Investigating the Changes in Ice Extent of Tidewater Glaciers along Oates Coast, East Antarctica

Joseph Davies

"I certify that this dissertation is entirely my own work and no part of it has been submitted for a degree or other qualification in this or another institution. I also certify that I have not collected data nor shared data with another candidate at Exeter University or elsewhere without specific authorisation."

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Abstract

The iceberg calving of outlet glaciers is an essential component of mass loss in Antarctica. Regional climate change along with ice-ocean interactions are changing the calving rates and ice dynamics of these glaciers. These mechanisms have the potential to release huge amounts of ice from the world's ice sheets and induce significant global sea level rise, which highlights the importance of ice-front measurements and the monitoring of glacier behaviour. Sequential satellite imagery spanning 25 years allowed the terminus area and ice front positions of five tidewater glaciers to be measured. The studied glaciers are situated along the Oates and Pennell coasts in East Antarctica and drain an estimated area of 73,500km^2. Since 1988/89 the combined terminus area of these glaciers has increased by ~1.1 km^2 yr-^{1}. The majority of these glaciers however have shown cyclic behaviour with no strong trend. No significant relationship was observed between sea/surface air temperature and terminus area which suggests that regional climate change is not the dominant control on terminus area. This paper aims to provide useful data for mass balance estimations of the East Antarctic Ice Sheet, and suggests possible explanations of the observed fluctuations.

1. Introduction and Literature Review

Iceberg calving of tidewater outlet glaciers is a major form of mass loss from the world's ice sheets (James et al., 2014). A recent study focused on the entire Antarctica ice sheet estimates a total calving flux of 1,321 ± 144 gigatonnes of ice per year (Depoorter et al., 2013).

It has been widely observed that tidewater outlet glaciers along the Greenland and West Antarctic ice sheets have been contributing more and more to sea level rise over the past few decades due to the increased thinning and retreat of ice, induced by anthropogenic climate change (Pfeffer et al., 2008; Rignot et al., 2011). These changes have also been observed in certain areas along the coasts of the much larger East Antarctic ice sheet (EAIS) (Rignot, 2006), but its overall mass balance has been estimated to be positive (Zwally & Giovinetto 2011). Studies estimate that the East Antarctic ice sheet gained 14 ± 43 gigatonnes of ice between 1992 and 2011 (Shepherd et al., 2012) this is possibly due to the fact that precipitation in the interior of the ice sheet increases under a warmer climate, leading to higher rates of snow accumulation (McMillian et al., 2014; Rignot, 2006). However increased accumulation alone does not necessarily imply that the ice sheet is in mass balance. Iceberg calving of tidewater glaciers has long been seen as the principal component of mass loss in East Antarctica, however recent observations suggest that bottom melt as a result of warmer deeper waters reaching the grounding line is more important than previously estimated (Depoorter et al., 2013; Pritchard et al., 2012; Greenbaum et al., 2015).

Iceberg calving rates of tidewater glaciers are known to follow cycles over decades or centuries, but the causes of these cycles however, are rather complex, and changes observed in many tidewater glaciers are not always synchronised with changes in climate

(Frezzotti, 1998). The fluctuations observed in tidewater glaciers are caused by a variety of glacial and non-glacial processes across timescales ranging from a few hours up to thousands of years (Frezzotti, 1997). Many of these processes can be influenced by climate, which means that it is important to try and understand both the direct and indirect impacts of climate change on glacier retreat.

1.1 Aims and Objectives

This study aims to measure and analyse the fluctuations in the areal extent of five tidewater glaciers situated along the coasts of Victoria Land and Oates Land, East Antarctica. These include the Rennick, Suvorov, Lillie, Kirkby and McMahon glaciers. Surface air temperature (SAT) data that has been collected since 1987 from the Eneide weather station within the Italian Mario Zucchelli Antarctic outpost, along with sea surface temperature (SST) data provided by the IRI Data Library will be compared with the changes in ice extent through statistical analysis to determine whether regional climate change is an important control on the extent of these glaciers.

The results of this study will provide a robust archive of ice-front fluctuation over the past few decades for the chosen glaciers. These data can then be used in conjunction with other studies in order to determine and estimate glaciological change across larger spatial scales over East Antarctica. It may also contribute to even larger investigations such as those stemmed from the World Glacier Monitoring Service, who compile and disseminate standardised data on glacier fluctuations worldwide.

A comprehensive time-series of ice-front changes will be created in order to analyse the trends and anomalies of glacial change along the Oates Coast. It must be noted that ice front change does not represent mass balance. This means that certain glaciers might be thinning but show little change in terminus position, or they might be thickening but retreating due to higher rates of calving. Ice thickness and accumulation data were unavailable, hence this study is unable to estimate the mass balance of the glaciers in question, but can provide estimates of calving rates which represent a large proportion of an East Antarctic glacier's output and subsequent contribution to sea-level rise (Depoorter et al., 2013).

1.2 Research Questions

There are several principal questions that lay the foundation of this study. These include:

- How has the terminus position of the Rennick, Suvorov, Lillie, Kirkby and McMahon glaciers changed over the past few decades?
- Do the cycles and/or trends in these changes agree with those observed in previous studies and EAIS estimates?
- How strongly are these changes linked with regional changes in surface air temperature and/or sea surface temperature?
- Are the relationships between the surface air temperature, sea surface temperature and areal extent for each glacier statistically significant?

1.3 Project Rationale

The EAIS alone holds the potential to raise global sea level by around 53m (NASA). Thomas Wagner of the NASA cryospheric program stated that "If we lose ice at the coasts [of Antarctica] from the warming ocean, we open the tap to massive amounts of ice in the interior." It is widely observed within published literature however, that the EAIS is relatively stable (Davis et al., 2005). This stability might therefore be visible within the results of this study.

The majority of the attention regarding Antarctic glaciers is focused on the West Antarctic ice sheet (WAIS) and the Antarctic Peninsula (Harig et al., 2015). This is due to the fact that many observations show widespread retreat and negative mass balances, contrary to observations across the EAIS (Davis et al., 2005). The glaciers in question are present in very few published studies, the most relevant study being that of Massimo Frezzotti (1997), which estimated the Ice front fluctuation of numerous glaciers across Victoria Land, including the five in this study. His record for these glaciers only extends up until 1991, therefore this study will extend this record whilst testing for any relationship between the changes in the glacier terminus area and regional sea/air surface temperatures (SST/SAT).

The largest of the studied glaciers is the Rennick Glacier which flows northward out of the Transantarctic Mountains and "potentially provides an excellent example of activity of east Antarctic coastal ice" - Paul Mayewski 1982. This research will contribute to the overall analysis of the behaviour of tidewater glaciers on a regional scale (Northern Victoria Land), but also on a much larger scale (of the entire EAIS).

1.4 Study Area

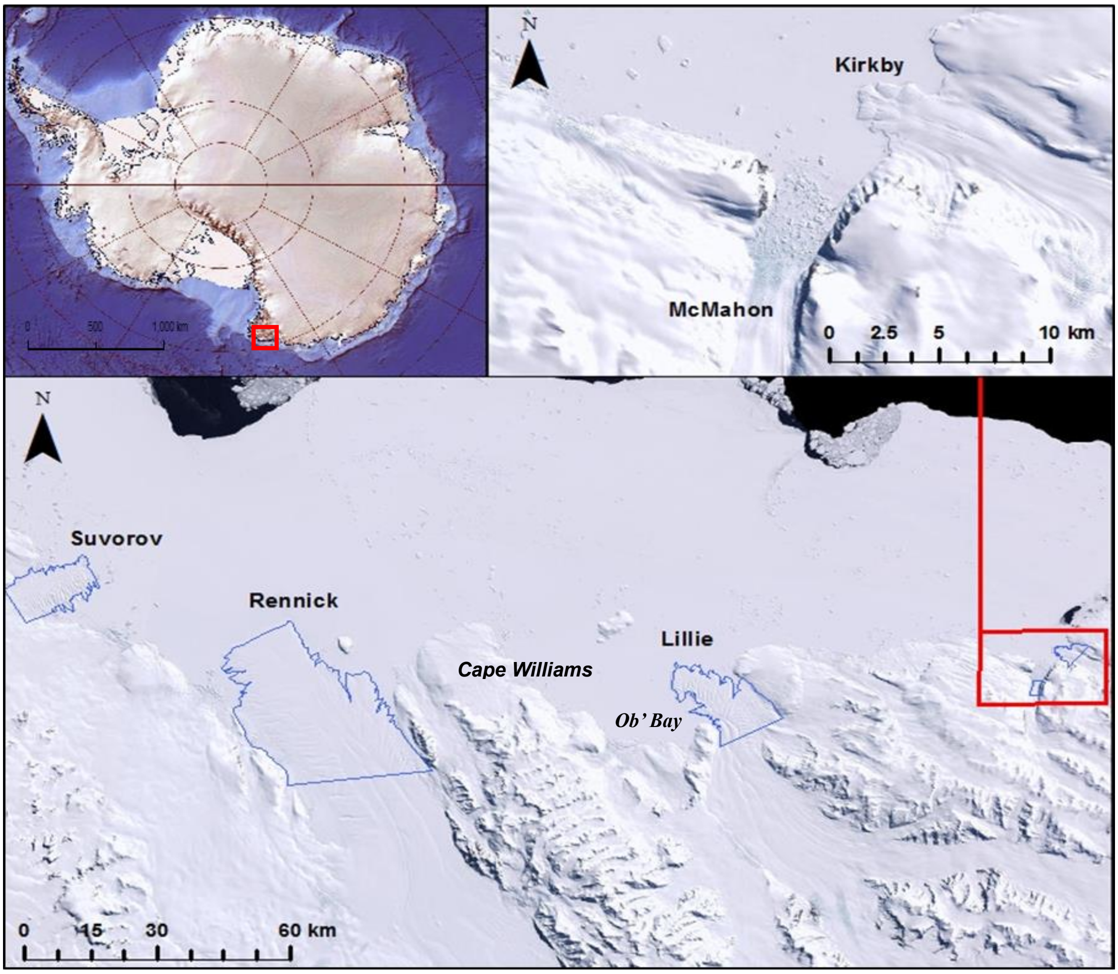


Figure 1.1: Top left: Overview map of Antarctica highlighting the study area. Bottom: image showing the locations of each glacier used in this study. Top right: enhanced zoom over the smaller glaciers. Imagery source: MODIS 2003 (Haran et al., 2005).

The following geographic information was acquired using the Geographic Names Information System run by the USGS. The area of focus stretches along the Oates and Pennell Coasts from 69°S, 160°E to around 70°S, 166°E and includes five ocean-terminating glaciers. The Rennick and Suvorov both terminate in Rennick Bay which is situated along the Oates Coast, which stretches from Cape Hudson to Cape Williams. The Kirkby, McMahon and Lillie glaciers however, are all situated along the Pennell Coast which is located between Cape Williams and Cape Adare.

Rennick Glacier (70"27'S 161'33'E)

At 370km long and 20-30km wide the Rennick glacier is the largest of the five and one of the largest in Antarctica (Herzfeld 2004). It has a basin of around 53,000km² (Frezzotti 1997) and flows between the explorers mountain ranges and the Kavrayskiy Hills into Rennick Bay which is situated on the Oates Coast. According to aircraft altimetry data (Weihaupt 1961), a significant proportion of the Rennick Glacier lies close to sea level, which means that it could be considerably affected by predicted sea level rise induced by the accelerated melting of the Greenland and West Antarctic ice sheets as a result of anthropogenic climate change (Pfeffer et al., 2008; Jacob et al., 2012; King et al., 2012).

Suvorov Glacier (69°55'S, 160°00'E)

The Suvorov glacier is located along the eastern part of the Oates Coast. Its terminus is around 9km wide and flows east from the Wilson Hills into the ocean, south of Northrup Head. Its basin is estimated to be around 1220km² (Frezzotti 1997).

Lillie Glacier (70°45'S, 163°54'E)

The Lillie glacier is situated on the Pennell Coast and is around 190km long and around 19km wide. It flows between the Bowers Mountains to the west and the Concord Mountains to the east into Ob' bay, forming an ice tongue (69°55'S 160°00'E). Its basin is estimated to be around 18 000km².

McMahon Glacier (70°43'S, 165°47'E)

Four of the five outlet glaciers form floating tongues as their ice is pushed past the grounding line, however with the McMahon glacier this is not the case, and its terminus position remains grounded (Frezzotti 1997). It is around 33km long and drains north between Buskirk Bluffs and Gregory Bluffs into Nielsen Fjord. Its basin is estimated to be around 652km².

Kirkby Glacier (70°40'S, 165°58'E)

The Kirkby glacier is around 30km long. It drains the central part of the Anare Mountains and flows between the Buell Peninsula and the Explorers Mountain Range. It meets the South Pacific Ocean at around 5km east of Cape North and forms an ice tongue.

1.5 Previous Studies

As previously stated, there is little published work on the glaciers in question. The most relevant study was conducted by Frezzotti in 1997 and includes records for all of the five glaciers up until 1991. These records include estimates of the iceberg calving flux and areal extent of each glacier, but offers no comparison to regional climate data.

Glacier	Basin (km^2)	1961-1965	Area (km^2)	1972-1980	Area (km^2)	1988-1991	Area (km^2)
Suvorov	1220	N 1961	269	O 1973	249	M 1991	247
		F 1965	245				
Rennick	53,000	N 1961	4044	O 1973	4013	J 1990	4057
		F 1965	3959				
Lillie	18,000	F 1965	997	S 1980	953	J 1990	958
McMahon	652	N 1961	3	N 1972	1.5	D 1989	0.0
Kirkby	597	N1961	11.5	N 1972	8	D 1989	8.5

Table 1.1: Changes in the terminus area of five tidewater glaciers in Northern Victoria Land. Key: N=November D=December J=January F=February M=March (source: Frezzotti 1997).

Table 1.1 shows the fluctuations observed by Frezzotti (1997) for the five glaciers between 1961 and 1991. These data only include three readings for the Lillie, McMahon and Kirkby glaciers, and four for the Suvorov and Rennick. This means that decadal change was estimated by using only one (or two) values for each decade, therefore inter-annual change is not clearly represented. In addition to this, some of the values were drawn from images acquired during different seasons (e.g. October 1973 and March 1991 for the Suvorov glacier). This means that seasonal differences in ice extent might lead to anomalies and therefore provide misleading results and comparisons. These weaknesses will be taken into account when comparing and contrasting the data with the results from this study. The main purpose of Frezzotti's data set will be to reinforce any observations and/or conclusions.

A more recent study of East Antarctica measured the fluctuations in the ice-front position of 175 tidewater glaciers (including the Rennick glacier) along the pacific coast. They concluded that the EAIS might be more susceptible to climate-driven change than previously thought (Miles et al. 2013). The fact that some studies observe climate-driven change within ocean-terminating glaciers and others don't, illustrates the fact that each individual glacier is affected by a different range of processes.

1.6 Climate

Many scientists attribute the observed worldwide glacier retreat to anthropogenic climate change. Around 87% of the glaciers along the Antarctic Peninsula have retreated over the past 50 years along with the collapse of numerous ice shelves, such as the famous Larsen B collapse in 2002 (Cook et al 2005, Rignot et al. 2004). This recession and collapse is not only said to be caused by rifting through hydrofracturing as a result of changing surface air temperatures, but also by the warming of the ocean. The Antarctic Circumpolar Current has warmed by +0.2°C since the 1950s, which has increased melting rates below many ice shelves, floating tongues and at the grounding lines of many vulnerable glaciers

(Gille 2008; Steig et al., 2012; Greenbaum et al., 2015). The EAIS however, has shown a cooling trend over the past 50 years (Turner et al., 2011) and there is still debate over whether the EAIS is in positive or negative mass balance (Shepherd et al. 2012). The observed thinning and retreat along the Antarctic Peninsula is contrast to the thickening of the EAIS observed in some studies (Bell et al., 2011). However certain outlet glaciers that drain the EAIS have been thinning and receding such as the Ninnis, Mertz, Frost and Totten glaciers (Rignot 2006; Greenbaum et al., 2015).

Certain climate models predict that rising atmospheric temperatures around East Antarctica will lead to higher rates of snowfall until the year 2500. This increase in snowfall could lead to higher rates of ice discharge from outlet glaciers and potentially cause an increase in global sea level of ~1.25m by 2500 (Winkelmann et al., 2012). Rates of both sea level rise and rising ocean temperatures observed and predicted by the IPCC (Solomon, 2007) might lead to higher calving rates among ocean-terminating glaciers, and can help explain the recession observed in many of these glaciers across Antarctica. Warmer sea surface temperatures can weaken the floating tongues of these glaciers whilst facilitating both basal and surface crevassing. Melting at the waterline induced by rising SSTs can lead to the undercutting of the terminus and the subsequent fracture of any overhanging ice (Todd & Christoffersen 2014). Rising SATs can increase surface meltwater production, and aggravate crevasse propagation through hydro-fracturing – a process that can lead to the break-up of large ice shelves and floating tongues (Benn et al., 2007). This however, is not as prevalent in East Antarctica, where SATs and insolation are extremely low (Rignot & Jacobs 2002).

2. Methodology

Due to the nature of the study and the inaccessibility of the studied area, primary data collection was not possible. Glacier fluctuation was therefore measured using sequential georeferenced satellite imagery, and compared with the nearest available sea and air surface temperature data. Various authors have used satellite imagery in order to measure ice-front fluctuations and provide reliable records of glacier change (Frezzotti 1998; Miles et al., 2013), but with regards to the area of focus, no published study has compared these fluctuations with sea and air surface temperature data.

2.1 Satellite Imagery

The satellite imagery was acquired from the Landsat archive, made available by the US Geological Survey. These included Landsat 1-5 (1972 – 1989), Landsat 4-5 (1982-1991), Landsat 7 ETM+ SLC-on (1999-2003), Landsat 7 ETM+ SLC-off (2003-present) and Landsat 8 OLI (2013-present). The 2003/04 imagery was also accessed through USGS, but using data acquired by MODIS which has a spatial resolution of 150 m to 200 m. Landsat 1-5 images have a spatial resolution of 60m, whereas Landsat 4-5, 7 and 8 all have a spatial resolution of 30m (USGS 2014).

All images were downloaded from the USGS website and were supplied with a common spatial reference (WGS 84 Antarctic Polar Stereographic). Images were selected based on their acquisition date and their cloud cover. The acquisition date of each image is within Antarctic summer (December to February), except for the Rennick and Suvorov glaciers in 1989 and 1991, which had no useful imagery during this period therefore images taken in March were used. Most images showed generally low cloud cover, but the terminus of the glacier might have been covered. This was the case especially for the McMahon glacier, where clouds tended to form regularly in Nielsen Fjord, blocking the view of its terminus position. This meant that for the years 1988/89, 2000/01 and 2008/09, images taken in March had to be used. Any anomalies observed within these images will be taken into account, and potentially attributed to seasonal variation.

Due to the fact that the Antarctic summer spans across two different years, the use of imagery from different years that were actually within the same summer period was avoided. For example if an image from December was used for 2001, then an image taken in January or February would not be used to represent 2002. In instances where imagery was limited, imagery from the following year was used to represent what was technically the year before its date of acquisition. For example following on from an image acquired in December 2001, if no suitable image was available for the following December in 2002, then an image from January or February 2003 could be used to represent the summer which started in 2002. This ensured that sufficient time had passed between the images, and that observed changes were inter-annual, and did not represent seasonal or monthly variation such as those used by Frezzotti (1997). Once downloaded, the images were then appropriately named and stored according to their spatial and temporal characteristics (see appendices).

2.2 Shapefile Polygons

Each image was then loaded into ArcMap to allow the areal extent of each glacier to be mapped. In order to do this, polygon shapefiles were created to represent each available year for each individual glacier (fig. 2.1). In order to allow visual comparisons of ice-front positions, these shapefiles were also georeferenced onto the WGS 84 Antarctic Polar Stereographic.

The shapefiles were created by carefully drawing around the terminus area of each glacier for each available year. Before drawing the polygons, fixed reference points needed to be plotted in order to measure change from the same locations on each image. In order to choose appropriate reference points, fixed geographical features such as mountain rock were identified. In addition to this, the satellite image archives for each glacier were reviewed within a simple image viewer application to ensure that glacier ice would not retreat past the reference points. The area of these shapefiles is referred to in this study as 'the terminus area'. Table 2.1 displays the coordinates of the reference points that were generated for each glacier.

	East Point	West Point
Rennick	162°5'49.754"E, 70°33'59.014"S	161°14'24.181"E, 70°30'11.425"S
Suvorov	160°4'56.362"E 69°53'17.319"S	160°7'26.636"E 69°58'21.099"S
Lillie	164°13'43.92"E 70°39'36.638"S	163°48'29.417"E 70°41'21.321"S
McMahon	165°47'10.971"E 70°44'59.136"S	165°42'56.589"E 70°44'30.116"S
Kirkby	166°8'14.34"E, 70°39'52.626"S	165°59'9.573"E 70°41'58.262"S

Table 2.1: Coordinates of the reference points used to calculate the terminus area for each glacier.

A few minor problems were encountered whilst drawing the polygons. In a few instances, especially for the Suvorov glacier, it was difficult to distinguish if an iceberg had actually detached from the ice tongue, or if it was still connected. In addition to this, seemingly detached icebergs that appeared floating within close proximity to the glacier tongue might have been attached under water, and therefore not regarded as a calving event. These instances were rare, and the icebergs that were uncertain were insignificant when compared with the inter-annual changes in area of the glacier tongues. This means that any misinterpretation of whether these icebergs were calved or not will not have any significant impact on the results and data analysis within this study. These minor uncertainties were mainly due to shadowing.

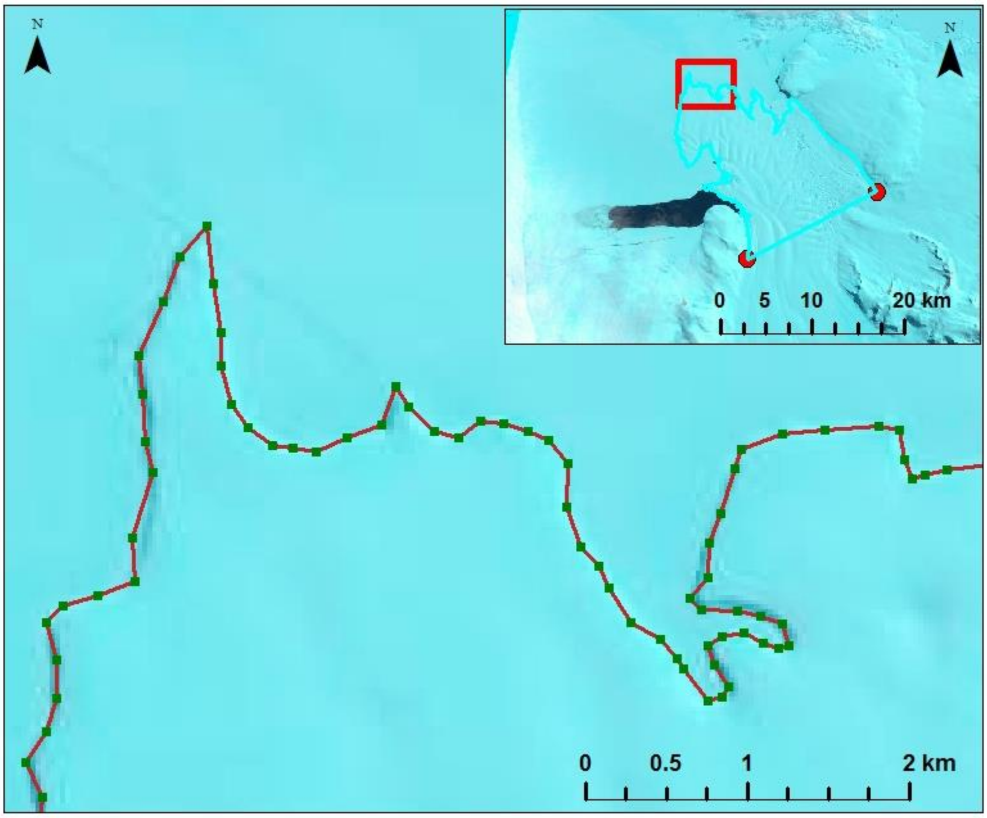


Figure 2.1: Landsat subscene of the Lillie glacier tongue (Path/row 67/110, December 1988) illustrating the techniques and reference points (top right) used to calculate the terminus area of each glacier.

The shadows created by the terminus cliff and from crevassing on the larger glaciers (Rennick, Suvorov, and Lillie) meant that it was difficult to perfectly pin-point the position of the ice. However these inaccuracies of a few metres will have little influence on the overall readings considering that their ice fronts are kilometres wide. Imagery taken from Landsat 7 after May 31, 2003 came with gaps in the data. This was due to the fact that the Scan Line Corrector (SLC) failed, and resulted in long black stripes running across each image. These gaps have little impact on the recordings for the larger glaciers, but with regards to the McMahon and Kirkby glaciers, the striping meant that certain parts of the terminus had to be estimated. The black stripes were particularly hindering for the 2011 image of the Rennick Glacier. This was solved by using the thermal infra-red image instead (see appendices).

2.3 Temperature Data

In order to determine the most suitable source of temperature data, different outposts and data records were investigated. The Mario Zucchelli Italian Antarctic outpost was deemed the most appropriate source for surface air temperature (SAT), as it was the nearest functional outpost to the study area. After correspondence with Paolo Grigioni, the Italian Antarctic Research Programme granted access to the "Eneide" automatic weather station data. The Mario Zucchelli station is situated in Terra Nova Bay along the Victoria Land coastline (74°41'40.6"S 164°06'50.1"E) (see fig. 2.2). The sea surface temperature (SST) data was accessed through the International Research Institute for Climate and Society. The 'IGOSS nmc Reyn_SmithOIv2 monthly' data set provided temperature data from 1981 to 2014. The data were recorded by ships and buoys and then processed using conversion algorithms (Reynolds et al., 2002). The coordinates closest to the study area were then selected (69.5S 162.5E), roughly 80 km out to sea from the Rennick and Suvorov ice tongues (fig. 2.2)

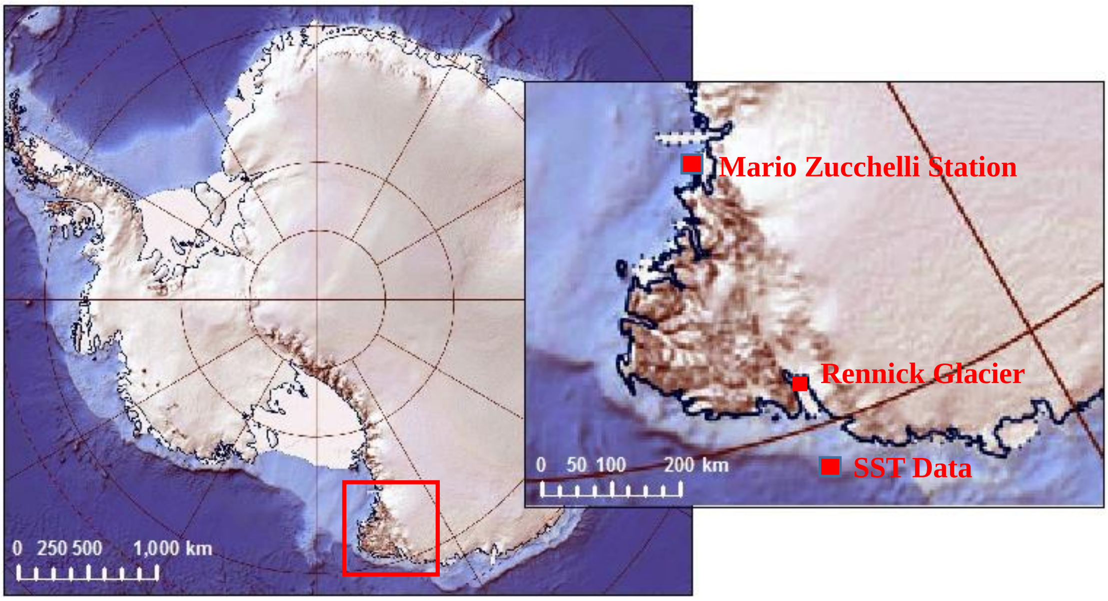


Figure 2.2: Map illustrating the locations of the temperature data acquired for this study, also showing the location of Rennick Glacier. Imagery source: MODIS 2003 (Haran et al., 2005).

For both SAT and SST, the summer months of December, January and February were averaged for each year studied. These data provide an overview of the regional climate and might help explain certain calving events, or the overall behaviour of terminus area of these glaciers. However, only one set of data was available for each variable, and ideally multiple sets of data taken from different locations would have been collected and averaged in order to provide a better representation of regional climate, whilst avoiding the influence of any local anomalies.

2.4 Statistics

In order to investigate whether a statistically significant relationship existed between regional climate and glacier extent, SPSS was used. A Pearson's correlation coefficient test was run between the area of the glacier terminus for each year, and the average summer SST and SAT (see appendices). The output values along with their significance value were noted down and presented in the results.

3. Results

This chapter presents the results from the study. The data is presented in the form of tables, maps and graphs. The findings are then discussed in chapter 4.

3.1. Data Catalogue

Year	*DJF SST (°C)*	*DJF SAT (°C)*	*Rennick (Km^2)*	*Suvorov (Km^2)*	*Lillie (Km^2)*	*McMahon (Km^2)*	*Kirkby (Km^2)*
1988/89	-1.35	-3.83	1018 (D)	196(D)	215 (D)	9 (M)	15.5 (D)
1989/90	-1.43	-3.06	1018 (M)	196 (M)	217 (F)	8.5 (F)	20.1 (F)
1990/91	-1.55	-1.99	1025 (J)	197 (M)	220 (J))	8.6 (D)	21.2 (D)
1991/92	-1.98	-4.08	1030 (M)	194 (J)	225 (F)	8.3 (D)	21.1 (D)
1992/93	-1.21	-2.08					
1993/94	-1.63	-2.98					
1994/95	-1.57	-4.12					
1995/96	-1.94	-3.90					
1996/97	-1.97	-4.23					
1997/98	-1.55	-2.43					
1998/99	-1.77	-2.08	1068 (D)	191 (J)	241 (D)	8.9 (D)	20.2 (D)
1999/00	-1.64	-3.83	1066 (J)	190 (J)	242 (D)	8.7 (M)	20.5 (D)
2000/01	-1.47	-3.85	1073 (J)	178 (D)	248 (F)	8.7 (J)	21.3 (J)
2001/02	-0.95	-2.28	1085 (N)	176 (J)	251 (D)	8.8 (F)	21.6 (F)
2002/03	-1.23	-1.08					
2003/04	-1.12	-2.21	1098 (N)	180 (D)	255 (F)	8.9 (F)	21.9(F)
2004/05	-1.94	-1.32					
2005/06	-1.41	-2.32		185 (D)		9 (D)	
2006/07	-1.54	-3.10	1125 (J)	181 (D)	258 (D)	8.9 (J)	22.5 (J)
2007/08	-1.67	-4.01	1118 (F)	194 (J)	259 (D)	9.6 (J)	23.1 (J)
2008/09	-1.71	-2.92	1126 (D)	192 (D)	262 (F)	9.4 (M)	22.9 (D)
2009/10	-1.47	-2.53	1122 (J)	184 (D)	265 (D)	9.5 (J)	23.7 (J)
2010/11	-1.39	-1.94	1101 (J)	181 (D)	142 (F)	9.5 (J)	24.4 (J)
2011/12	-1.31	-2.50	1115 (J)	186 (J)	143 (D)	9.2 (D)	24.4 (D)
2012/13	-1.34	-2.72	1128 (F)	189 (F)	148 (F)	8.6 (F)	20.4 (F)
2013/14	-1.16	-1.55	1138 (D)	192 (J)	150 (D)	9 (D)	20.2 (D)

Table 3.1. Catalogue of changes in average SST, SAT and ice extent (with month of image acquisition) between 1988 and 2013 for five tidewater glaciers in Victoria Land, East Antarctica. Key: D= December J=January F= February M = March.

Table 3.1 displays all the data used within this study. The highest average sea surface temperature of the studied time period was recorded in the summer of 2001/02, whereas the lowest average summer temperature was recorded in 1991/92. The lowest recorded average surface air temperature was also in 1991/92 but the highest was in 2002/03. Due to the fact that imagery was unavailable between 1992/93 and 1997/98, no values of ice extent are available for this period. Regardless of this, the SST and SAT values however, have been displayed. These temperature data provide an insight into the climatic changes leading up to the next available set of imagery, meaning that any significant changes in ice extent can be compared with, and evaluated using the changes in temperature that preceded the image. This was also the case for 2002/03 and 2004/05.

3.2. Temporal Variation in Ice Extent

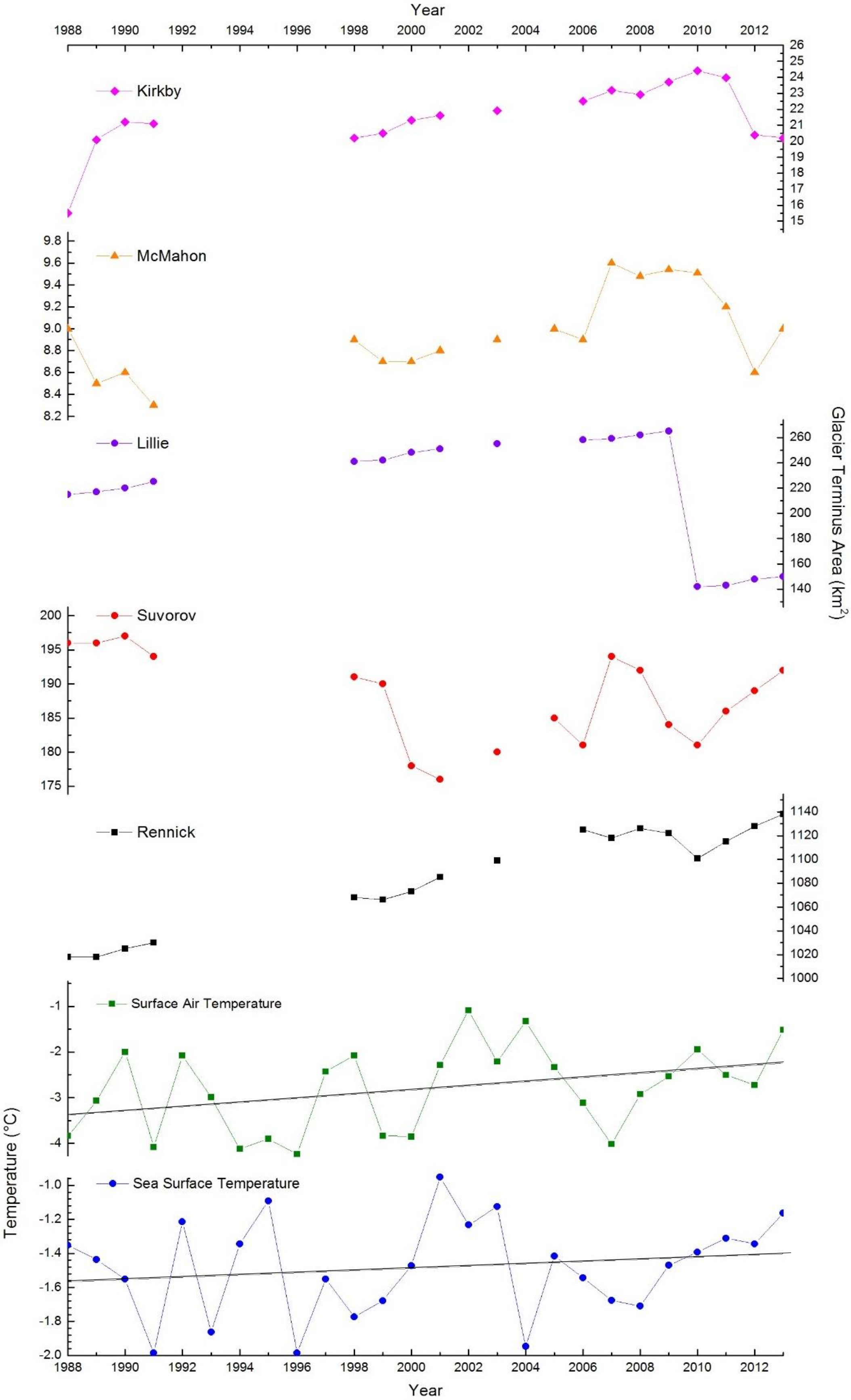


Figure 3.1 Series of graphs illustrating the changes in the terminus area for the five glaciers studied, along with the changes in both sea and air surface temperature between 1988 and 2013.

	RENNICK (km²)	SUVOROV (km²)	LILLIE (km²)	MCMAHON (km²)	KIRKBY (km²)	Total Change (km²)
1988/89	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	
1989/90	0 (0.0)	0 (0.0)	+2 (+0.9)	-0.3 (-4.5)	+4.6 (+29.6)	+6.3
1990/91	+7 (+0.6%)	+1 (+0.5)	+3 (+1.3)	+0.1 (+1.1)	1.1 (+5.4)	+12.2
1991/92	+5 (+0.4)	-3 (-1.5)	+5 (+2.2)	-0.3 (-3.4)	-0.1 (-0.4)	+6.6
1992-97	N/A	N/A	N/A	N/A	N/A	
1998/99	+38 (+3.6)	-3 (-1.5)	+16 (+7.1)	+0.6 (+7.2)	-0.9 (-4.2)	+50.7
1999/00	-2 (-0.1)	-1 (-0.5)	+1 (+0.4)	-0.2 (-2.2)	+0.3 (+1.4)	-1.9
2000/01	+7 (+0.6)	-12 (-6.3)	+6 (+2.4)	0 (+0.0)	+0.8 (+3.9)	+1.8
2001/02	+12 (+1.1)	-2 (-1.1)	+3 (+1.2)	+0.1 (+1.1)	+0.3 (+1.4)	+13.2
2002/03	N/A	N/A	N/A	N/A	N/A	
2003/04	+14 (+1.2)	+4(+2.2)	+4 (+1.5)	+0.1 (+1.1)	+0.3 (+1.3)	+22.4
2004/05	N/A	N/A	N/A	N/A	N/A	
2005/06	N/A	+5 (+2.7)	N/A	+0.1 (+1.1)	N/A	+5.1
2006/07	+26 (+2.8)	-4 (-2.1)	+3 (+1.1)	+0.6 (+6.6)	+0.6 (+2.7)	+26.2
2007/08	-7 (-0.6)	+13 (+7.1)	+1 (+0.3)	-0.2 (-2.1)	+0.7 (+3.0)	+7.5
2008/09	+8 (+0.7)	-2 (-1.0)	+3 (+1.1)	-0.1 (-1.2)	-0.3 (-1.2)	+8.6
2009/10	-4 (-0.3)	-8 (-4.1)	+3 (+1.1)	- 0.06 (-0.6)	-0.8 (+3.4)	-9.9
2010/11	-21 (-1.8)	-3 (-1.6)	-123 (-46.4)	- 0.03 (-0.3)	-0.7 (+2.9)	-147.73
2011/12	+14 (+1.2)	+5 (+2.7)	+1 (+0.7)	-0.31 (-3.2)	-0.4 (-1.8)	+19.29
2012/13	+13 (+1.1)	+3 (+1.6)	+5 (+3.5)	-0.6 (-6.5)	-4.1 (-15.8)	+16.3
2013/14	-10 (-0.8)	+3 (+1.5)	+2 (+1.3)	+0.4 (+4.6)	+0.2 (+0.9)	-4.4
Total	*+4 km² yr⁻¹*	*-0.16 km² yr⁻¹*	*-2.6 km² yr⁻¹*	*-0.2 km² yr⁻¹*	*+0.06 km² yr⁻¹*	*+1.1 km² yr⁻¹*

Table 3.2 Values showing the inter-annual change and (percentage change) in the terminus area of the five glaciers between 1988/89 – 2013/14.

3.3. Rennick

Since 1988, the floating area of the Rennick glacier has generally shown a steady trend of advance (Fig. 3.1). Between 1989/90 and 1998/99, the terminus area of the glacier increased by ~4.9% (an advance of ~ 50 km²). It then retreated by around 2 km² up until 2000/01, and subsequently advanced until 2006/07. This advance between 2000/01 and 2006/07 saw the terminus of the glacier increase by ~52 km² (~4.8%). Between 2008/09 and 2010/11 the glacier retreated by ~2%, losing 25 km² of its ice tongue. Following this, it advanced by ~3.1% (48 km²) until 2012/13, and the most recent record of the glacier (2013/14) shows a reduction from the previous year of ~10 km². The area of the glacier tongue increased by an average of 6 km² yr^{-1} since 1989/90 but decreased between 1998/99 - 1999/00, 2006/07 – 2007/08 and 2008/09 – 2010/11. The largest increase in area was between 1991/92 – 1998/99, whereas the highest decline in area was between 2009/10 – 2010/11.

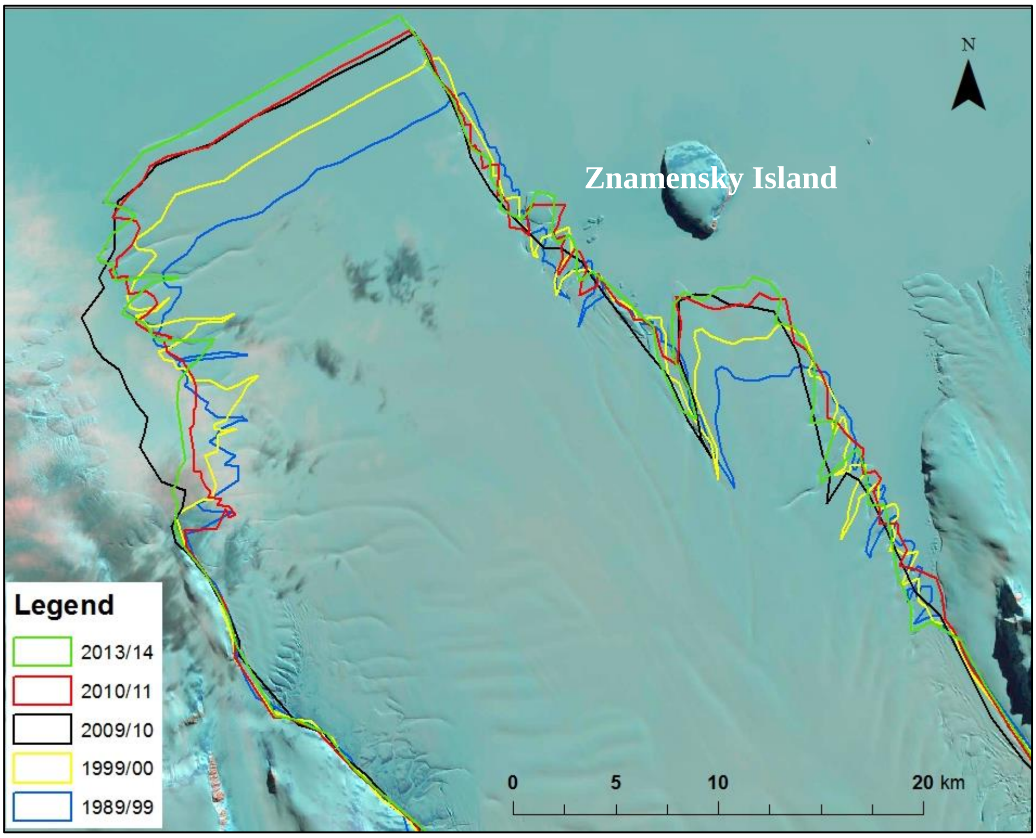


Figure 3.2: Landsat subscence (path/row 69/110, December 2013) showing the ice-front fluctuation of the Rennick Glacier over time.

Over the entire 25 year period, the Rennick Glacier terminus area grew by an average of ~4 km^2 yr^{-1}. It must be noted that the significant reduction in the total area of the terminus between 2009/10 and 2010/11 does not mean that it retreated. Fig. 3.2 illustrates how the terminus area of the Rennick glacier significantly reduced in size between 2009 and 2011, but did not necessarily cause a retreat or advance of the ice front. The principal calving event for this period appears to have happened along the western side of the terminus area (fig. 3.2). The 'secondary tongue' on the eastern side of the terminus area, south of Znamensky Island has shown a consistent trend of advance since 1989/99. Frezzotti (1997) observed a significant calving event between 1961 and 1965 for this part of the glacier, when the 'secondary tongue' advanced past the eastern side of Znamensky Island and retreated to a position similar to that of 1989/99 (fig 3.2).

3.4. Suvorov

The floating tongue of the Suvorov glacier has displayed more sporadic rates of change in areal extent. Between 1989/90 and 1999/00 the terminus fluctuated between small rates of advance and decline (~2 km^2 yr^{-1}). Following this, there was a significant calving event between 1999/00 and 2000/01 where the glacier tongue reduced in size by ~12 km^2 (a reduction in area of ~6.3%). The glacier tongue then continued to retreat until 2001/02, and between 2001/02 and 2005/06 it increased by ~5.1% (~9 km^2). In contrast to the calving event observed between 1999/00 and 2000/01, the terminus area increased significantly between 2006/07 and 2007/08 by around 13 km^2, an increase of ~7.1%. This increase was followed by a steady retreat of ~4.3 km^2 yr^{-1} up until 2011/12. From 2011/12 to 2013/14 the glacier tongue showed a strong trend of advance by around 3.7 km^2 yr^{-1} and a total increase in area of ~6%. This pattern of retreat between 2009/10 and 2010/11 followed by advance between 2010/11 and 2013/14 is very similar to that shown by the

Rennick glacier (see Fig. 3.1).

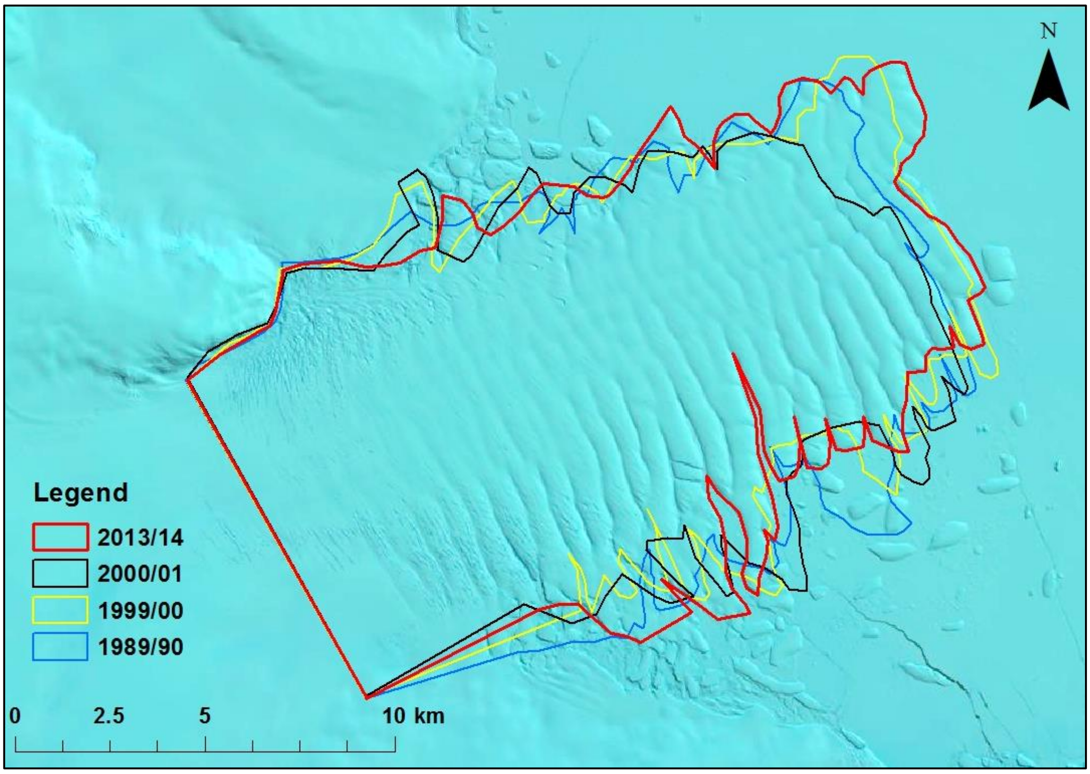


Figure 3.3 Landsat subscene (path/row 71/109) showing the ice-front fluctuation of the Suvorov Glacier over time.

The significant reduction in area of the Suvorov glacier tongue between 1999/00 and 2000/01 is illustrated in fig 3.3. No significant calving events have been observed since 1989/90 compared to the scale of the Lillie tongue collapse in 2010 (Fig. 3.1). The fluctuation in terminus position might indicate that calving events, when compared with the other glaciers in this study, are of a higher frequency but smaller scale. The visible ice melange and icebergs shown in fig. 3.3 suggest that calving takes place along the Northern, Southern and Eastern edges of the ice tongue. Significant longitudinal crevassing of the glacier tongue was also observed in each available image, which might help explain why calving occurs so frequently. Over the 25 years studied, the terminus area of the Suvorov glacier decreased by -0.16 km^2 yr^{-1}.

3.5. Lillie

Between 1989/90 and 2009/10 the Lillie glacier tongue showed a steady rate of advance, on average ~2.3 km² yr^{-1}. Without a single year of retreat recorded within this period, the tongue advanced by ~23%, a total of ~50 km². Between 2009/10 and 2010/11 a significant calving event occurred, the largest observed within this study (fig. 3.4). The glacier tongue lost around 46% of its ice, totalling a mass loss of ~123 km². Following this event, the ice tongue proceeded to advance at a similar rate (~2.6 km² yr^{-1}) to that previously observed between 1989/90 and 2009/10 (~2.3 km² yr^{-1}) (fig. 3.1).

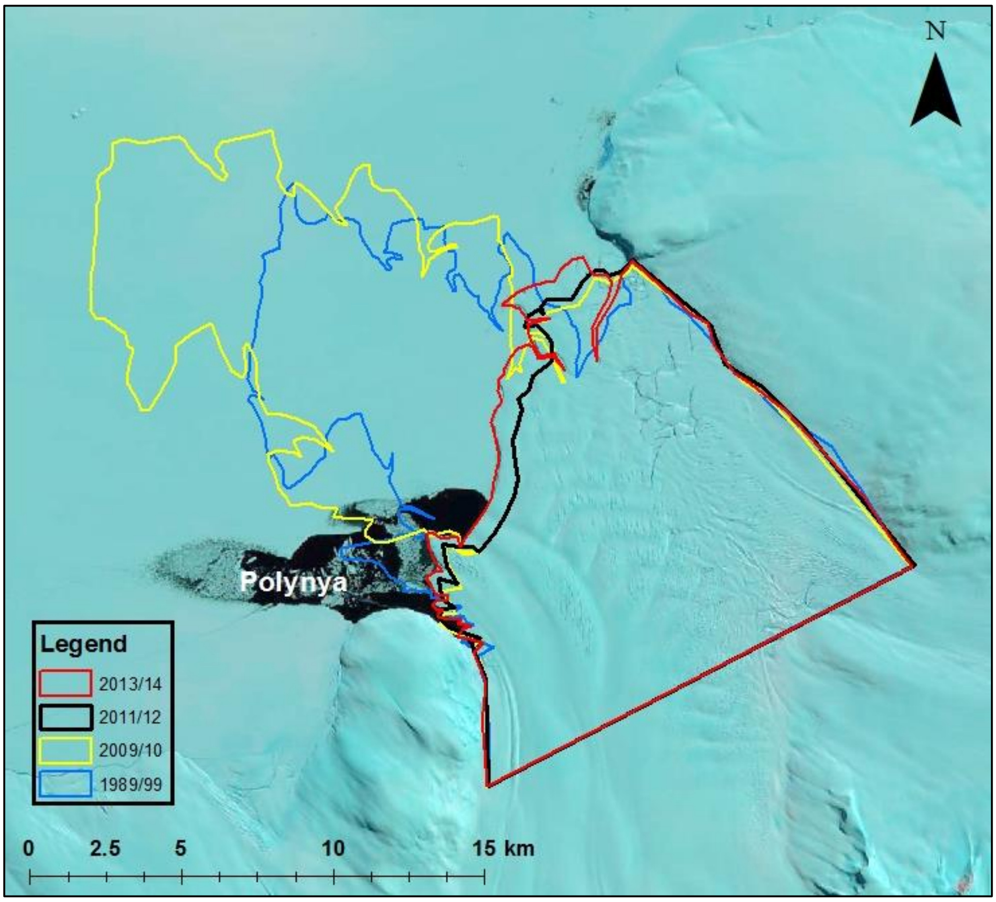


Figure 3.4: Landsat subscene (Path/Row 67/110 February 2014) showing the variation in the extent of the Lillie glacier tongue.

Figure 3.4 illustrates the changes in the extent of the Lillie floating tongue since 1989/99. The scale of the 2009/10 – 2010/11 calving event can be seen roughly as the difference between the extent of the yellow and black shapefiles, equating to around 123 km² of ice. The total average rate of retreat for the Lillie tongue over the observed period was around -2.6 km² yr-[1], however this value does not fully illustrate the pattern of fluctuation, which is characterised by a consistent advance (by ~2.3 km² yr-[1] between 1989 and 2009) followed by a large calving event, and the detachment of the floating tongue.

3.6. McMahon

The fluctuations in the ice front of the McMahon glacier were significantly smaller when compared to the other glaciers in this study, mainly due to the fact that it does not form a floating tongue. Over the observed temporal range, the advance or retreat of the terminus did not exceed 1 km² yr^{-1}. The highest rate of advance was observed between 2005/06 and 2006/07 (Fig. 3.1), where the glacier terminus area increased by ~6.6% (~0.6 km²). The most significant retreat of the ice front was observed between 2011/12 and 2012/13 where the terminus area was reduced by ~6.5% (~0.6 km²).

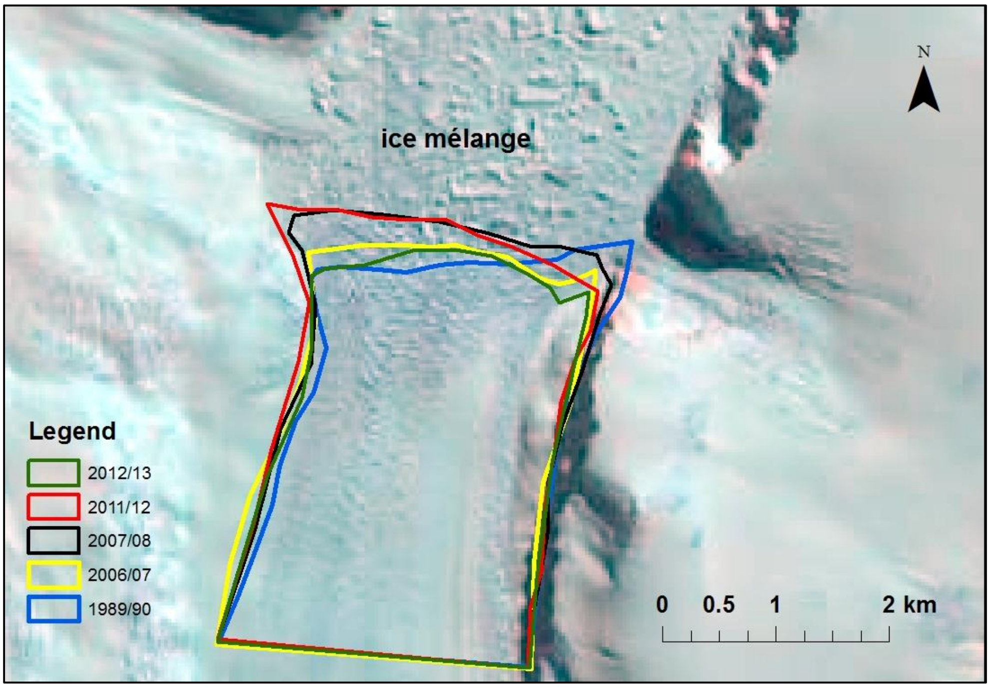


Figure 3.5: Landsat subscene of McMahon Glacier (path/row 66/110 January 2014) showing the ice-front fluctuation of the McMahon Glacier over time.

Figure 3.5 displays the most significant changes observed between 1989/90 and 2012/13 for the McMahon glacier. In contrast to the other glaciers studied, the McMahon glacier only experiences calving at the ice front. The extension of the far west and east sides of the terminus can be seen in 1989/90 and 2011/12 (fig. 3.5). This ice however might belong to the two small tributaries on either side of the fjord. Although the terminus position changes its shape over time, the lack of significant advance or retreat indicates that no major calving events, or significant changes in ice velocity have occurred over the studied period.

3.7. Kirkby

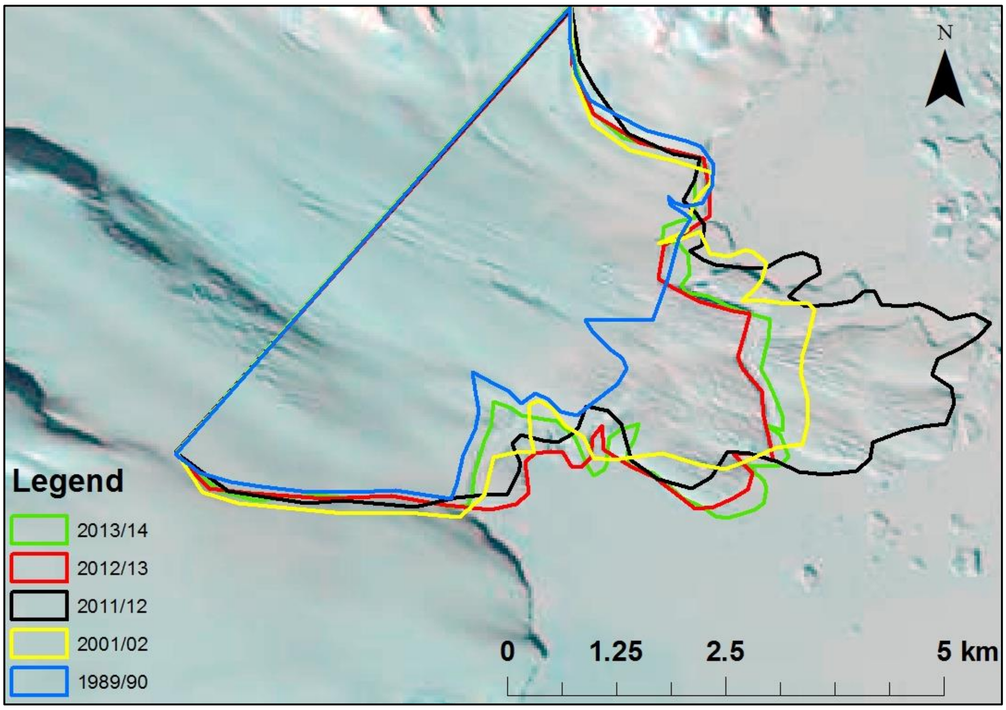


Figure 3.6. Landsat subscene of McMahon Glacier (path/row 65/110 January 2012) showing the ice-front fluctuation of the McMahon Glacier over time.

The record of the Kirkby glacier tongue is characterised by two main events. Firstly, the acceleration and advance of the glacier between 1988/98 and 1989/90. Over this period, the terminus area grew by ~29.6% (~4.6km²) and arrived at a similar position to that shown for 2001/02 in fig. 3.6. Between 2001/02 and 2011/12 the tongue displayed an advance of ~0.28 km² yr^{-1} (table 3.2). Between 2011/12 and 2012/13 ~4 km² of ice detached from the Kirkby tongue. This calving event involved the fracture of a large iceberg from the eastern side of the terminus (fig. 3.6). The detached iceberg can be seen roughly as the size of the difference between the 2011/12 extent and the 2012/13 extent shown in fig. 3.6. In a similar manner to the Lillie tongue, the Kirkby then proceeded to advance at a similar rate to that observed before the calving event (~0.2 km^2 yr^{-1}). The original position of the ice front in 1989/90 indicates that this process of advancement followed by the detachment of a significant proportion of the ice tongue has happened before, and is cyclic behaviour of the Kirkby glacier.

3.8. Overall Fluctuation

The estimated total increase in areal extent of the studied glaciers is ~1.1 km^2 yr-1. However the terminus area of all the glaciers apart from the Rennick and Kirkby showed an overall trend of reduction in size (Fig. 3.1). It must be noted that these overall averages of inter-annual change do not fully represent the patterns of fluctuation observed. The Lillie and Kirkby ice tongues for example displayed cyclic behaviour of consistent advancement followed by subsequent collapse. The Rennick glacier showed a steady rate of advance with no significant calving events (table 3.2) and the Suvorov displayed a much more sporadic pattern of inter-annual change, with both large extensions and reductions in area, but no significant trend. The McMahon displayed the lowest variation and no significant calving events were observed.

3.9. Relationships between Terminus Area and Temperature

The SAT and SST records (table 3.1 & fig. 3.1) show that average summer temperatures for the Eneide station have not risen above 0˚C. Since 1988/89, SAT has fluctuated between -1˚C and -4 ˚C, and has shown an overall trend of warming (see fig. 3.1). SST has fluctuated between -1 ˚C and -2 ˚C since 1988/89 and has also shown a trend of warming.

The following table displays the output values of the correlation tests carried out using SPSS. The significance values shown between the brackets indicate that no statistically significant relationship exists between regional average summer SAT and glacier terminus area. For SST however, a statistically significant (0.041) relationship was found for the Suvorov glacier, which indicates that sea surface temperatures might influence the area of the Suvorov ice tongue. The remaining glaciers however, have no statistically significant relationship with SST (table 3.3).

Glacier Name	Average SST	Average SAT
Rennick	0.259 (0.315)	0.334 (0.191)
Suvorov	-0.499 (0.041)	-0.213 (0.413)
Lillie	-0.300 (0.242)	-0.400 (0.112)
McMahon	0.090 (0.732)	0.179 (0.491)
Kirkby	-0.037 (0.888)	0.259 (0.316)
Total Change in Area	-0.104 (0.691)	-0.172 (0.509)

Table 3.3. Pearson correlation output values and their (Significance). Representing the statistical relationship between the extent of each glacier, SST and SAT.

4. Discussion

The results generated from this study are useful for monitoring the behaviour of East Antarctic glaciers, however any study that aims to measure the total volume of mass loss through calving should use some form of synthetic-aperture radar in order to infer the thickness of the ice.

The archive of Landsat imagery acquired provides a good overview of the changes in the extent of these glaciers. Nevertheless, the seasonal variations in the terminus position of the glaciers are not visible from these 'snapshots', and ideally, an average would be taken across multiple images acquired within the summer months. These data however, are not available for the studied temporal and spatial scale.

4.1 Relationships and Trends

There appears to be no statistically significant relationship between SST, SAT and glacier extent. This might be attributed to the fact that the observed temperatures are not high enough to induce significant melt. Average summer SST was -1.4 ˚C and the average SAT was -2.8 ˚C (table 3.1). This combined with the fact that East Antarctica receives low insolation, indicates that the key calving mechanisms imposed on these glaciers are not driven by SST or SAT. These processes might include hydrofracturing as a result of surface meltwater (fig. 4.1), and the undercutting of the glacier terminus induced by melting at the waterline (Benn et al., 2007). No meltwater ponding was observed for any of the glaciers in question.

Although we can accept that there is no statistically significant relationship between these variables, it does not completely rule out the possibility that changing surface temperatures can influence the glacier terminus area. The relationship isn’t significant where the temperatures are not high enough to induce significant melt at the surface. This is to say that if the temperature range exceeded the melting point of the ice, the relationship would most likely be significant.

There are visible signs of correlation, but for shorter time scales. For the period leading up to the major calving events observed in this study (2008/09 – 2011/12), there was a trend of temperature increase for both SAT and SST (fig. 3.1). This indicates that the observed reduction in area of the Rennick, Suvorov and Lillie termini in 2010/11 might be explained by this temperature trend. After all, the melting point of the ice at the termini can be below 0˚C (Benn & Evans, 2014). This is a result of the salinity of the sea water combined with the heat transfer between the ice and the ocean (Knight, 1999). The seasonal presence of sea ice along the study area provides evidence of this phenomenon (Mayewski 1979). It is also important to note that the significant increase in the size of the Suvorov and McMahon termini between 2006/07 and 2007/08 was preceded by a reduction in both SST and SAT (fig. 3.1) and a statistically significant relationship was found between the Suvorov and SAT (table 3.3). This indicates that as temperatures fall consistently over a period of ~4 years, ice production increases and causes the terminus area to grow. An increase in ice discharge however, might also be caused by rising temperatures in the interior of the ice sheet, which lead to higher rates of precipitation (Rignot 2006).

4.2 Oceanic Forcing

The lack of forcing observed from SST and SAT however, does not rule out oceanic forcing and the influence of temperatures at lower depths. Sea surface temperature is generally seen a poor indicator of oceanic forcing, especially in East Antarctica where sea surface temperatures are rarely high enough to induce substantial melt (Bindschadler 2006). Warmer waters found at lower- intermediate depths however, might have a strong influence on the grounding line melt rates of Antarctic outlet glaciers (Bindschadler 2006).

A recent study observed that circumpolar deep water was reaching the grounding line of the Totten glacier, along the pacific coast of East Antarctica, roughly 1700km from the Rennick glacier, (Greenbaum et al., 2015). The warmer deep waters induce basal melt and facilitate glacier acceleration (Fig. 4.1b).

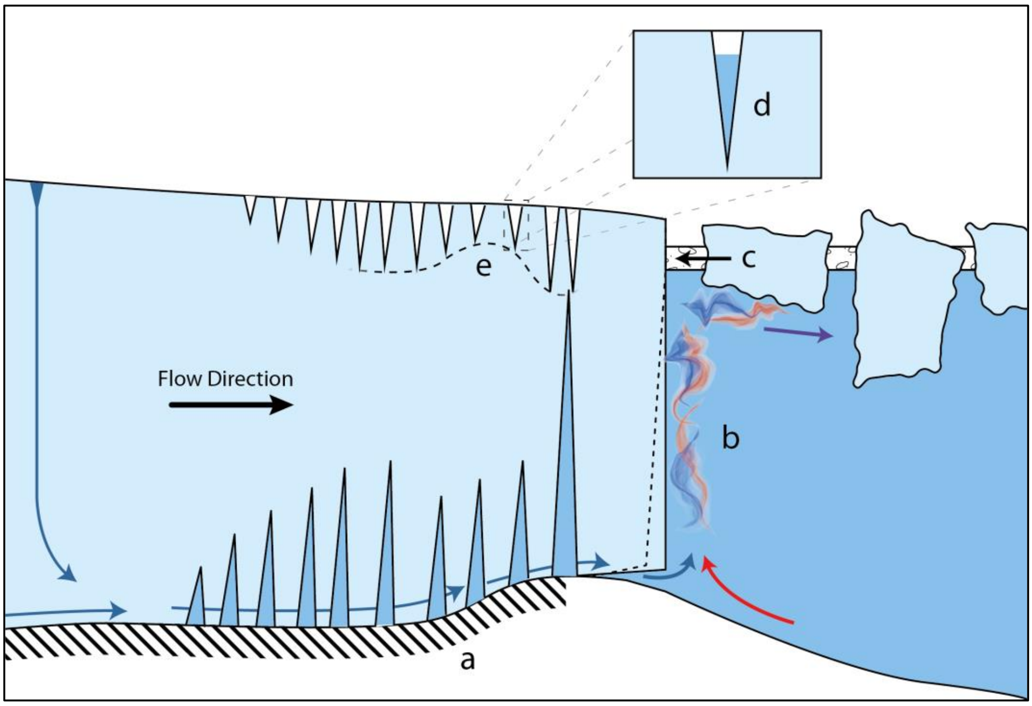


Figure 4.1: *Calving processes at the terminus of a tidewater glacier (where c represents a floating tongue) Source: Todd & Christoffersen (2014).*

This basal acceleration enhances crevasse propagation (Fig. 4.1a) and therefore plays a key role in determining the rate of calving. The thinning at the grounding lines of these glaciers might constitute a more important form of mass loss from East Antarctica than previously estimated (Rignot et al., 2011).

When observing the changes in terminus area of these glaciers from only one dimension, it is important to consider the implications of sea ice and ice mélange (fig. 4.1c). These can apply a buttressing resistance that can act against the advance of the glacier. The McMahon glacier for example is confronted by ice mélange and sea ice that can be constrained by the surrounding fjord topography and therefore stabilise the movement of the terminus (fig. 3.5), which explains why such little variation was observed (table 3.1).

4.3 Key Observations

The average change in the terminus area of the glaciers studied was ~1.1 km² yr-^{1}. However, the Rennick glacier is significantly larger than the other glaciers which means that it has a greater influence on the overall average. The average value excluding the Rennick glacier would be around -2.9 km² yr-^{1} which indicates that the majority of these glaciers have retreated since 1988/89.

The main calving events observed within this study occurred on the Lillie and Kirkby floating ice tongues. The 2010/11 detachment of the Lillie ice tongue resulted in ~123 km² of ice being released into Ob' bay (table 3.2). The presence of the Polynya shown in Figure 3.4 indicates that the weakening and subsequent fracture of the ice tongue might have been influenced by the upwelling of deeper warm water (Massom et al., 1998). The polynya is located on the south-western edge of the Lillie glacier and it is now in the position of the former ice tongue, suggesting that enhanced melting along the underside of the tongue may have taken place. Although the formation of latent heat (coastal) polynya is usually attributed to strong katabatic winds, they are often areas of enhanced melt (Massom et al., 1998; Budillon & Spezie, 2000). This means that regardless of how it was formed, the polynya most likely had an effect on the detachment of the Lillie tongue. In addition to this, the ice tongue may have been weakened by tidal activity. Wave oscillation can modify the stress fields along the ice tongue and enhance crevasse propagation (Jeffries 1985; MacAyeal et al., 2006). The apparent curvature of the ice tongue in 2009/10 combined with the fact that it was almost perpendicular to the ocean provides evidence for this hypothesis, indicating that the tongue rotated in an anti-clockwise direction before detaching (fig. 3.4).

Following the loss of its tongue, the Lillie glacier returned to its previous rate of advance (~2.6 km² yr^{-1}) which might indicate that crevasse propagation as a result of changing ice velocities through flow acceleration (fig. 4.1a/e) was not the dominant cause of this calving event. Frezzotti (1997) also observed a similar retreat between 1965 and 1980 (table 1.1), which suggests that this phenomenon might be cyclic.

The Kirkby calving event in 2011/12 saw the detachment of ~4km² of ice from its terminus. The cyclic behaviour of the Kirkby glacier tongue appears to be synchronous with that of the Lillie. Frezzotti also observed a similar reduction in area between 1965 and 1980 (table 1.1), and following the 2011/12 event, the velocity of its terminus returned to its previous rate (~0.2 $km^2\ yr^{-1}$). This indicates that the dominant mechanisms controlling the calving rates of these glaciers might be the same.

This observed synchronicity entertains the possibility that storm surges or weather anomalies influence the detachment of the ice tongues. Brunt et al. (2011), attributed the break-up of the Sulzberger Ice Shelf in March 2011 to the Honshu Tsunami, which was triggered 13,000 km away. This might well have had an impact on the terminus area of the glaciers mentioned in this study, and supports the hypothesis that the detachment of the Kirkby ice tongue such as that observed in 2011/12, is driven by storm surging.

The Suvorov ice tongue displayed a calving pattern characterised by small and frequent events. Although it technically lost around ~0.16 $km^2\ yr\text{-}^{1}$, this does not necessarily imply that its terminus is retreating. The abundance of longitudinal crevasses (fig. 3.3) can be seen as a first-order control on calving for the Suvorov ice tongue, leading to the detachment of icebergs on its northern, eastern and southern sides. Further secondary mechanisms will be superimposed on these crevasses. These might include the stress imbalances between the ice and the ocean as it meets the terminus cliff (Reeh 1968), the forces applied by wave activity (Jeffries 1985), or submarine melting (Benn et al., 2007). This higher frequency of smaller calving events means that the Suvorov tongue does not surpass a ‘threshold’ similar to that of the Lillie or Kirkby, which might help explain why its tongue does not detach.

4.4 Comparisons with Other Studies

The Lillie and Kirkby glacier tongues are characterised by cycles of consistent advance followed by their subsequent collapse. These findings agree with the observations of Frezzotti in 1997 (table 1.1), and share similar trends to those of numerous other ice tongues in Antarctica (Frezzotti & Mabin 1994). The Suvorov and Rennick glacier tongues however, are characterised by smaller but more frequent calving rates that maintain the position of the terminus front without significant variation. The McMahon also appears to be stable, primarily due to its fjord topography combined with the buttressing resistance provided by ice mélange and sea ice. Frezzotti recorded a significant retreat of the McMahon terminus position, from ~3 km^2 in 1961 to ~ 1.5 km^2 in 1972, followed by a further reduction to 0 km^2 in 1989. No such retreat was observed in this study which might indicate that its terminus has since stabilised.

The lack of significant recession observed for these glaciers agrees with previous studies across East Antarctica, which emphasise the estimated stability of the EAIS (Bell et al., 2011; Boening et al., 2012). These observations however are contrary to the most recent studies of East Antarctic glaciers which have observed significant grounding line thinning and terminus retreat, attributed to warm circumpolar deep water (Greenbaum et al., 2015).

McMillan et al., (2013) observed an outburst flood of the Cook Subglacial Lake, located around 200 km away from Rennick glacier. Between 2007 and 2008 roughly 6 km^3 of water was released. Following this event, the Rennick glacier advanced by around 8 km^2. Many studies have documented glacier acceleration as a result of outburst floods in Antarctica (Stearns et al., 2008), but in order to infer whether the two events are linked, and whether the floodwater drained into the Rennick, a comprehensive analysis of its drainage basin topography must be carried out.

5. Conclusions

The termini of the Suvorov, Lillie and McMahon glaciers have retreated since 1989/90 whereas the Kirkby and Rennick have advanced. The total change in the terminus area of these glaciers is estimated to be around +1.1 km^2 yr^{-1} however, the majority of these glaciers display cyclic behaviour with no strong trend. The two main calving events observed within this study are the 2009/10 and 2011/12 detachments of the Lillie and Kirkby ice tongues, which have not yet been documented by any other study. The ice front positions observed by Frezzotti (1997) indicate that these events occur in cycles, characterised by years of consistent advance followed by large scale fracture and detachment. There appears to be no significant overall relationship between terminus area and regional SST/SAT, which might be attributed to the sub-freezing temperatures experienced all year round. This does not rule out the influence of deeper ocean water, which has the potential to melt the grounding lines of these glaciers and enhance mass loss (Greenbaum et al., 2015). A statistically significant relationship between the Suvorov glacier and SAT was observed however, which suggests that atmospheric forcing might be an important control on its terminus area. The time delay between atmospheric forcing and subsequent calving is not accounted for in the statistical tests used and only one set of regional data was available to represent SAT, instead of multiple local datasets. Both SST and SAT displayed a warming trend since 1989 which means that there is still a possibility of warming regional surface temperatures being responsible for the observed retreat of the Suvorov, Lillie and McMahon glaciers over the past few decades.

5.1 Further Research

Results from this study will hopefully contribute to the effort of improving ice-sheet mass balance estimates of the EAIS, and the contribution of outlet glaciers to sea-level change. In order to estimate the total contributions of these glaciers, the thickness of the terminus ice must be inferred using more advanced techniques such as radio-echo sounding. There are a number of phenomena documented in this study that can be investigated further. The presence of Polynya where the Lillie tongue used to be suggests that the heat flux associated with coastal polynya might be a key mechanism responsible for the observed calving events. In addition to this, storm surging and its influence on the calving rates of these glaciers can also be investigated further. Techniques used by authors such as Brunt et al. (2011) can help link large scale tidal events such as the Honshu tsunami to iceberg calving. The drainage basin topography of the Rennick glacier must also be investigated, in order to infer whether outburst floods such as the 2007 Cook subglacial lake event (McMillan et al., 2013) had any effect on the velocity of the glacier ice and any subsequent mass loss.

6. Appendices

6.1 Landsat Imagery

The following tables display the entity ID for each Landsat image used. For MODIS imagery see bibliography.

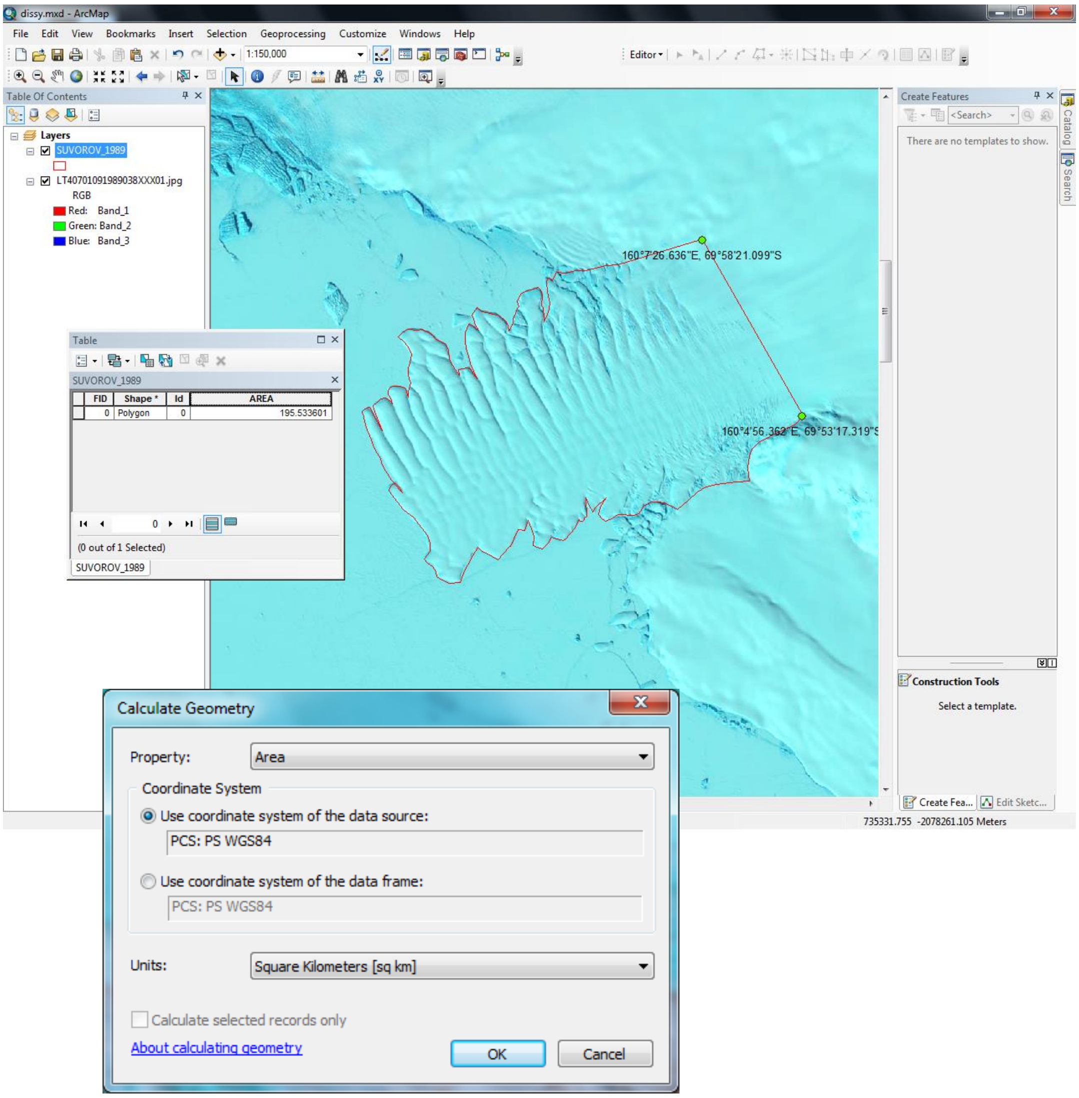
	Rennick	Suvorov	Lillie
1988/89	LT5070109014XXX06	LT40701091988038XXX01	LT40661101989346XXX02
1989/90	LT5070109014XXX03	LT40701091989038XXX01	LT40661101989382XXX02
1990/91	LT4068110027XXX03	LT50701091990084XXX03	LT40661101990372XXX02
1991/92	LT5070109084XXX03	LT50701091991084XXX03	LE70661101991337EDC00
1998/99	LE4069110002EDC00	LE70691091999363EDC00	LE70661101991345EDC00
1999/00	LE7069110363EDC00	LE70711092000012EDC00	LE70651102000003EDC00
2000/01	LE7070109021EDC00	LE70711092000012EDC00	LE70661102000347EDC00
2001/02	LE7068110329EDC00	LE70701092001327EDC05	LE72121342001344EDC00
2002/03	LE7069119323EDC01	LE70711092002337EDC00	LE70661102001347EDC00
2003/04	MODIS	MODIS	MODIS
2004/05	LE7069145323EDC01	LE70721092003011EDC00	LE70661102003347EDC00
2005/06	LE7069155673EDC03	LE70701092506037EDC00	LE70661102004347EDC00
2006/07	LE70681102007346EDC00	LE70701092006037EDC00	LE70661102005347EDC00
2007/08	LE70701092008027EDC00	LE70701092007312EDC00	LE70661102006377EDC00
2008/09	LE7070109333EDC00	LE70701092008315EDC00	LE70661102008351EDC00
2009/10	LE7069110201057EDC00	LE70701092009333EDC00	LE70671102009368EDC00
2010/11	LE70691102010EDC00	LE70701092010016EDC00	LE70661102010340EDC00
2011/12	LE7070109201019EDC00	LE70701092011019EDC00	LE70651102011382EDC00
2012/13	LC8070110304LGN00	LC80711092013327LGN00	LE70661102012324EDC00
2013/14	LC8070119304LGN00	LC80711092014362LGN00	LC80651102013311LGN00

	McMahon	Kirkby
1988/89	LT40661101989346XXX02	LT40661101989346XXX02
1989/90	LT40661101989362XXX02	LT40661101989362XXX02
1990/91	LT40661101990362XXX02	LT40661101990362XXX02
1991/92	LE70661101991347EDC00	LE70661101991347EDC00
1998/99	LE70651102000002EDC00	LE70651102000502EDC00
1999/00	LE70661102000347EDC00	LE70661102000247EDC00
2000/01	LE72121342001344EDC00	LE72121342001374EDC00
2001/02	LE70661102001347EDC00	LE70661102001347EDC00
2002/03	LE70661102002347EDC00	LE70661102002347EDC00
2003/04	MODIS	MODIS
2004/05	LE70661102004347EDC00	LE70661102004347EDC00
2005/06	LE70661102005347EDC00	LE70661102005347EDC00
2006/07	LE70661102006347EDC00	LE70661102006347EDC00
2007/08	LE70661102008351EDC00	LE70661102008351EDC00
2008/09	LE70671102009344EDC00	LE70671102009389EDC00
2009/10	LE70661102010340EDC00	LE70661102010340EDC00
2010/11	LE70651102011352EDC00	LE70651102011352EDC00
2011/12	LE70661102012314EDC00	LE70661102012374EDC00
2012/13	LC80651102013317LGN00	LC80651102013457LGN00
2013/14	LC80651102015003LGN00	LC80651102015063LGN00

6.2 Calculating the terminus area

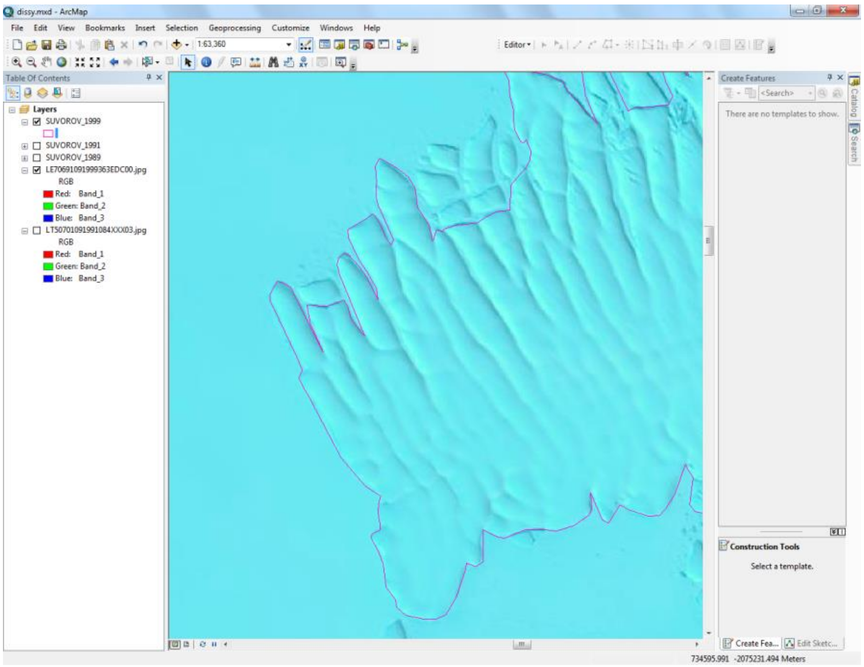
The following images illustrate how the terminus area for each glacier was calculated.

The fixed reference points mark the start of the terminus area. A new column was added to the data properties table of each Shapefile. The area was then calculated by right clicking the 'Area' column and selecting 'calculate geometry'. The units were then set to km^2.



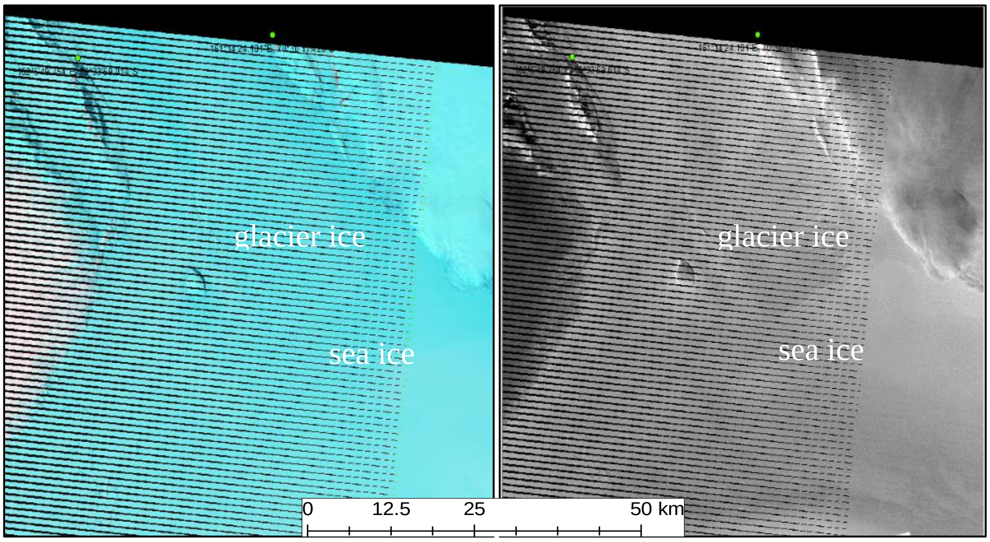
6.3 Iceberg calving

For the Suvorov glacier, iceberg calving was accounted for by simply drawing around the detached icebergs.



6.4 SLC striping

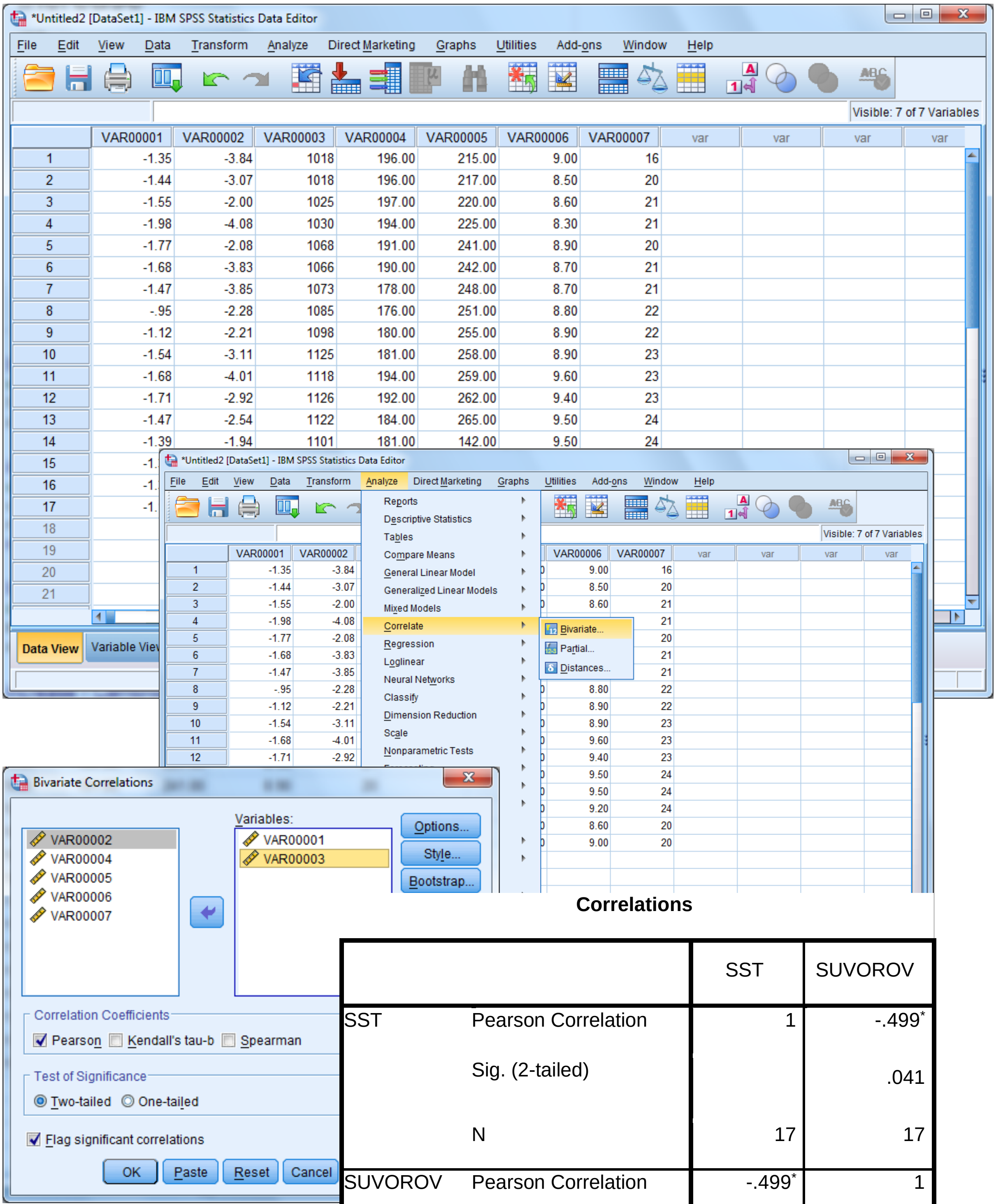
Where the SLC striping impeded the visibility of the Rennick glacier ice in 2011, the infra-red image was used instead.



Landsat images (path/row 68/110, January 2011) illustrating the effect of infra-red imagery on glacier ice visibility.

6.5 Statistics

The following images illustrate how the Pearsons correlation values were obtained using SPSS. For full output values see table 3.3.



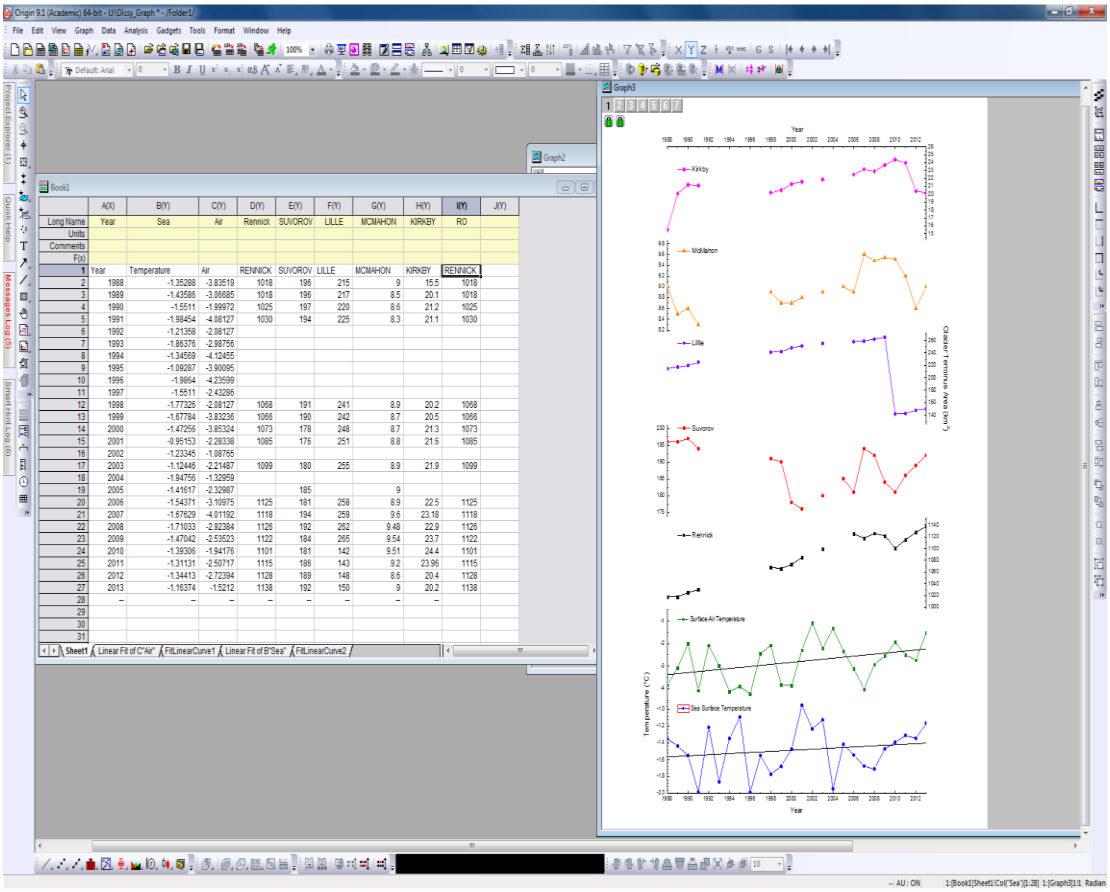
Correlations

		SST	SUVOROV
SST	Pearson Correlation	1	-.499*
	Sig. (2-tailed)		.041
	N	17	17
SUVOROV	Pearson Correlation	-.499*	1
	Sig. (2-tailed)	.041	
	N	17	17

*. Correlation is significant at the 0.05 level (2-tailed).

6.6 Graphs

Figure 3.1 was produced using Origin software. The variables for each glacier, along with SST and SAT were plotted onto separate graphs using a stacking system. A linear fit was then added to the temperature data in order to illustrate the warming trend. The missing data were not filled using straight lines in order to avoid a misleading record of glacier behaviour.



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