocean temperatures and circulation and the intensification of circumpolar atmospheric circulation over the last few decades is thought to be responsible for recent warming ocean temperatures, increased surface melting and a reduction in sea ice in various parts of the Antarctic ice sheet (Pritchard et al., 2012).

4. **Bed topography**

   Bed topography has been observed to have an important influence on glacier retreat rates (Jamieson et al., 2012). While the current resolution of the Bedmap 2 bed elevation data was considered to be too low (1 km) (Fretwell et al., 2013) to be appropriate for this study, it would be useful to incorporate it into future studies when higher resolution topographic data becomes available.

5. **Glacier response times**

   This research would benefit from a knowledge of the response times of the glaciers in the region. This would allow a better understanding of the timescales on which glaciers would be expected to respond to external forcings and aid the identification of different drivers of glacier terminus change.

6. **Surface mass balance changes**

   This research would also benefit from an understanding of the surface mass balance changes occurring in the study area. This would allow a direct connection to be observed between glacier mass balance and terminus position changes and, in particular, would be useful to investigate whether a general trend of increasing precipitation in the interior of the EAIS has had an influence on surface mass balance changes in the study area which may be reflected in the general lack of strong trends observed in glacier terminus behaviour in the region.

7. **Percentage glacier area change**

   While it was not possible in this study to calculate percentage area change (due to not having data on total glacier area in the region), this would be a useful development for this study as it would allow a more accurate comparison between outlet glaciers of different sizes.

Chapter 7: CONCLUSIONS

This study has contributed to a small but growing pool of data on outlet glacier terminus change in the EAIS. Research on the behaviour of outlet glaciers (especially marine-terminating glaciers) on the margins of ice sheets is growing in importance as it is increasingly being acknowledged that they are important channels of ice sheet mass loss (Shepherd and Wingham, 2008; Pritchard et al., 2009; Carr et al., 2013a). This is the first study to investigate glacier terminus changes on inter-annual time-scales in Victoria Land, Oates Land and George V Land, East Antarctica. The results from this investigation show that, unlike in the vast majority of mountain glacier regions (Oerlemans, 2005) and extensive marginal areas of the Greenland and West Antarctic ice sheets (including the Antarctic Peninsula), there was no obvious trend of glacier retreat from 1972 to 2013. Median glacier terminus change for all glaciers revealed that they were generally advancing from 1997 onwards. However, at shorter time-scales, differences were identified in the pattern and magnitude of terminus change between the three adjacent drainage basins. Glaciers in Victoria Land exhibited the smallest terminus changes (long-term s.d.: 42.7 m yr^{-1} from 1972 to 2013) and showed no obvious trends of advance or retreat. Glaciers in Oates Land experienced larger terminus changes (s.d.: 47.6 m yr^{-1}) and exhibited a trend of advance from 1988 onwards. Glaciers in George V Land experienced the largest terminus changes (s.d.: 228.7 m yr^{-1}) and also exhibited a predominant trend of advance from 1988 onwards, albeit with some large retreats observed during the 1997-2001 epoch (54% of glaciers retreated). These regional differences in the magnitude of glacier change did not appear to correspond with regional differences in air temperature or sea ice and it is suggested that they are more likely a function of a spatial gradient in glacier size from smaller glaciers in Victoria Land to larger ones in George V Land.

On inter-annual time-scales, air temperature changes did not appear to have a strong influence on glacier behaviour in the study area apart from in Oates Land where a slow-down in glacier advance during the last (2009-2013) coincided with the warmest mean summer air temperatures experienced in any of the regions in any of the epochs (mean summer temperature: 0.2 °C). Potential links were found between sea-ice concentrations and glacier change on inter-annual time-scales but not enough to sufficiently explain all of the variation in glacier behaviour in the study area.

The results from this study show that the magnitude of outlet glacier terminus change was strongly influenced by glacier terminus type during all epochs. Marine-terminating glaciers experienced larger changes in terminus position (long-term range: 292.8 m yr^{-1}) compared with land-terminating glaciers (long-term range: 8.4 m yr^{-1}), and within marine-terminating glaciers, those with an unconstrained floating terminus exhibited the most variation (long-term range: 916.7 m yr^{-1}). There was no pattern in the location of glaciers that exhibited major calving events and, in many places, glacier terminus behaviour was asynchronous between neighbouring glaciers. It is concluded that during the study time period, short-term glacier terminus variations were more closely linked to non-climatic drivers such as terminus type and geometry than to inter-annual variations in air temperature or sea ice. It is suggested that glaciers in Victoria Land are likely to be relatively stable in the next few centuries, unless major changes occur in the ocean-atmosphere system, but that those in Oates (and possibly George V Land) are more vulnerable to smaller changes (e.g. air temperature increase of the order of a few degrees and changes in sea-ice configurations), similar to that observed in Wilkes Land (Khazendar et al., 2013; Miles et al., 2013).

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Appendix A: STATISTICAL TEST RESULTS

Table 1: Wilcoxon tests for significant differences between terminus position change rates in all glaciers between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013. Significant values are highlighted in red.

			Rate of terminus position change (m yr^{-1})				
Sample	**Epoch**	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
All glaciers	1972-1988	129	-758.2	-2.5	0.2	1100.5	0.00005
	1988-1997	129	-159.4	4.5	48.4	854.0	
	1988-1997	129	-159.4	4.5	48.4	854.0	0.6
	1997-2001	124	-4199.6	9.9	-25.3	601.9	
	1997-2001	124	-4199.6	9.9	-25.3	601.9	0.05
	2001-2005	70	-939.4	45.8	47.4	1007.7	
	2001-2005	70	-939.4	45.8	47.4	1007.7	0.5
	2005-2009	65	-535.6	68.1	81.1	1022.0	
	2005-2009	65	-535.6	68.1	81.1	1022.0	0.0005
	2009-2013	124	-14177.1	7.2	-135.3	742.9	

Table 2: Wilcoxon tests for significant differences between terminus position change rates in glaciers in Victoria Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2006, 2001-2006 and 2006-2009, 2006-2009 and 2009-2013. Significant values are highlighted in red.

			Rate of terminus position change (m yr^{-1})				
Sample	**Epoch**	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
Victoria Land	1972-1988	69	-86.0	-1.1	11.0	470.7	0.8
	1988-1997	67	-90.5	-1.8	11.4	451.1	
	1988-1997	67	-90.5	-1.8	11.4	451.1	0.05
	1997-2001	65	-133.0	7.0	16.2	466.6	
	1997-2001	65	-133.0	7.0	16.2	466.6	0.2
	2001-2006	65	-1481.0	-2.9	-17.7	188.3	
	2001-2006	65	-1481.0	-2.9	-17.7	188.3	0.08
	2006-2009	64	-60.3	1.6	28.3	501.7	
	2006-2009	64	-60.3	1.6	28.3	501.7	0.9
	2009-2013	69	-1044.5	5.4	-10.1	343.2	

Table 3: Wilcoxon tests for significant differences between terminus position change rates in glaciers in Oates Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013. Significant values are highlighted in red.

			Rate of terminus position change (m yr^{-1})				
Sample	**Epoch**	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
Oates Land	1972-1988	48	-263.1	-6.7	-10.9	108.1	0.0005
	1988-1997	47	-159.4	22.7	32.0	193.1	
	1988-1997	47	-159.4	22.7	32.0	193.1	0.9
	1997-2001	46	-600.8	24.4	2.8	209.7	
	1997-2001	46	-600.8	24.4	2.8	209.7	0.2
	2001-2005	39	-464.2	68.0	33.6	276.3	
	2001-2005	39	-464.2	68.0	33.6	276.3	0.9
	2005-2009	35	-317.1	60.3	37.0	414.7	
	2005-2009	35	-317.1	60.3	37.0	414.7	0.07
	2009-2013	44	-2305.5	12.8	-100.1	265.5	

Table 4: Wilcoxon tests for significant differences between terminus position change rates in glaciers in George V Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013. Significant values are highlighted in red.

			Rate of terminus position change (m yr^{-1})				
Sample	**Epoch**	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
George V Land	1972-1988	12	-758.2	-49.8	-17.8	1100.5	0.05
	1988-1997	15	-17.6	195.3	264.7	854.0	
	1988-1997	15	-17.6	195.3	264.7	854.0	0.09
	1997-2001	13	-4199.6	-31.5	-331.7	601.9	
	1997-2001	13	-4199.6	-31.5	-331.7	601.9	0.1
	2001-2005	13	-88.6	211.2	264.6	1007.7	
	2001-2005	13	-88.6	211.2	264.6	1007.7	0.8
	2005-2009	13	-257.7	98.5	258.3	1022.0	
	2005-2009	13	-257.7	98.5	258.3	1022.0	0.8
	2009-2013	13	-14177.1	132.7	-899.8	742.9	

Table 5: Wilcoxon test for significant differences between terminus position change rates for marine-terminating glaciers and land-terminating glaciers in Victoria Land for the period 1972 to 2013.

Marine vs Land		**Rate of terminus position change (m yr^{-1})**				
Sample	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
Marine	25	-75	0.6	21.4	217.8	0.2
Land	44	-6	-0.6	-0.7	2.3	

Table 6: Kruskal Wallis test for significant differences between terminus position change rates for glaciers with floating constrained, floating unconstrained and grounded termini for the period 1972 to 2013.

Terminus type		**Rate of terminus position change (m yr^{-1})**				
Sample	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
Floating constrained	14	-75.0	0.7	-6.6	30.9	0.07
Floating unconstrained	58	-342.8	7.9	22.0	574.0	
Grounded	14	-19.0	-0.6	-0.2	18.0	

Table 7: Kruskal Wallis test for significant differences between terminus position change rates for glaciers with converging, diverging and parallel fjord shapes and for glaciers without a fjord, for the period 1972 to 2013.

Fjord shape		**Rate of terminus position change (m yr^{-1})**				
Sample	**n**	**Min**	**Median**	**Mean**	**Max**	**P-value**
Converging	15	-241.9	4.6	-12.8	33.4	0.9
Diverging	28	-101.6	1.0	8.5	217.8	
Parallel	16	-342.8	2.5	-8.4	156.8	
No fjord	24	-72.9	5.6	53.1	574.0	

Table 8: Two sample *t*-tests for significant differences between mean annual air temperatures in Victoria Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2006, 2001-2006 and 2006-2009, 2006-2009 and 2009-2013.

Region	Epoch	Mean annual temperature (°C)	Standard Deviation	P-value
Victoria Land	1972-1988	-16.9	8.4	0.9
	1988-1997	-16.8	8.6	
	1988-1997	-16.8	8.6	0.7
	1997-2001	-16.2	8.7	
	1997-2001	-16.2	8.7	0.6
	2001-2006	-17.1	9.2	
	2001-2006	-17.1	9.2	0.5
	2006-2009	-15.7	8.2	
	2006-2009	-15.7	8.2	0.9
	2009-2013	-15.4	8.1	

Table 9: Two sample *t*-tests for significant differences between mean annual air temperatures in Oates Land between 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013.

Region	Epoch	Mean annual temperature (°C)	Standard Deviation	P-value
Oates Land	1988-1997	-12.4	8.3	0.8
	1997-2001	-12.0	8.2	
	1997-2001	-12.0	8.2	0.9
	2001-2005	-11.9	8.5	
	2001-2005	-11.9	8.5	0.9
	2005-2009	-11.7	8.0	
	2005-2009	-11.7	8.0	0.6
	2009-2013	-10.8	7.9	

Table 10: Two sample *t*-tests for significant differences between mean annual air temperatures in George V Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013.

Region	Epoch	Mean annual temperature (°C)	Standard Deviation	P-value
George V Land	1972-1988	-10.4	6.0	0.6
	1988-1997	-10.7	6.1	
	1988-1997	-10.7	6.1	0.6
	1997-2001	-11.3	5.9	
	1997-2001	-11.3	5.9	0.7
	2001-2005	-10.7	6.0	
	2001-2005	-10.7	6.0	0.9
	2005-2009	-10.8	5.8	
	2005-2009	-10.8	5.8	0.9
	2009-2013	-11.0	6.3	

Table 11: Two sample *t*-tests for significant differences between mean summer air temperatures in Victoria Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2006, 2001-2006 and 2006-2009, 2006-2009 and 2009-2013.

Region	Epoch	Mean summer temperature (°C)	Standard Deviation	P-value
Victoria Land	1972-1988	-5.2	3.5	0.9
	1988-1997	-5.3	3.8	
	1988-1997	-5.3	3.8	0.7
	1997-2001	-4.9	2.7	
	1997-2001	-4.9	2.7	0.6
	2001-2006	-4.3	3.1	
	2001-2006	-4.3	3.1	0.7
	2006-2009	-4.9	4.5	
	2006-2009	-4.9	4.5	0.8
	2009-2013	-4.5	3.0	

Table 12: Two sample *t*-tests for significant differences between mean summer air temperatures in Oates Land between 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013.

Region	Epoch	Mean summer temperature (°C)	Standard Deviation	P-value
Oates Land	1997-2001	-0.2	1.5	1.0
	2001-2005	-0.2	1.8	
	2001-2005	-0.2	1.8	0.9
	2005-2009	-0.3	1.9	
	2005-2009	-0.3	1.9	0.5
	2009-2013	0.2	1.5	

Table 13: Two sample *t*-tests for significant differences between mean summer air temperatures in George V Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013.

Region	Epoch	Mean summer temperature (°C)	Standard Deviation	P-value
George V Land	1972-1988	-1.8	1.7	0.2
	1988-1997	-2.3	1.8	
	1988-1997	-2.3	1.8	0.4
	1997-2001	-2.9	1.6	
	1997-2001	-2.9	1.6	0.2
	2001-2005	-2.0	1.5	
	2001-2005	-2.0	1.5	0.5
	2005-2009	-2.5	1.9	
	2005-2009	-2.5	1.9	0.7
	2009-2013	-2.2	2.1	

Table 13: Two sample *t*-tests for significant differences between mean annual sea-ice concentrations in Victoria Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2006, 2001-2006 and 2006-2009, 2006-2009 and 2009-2013.

Region	**Epoch**	**Mean sea-ice concentrations (%)**	**Standard Deviation**	**P-value**
Victoria Land	1972-1988	60.8	31.3	0.9
	1988-1997	61.4	32.1	
	1988-1997	61.4	32.1	1.0
	1997-2001	61.7	31.3	
	1997-2001	61.7	31.3	0.6
	2001-2006	64.6	29.8	
	2001-2006	64.6	29.8	1.0
	2006-2009	64.6	29.9	
	2006-2009	64.6	29.9	0.8
	2009-2013	63.1	32.2	

Table 14: Two sample *t*-tests for significant differences between mean annual sea-ice concentrations in Oates Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013.

Region	**Epoch**	**Mean sea-ice concentrations (%)**	**Standard Deviation**	**P-value**
Oates Land	1972-1988	64.3	32.2	0.1
	1988-1997	71.0	28.4	
	1988-1997	71.0	28.4	0.8
	1997-2001	72.2	27.8	
	1997-2001	72.2	27.8	0.9
	2001-2005	71.4	28.8	
	2001-2005	71.4	28.8	0.5
	2005-2009	75.0	27.1	
	2005-2009	75.0	27.1	0.8
	2009-2013	76.7	24.7	

Table 15: Two sample *t*-tests for significant differences between mean annual sea-ice concentrations in George V Land between 1972-1988 and 1988-1997, 1988-1997 and 1997-2001, 1997-2001 and 2001-2005, 2001-2005 and 2005-2009, 2005-2009 and 2009-2013. Significant values are highlighted in red.

Region	Epoch	Mean sea-ice concentrations (%)	Standard Deviation	P-value
George V Land	1972-1988	75.5	19.7	0.0004
	1988-1997	82.9	9.0	
	1988-1997	82.9	9.0	0.2
	1997-2001	80.7	14.4	
	1997-2001	80.7	14.4	0.5
	2001-2005	78.5	16.6	
	2001-2005	78.5	16.6	0.03
	2005-2009	84.2	5.3	
	2005-2009	84.2	5.3	0.6
	2009-2013	84.9	7.1	

Table 16: Linear regressions to test the long-term (1979-2014) trends of sea-ice concentrations in Victoria Land, Oates Land and George V Land.

Region	Epoch	R^2	P-value
Victoria Land	1979-2014	0.20	0.04
Oates Land	1979-2014	0.54	0.01
George V Land	1979-2014	0.15	0.05