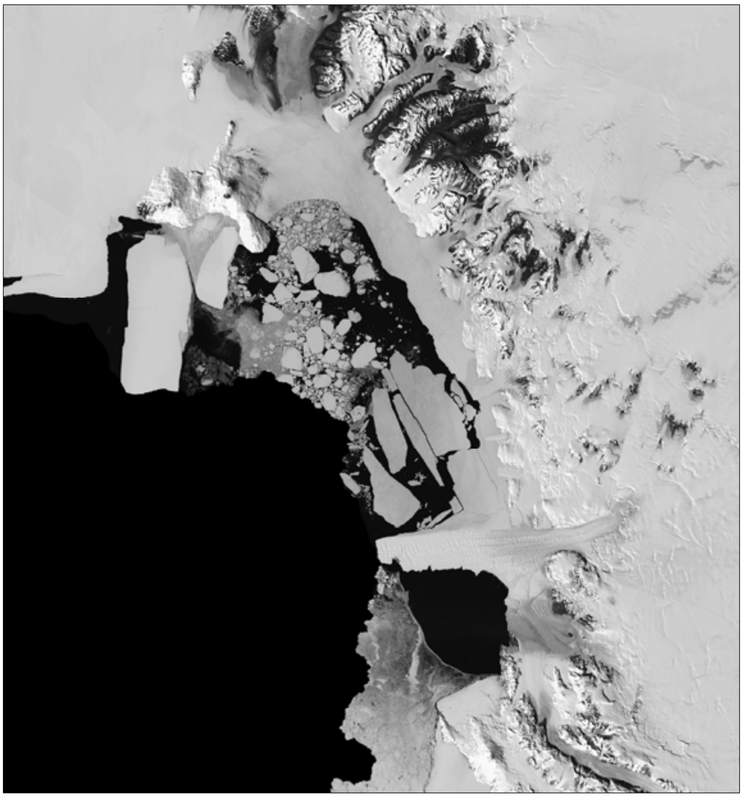
Graduate Certificate in Antarctic Studies

Individual Project

Change detection around the West Antarctic Coastline between 1997 and 2001 using satellite derived images



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Abstract

The Southern Ocean and the area of the Antarctic Ice Sheet are intrinsically linked to global climate; and changes in shape and extent of the Antarctic Ice Shelf may be diagnostic indicators of climate change. The recent recession of ice shelves around the West Antarctic coastline has been subject to major scrutiny by glaciologists and the media. This project aims to reveal the recent changes in area along the West Antarctic coastline that have not yet been measured. This change detection was analysed, using ENVI and ArcGIS software, around the West Antarctic coastline in 1997 and in 2001. The most recent satellite image of Antarctica, Landsat Image Mosaic of Antarctica completed in 2007, was compared to the Radarsat Image Mosaic of Antarctica (1997). Measurements of changes in area revealed that retreat and break up of the larger ice shelves (37,341.85 km^2) in the region was the most prominent change. The Ronne Ice Shelf unexpectedly retreated the most, followed by the Ross Ice Shelf, the Northern Larsen Ice Shelf and the Thwaites Glacier. Sea ice expanded by a total of 35,806.78 km^2. In addition, iceberg and ice shelf advance were investigated. The change detection results closely correlate with climate change records taken from nearby Antarctic stations. During the four-year study period the temperature increased by one-degree Celsius. It can be concluded that ice shelves are an indicator of climate change in the region.

Introduction

The Southern Ocean and the area and volume of the Antarctic Ice Sheet (AIS) are inextricably linked to global climate: therefore changes in shape and extent of the AIS may be diagnostic indicators of climate change. Accelerated retreat and break up of ice shelves has been observed around Antarctica over the last two decades, and has been associated with pronounced regional atmospheric warming in some sections of the continent. A comparison between the West Antarctic coastline in 1997 and again in 2001 is discussed in relation to ice shelf and sea ice change. This project reveals these recent changes by analysing the latest satellite image of Antarctica, that of Landsat Image Mosaic of Antarctica (2007) with the Radarsat Image Mosaic of Antarctica (1997) using ENVI and ArcGIS software. Change detection in areal extent of ice shelves and sea ice is discussed. A review of the literature reveals that the iceberg calving around Antarctica is occurring naturally and also anthropocentrically through the use of fossil fuels which increases carbon dioxide fluxes into the atmosphere and warms certain regions.

Background

The AIS system is composed of the ice sheet and the ice streams which flow out to ice shelves and the glaciers and ice tongues. Figure 1 illustrates this cryospheric system. Ice shelves are thick, floating platforms of ice and comprise the floating seaward margins of polar ice sheets fringing approximately 45 % of the Antarctic continent (Lawson et al., 2006). They vary between 100 and 1000 m in thickness. Ice shelves are important in the global Earth system process for a number of reasons, namely: ice shelves play a significant role in the global ice-volume-sea-level system because the calving of icebergs from their terminus accounts for approximately 90 % of Antarctic ice loss; ice shelves control the dynamics of upstream inland Antarctic ice; and rapid heat exchange in sub-iceshelf cavities has a significant impact on the global ocean heat budget (Lawson et al., 2006).

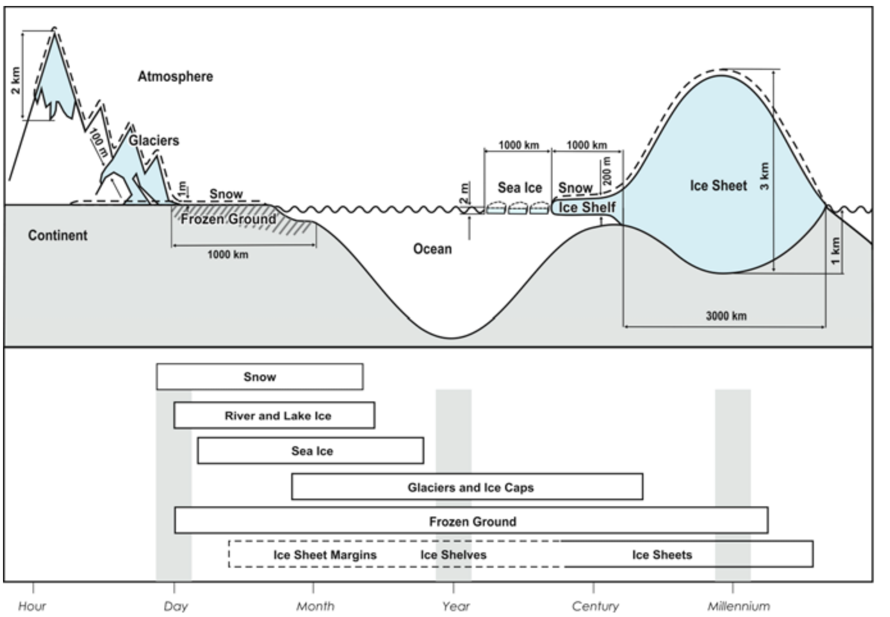


Figure 1: Components of the cryosphere and their time scales. Source: IPCC (2008)

Ice shelves are sensitive indicators of climate change because of their interaction with atmospheric and oceanographic processes, although they do not contribute directly to sea level rise as they are already floating. However, release of their ice through melting and runoff and iceberg calving can affect patterns of ocean circulation. Most of the mass lost from the AIS takes place in the ice shelves and glacier tongues through iceberg calving from their fronts or basal melting from below (Fricker et al., 2002). Studying these ablation processes in combination with accumulation processes (for example, precipitation and basal freezing) determines the mass balance of an ice mass. Mass balance is important because it assists in interpretation and analysis of global change (Figure 2). In order to understand past sea level change and predict future change it is essential to measure the current balance status of Antarctica and resolve the large uncertainties that exist in the ice mass budget. Measuring the gain and loss of the ice front around the coastline is a very important part of the equation.

Current mass balance estimates by Rignot and Thomas (2002) concluded that the West Antarctic Ice Sheet (WAIS) is mostly likely becoming thinner overall, although it is thickening in the west and thinning in the north. The mass balance of the East Antarctic Ice Sheet (EAIS) is unknown, but thought to be in near equilibrium. Fricker at al. (2002) argues that the AIS is a stable system that is currently undergoing changes that are part of its natural calve-advance cycle. They suggest that its cycle may be representative of a period of 60-70 years. In contrast, Fricker et al. (2002) argues that changes in area and volume of polar ice sheets are intrinsically linked to changes in global climate. This is because prolonged melt seasons and formation of extended melt water streams and ponds amplify the disintegration of ice shelves. Melting of the WAIS alone could cause a sea-level rise of approximately six meters.

Measurement of changes in area and mass balance of the AIS was given a very high priority in recommendations by the Polar Research Board of the National Research Council in 1986, the Scientific Committee on Antarctic Research (SCAR) in 1989 and by the National Science Foundation’s Division of Polar Programs in 1990 (Ferrigano et al., 2005).

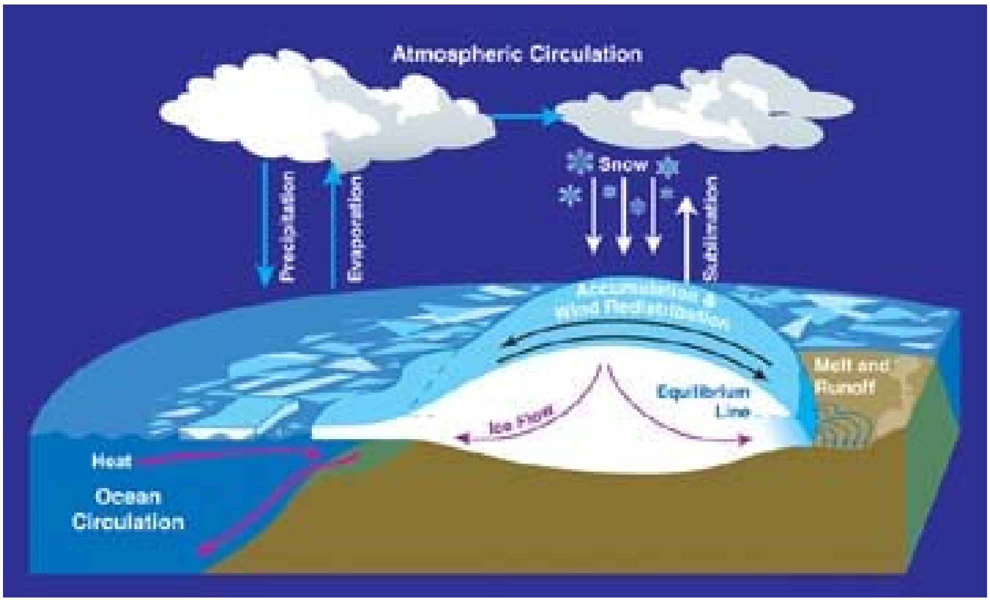


Figure 2: Mass balance - schematic diagram of ice sheet ablation and accumulation zones. Source: Zwally et al. (2002)

The degree of irregularity in the Antarctic coastline varies. The differences in the shape and morphology of the coastline reveal differences in the glaciological and oceanographical processes acting on the different regions. The length of the Antarctic coastline is 43,449 km measured from a 25 m resolution coastline coverage (Lui and Jezek, 2004). Calving is the process where ice breaks off from ice masses around the coastline and produces icebergs. This changes the position of ice fronts on the coastline. Iceberg calving events can be episodic in nature and may produce icebergs ranging in size from a few hundred meters up to many tens of kilometres (Fricker et al., 2002). The time interval between events for any given part of the ice margin may range from one year up to a few decades. Monitoring of iceberg calving in Antarctica through satellite imagery has become commonplace. The ice shelves of the WAIS have been subjects of recent scrutiny since they produced several large icebergs over two years in the 1990s. Icebergs of significant size also calved in the EAIS over 1999/2000 summer season form the Ninnis Glacier Ice Tongue. Table 1 further summarises literature on the recent change on the Antarctic coastline. Ice fronts, glacier tongues and ice shelves are the most dynamic and changeable features in the coastal regions of Antarctica (Swithinbank et al., 1997).

Table 1: Literature summary of recent Antarctic ice-shelf and ice tongue change

Region	**Area**	**Date range**	**Area change (km^2)**	**Advance/ retreat/ no change**	**Notes**	**Reference**
Victoria Land (extends from Williamson Head (69°11'S, 158°E) to McMurdo Sound (77°S, 163°E))	Floating glaciers	1956-65 to 1072-73	978 km^2	Retreat	- Iceberg calving flux of 134 km^2 yr^{-1} - See appendix 1	Frezzotti (1997)
	Floating glaciers	1972-73 to 1989-81	272 km^2	Advance	- Iceberg calving flux of 53 km^2 yr^{-1} - Most glaciers have shown a cyclic behaviour without a strong trend	Frezzotti (1997)
	Hells Gate Ice-Shelf (Terra Nova Bay) and McMurdo Ice Shelf	Since 20th Century		Significant retreat	- Exception to trend above -Surface reduction and disappearance of glacier tongues - Probable reason – increased energy available for melt water production of marine ice that progressively warmed these thin ice-shelves and the increased calving (climate change - Temperature analysis at Scott Base shows increase in annual mean temperature of 0.42°C between 1961-90 and McMurdo Station shows an increase of 1.51°C between 1956-1990) -Drygalski Ice Tongue, Erebus Ice Tongue and Nordenskjold Ice Tongue show a cyclic variation of 20-50 year areal extension	Frezzotti (1997), Braaten and Dreschhoff (1992), Jones (1995)
	Cape Adare Glaciers	Since 1958		Significant retreat	-Exception to trend above -Surface reduction and disappearance of glacier tongues - Probable reason – increased melting at the ice-ocean interface related to a major intrusion of Circumpolar Deep Water from nearby continental slope	Frezzotti (1997)
	Pennell Coast				-Rapid variations in areas of floating glaciers in the	Frezzotti (1997)

					order of 7-15 years -No glacier tongue	
	Borchgrevin-k Coast				-Rapid variations in areas of floating glaciers in the order of 7-15 years -No glacier tongue	Frezzotti (1997)
	Scott Coast				- Cyclic variations of 20-50 years in areal extension	Frezzotti (1997)
George V Coastline, East Antarctica	Ninnis Glacier Tongue	January 2001		Retreat	-Large change in coastline -Removed half of floating ice tongue -Produced a ~800 km^2 Iceberg -Cumulation of events that began before 1989 -Incomplete fracture noted in 1996 -Slowness of calving process is evident in satellite SAR images -Iceberg stagnated before it drifted away and this reflects other past calving events in the region - Related to the ‘locking in’ behaviour of the associated fast ice	Massom (2003)
Bakuits Coast, West Antarctica (Between Wrigley Gulf and the western part of Pine Island Bay)		1972-2002	~12,000 km^2	Retreat	-Most of the area is composed of the constantly moving, floating ice front of the ice shelves	Swithinbank et al. (2002)
	Thwaites Glacier System	2002	5500 km^2	Retreat	-Dynamically moving, shown most change in the region -Massive iceberg calved from the Thwaites Glacier Tongue (65 % of the tongue area) -Tongue is now the shortest it has been since 1947	Swithinbank et al. (2002)
	Getz Ice Shelf	1972-2002	Raging from 1 km to 20 km	Advance and retreat		Swithinbank et al. (2002)
	Getz Ice Shelf	1997		Retreat		Swithinbank et al. (2002)
	Dotson and Crosson Ice-Shelves	1972-2002	13 km retreat the 10 km advance	Advance and retreat		Swithinbank et al. (2002)
Eights Coast, West Antarctica		1972-2001		Retreat	- Mainly retreat and a few areas of advance along the coastline	Swithinbank et al. (2001)
	Pine Island Glacier	2001	700 km^2	Retreat	- Tabular iceberg calved in November 2001 - Crevasse on floating	Swithinbank et al. (2001)

					terminus of the glaciers likely to be the cause - Spanned a week - Dynamic and fast flowing glacier, having the second most active flowing drainage basin in Antarctica	
		1992-2001	31 km^2	Retreat	-Lost from the interior	Swithinbank et al. (2001)
	Walgreen Coast (north of Pine island Glacier)	1972-2001	4 km^2	Constant	- Ice front remained constant - Small retreat of 4 km^2	Swithinbank et al. (2001)
	Eights Coast			Advance and retreat	- Demas Ice Tongue retreated 3 km^2 1973-1989 - Thurston Island glaciers retreated - Wagoner Inlet ice front advanced 1 km 1973-1984 -Payne Glacier and Sikorski Glacier retreated - Franken Glacier advanced - Koether Inlet remained constant	Swithinbank et al. (2001)
	Bryan Coast	1972-2001		Advance and retreat		Swithinbank et al. (2001)
	Abbot Ice Shelf	1972-2001	30, 560 km^2	Constant		Swithinbank et al. (2001)
Saunders Coast, West Antarctica	West edge of the Saunders Coast to land Glacier	1972-1997		Advance	- Very little calving	Swithinbank et al. (1997)
	Front of the Land Glacier	-1973 to 1997	1000 km^2	Retreat	-16.1 km advance 1973-1988 - 4.5 km retreat 1988-1997	Swithinbank et al. (1997)
	East of Land Glacier	1972-1997		Retreat	-Complex -Advance and retreat -Ice tongues fractured and moved seaward or melted	Swithinbank et al. (1997)
Ronne Ice Shelf, West Antarctica		1992-1993	~480 km^2	Retreat	- Iceberg broke off	Ferrigano et al. (2005)
		1998	~5600 km^2	Retreat	- The ‘A-38’ iceberg calved from the ice front northwest of Berkner Island	Ferrigano et al. (2005)
		2000		Retreat	- Three more icebergs (A-43A, A-43B, A-44) broke off - The 1998 and 2000 calving events removed 40-50 years of ice advance and returned the	Ferrigano et al. (2005)

					ice front to the location mapped in the 1940s -These events are not thought to be associated with climate change but rather a result of cumulative strain	
Amery Ice Shelf, East Antarctica		1963-64	10,000 km^2	Retreat	- Large iceberg broke from the ice front -The rate of forward advance of the ice front is presently 1300-1400 ma^{-1}	Fricker et al. (2002)
		2000			- Rifts 26 km in length are likely to become tabular iceberg in the future -Follows a regular pattern	Fricker et al. (2002)
Antarctic Peninsula	Larsen Ice Shelf (LIS)	Since 1940s		Retreat	- Slow retreat, accelerated after 1975	Rack et al. (1998)
	(LIS)	1975-1986-89	Area decrease of 9300 km^2	Retreat		Rack et al. (1998)
	LIS	1980s	95000 km^2			Rack et al. (1998)
	Northern Larsen Ice-Shelf (north of Jason Peninsula)	1995	Decrease from 16200 km^2 to 10600 km	Retreat	-In January 1995 a single main event occurred when the two northern-most sections disintegrated almost completely - 4200 km^2 of the ice shelf disintegrated within a few days -Pronounced trend of atmospheric warming since 1945 has been observed on the west coast and at Marambio Station on the east coast since 1971 (mean summer temperature in 1992/93 was higher than 0°C for the first time since the beginning of the record) - The significant decrease in ice occurred during a period of intense north-westerly winds and high temperatures - The observed decrease in net accumulation on the Northern LIS was probably caused by the increasing melt rates due to this warming trend - See appendix 2	Rack et al. (1998), Rott et al., (1998)

	Northern LIS	1997		Retreat and advance	-The northernmost part of the eastern ice front retreated by several kilometres since 1995, whereas the southern part advanced by several hundred meters	Rack and Rott (2004)
	Northern Larsen Ice Shelf	2000		Retreat	- Retreat Sjogren Boydell outlet glacier between 1993-2000 left only 3 km of floating ice in front of the glacier - Retreat of the grounding ice started in 1995/96 amounting to 24 km^2 to October 2000 - After collapse in 1995 a small ice shelf was left in Rohss bay with an rea of 159 km^2 - Ice shelf at the Larsen inlet disappeared almost co lastly in 1989, by 2000 the small recent disappeared and the ice front retested 0.5 km^2 beyond the original grounding line	Rott et al. (2002), Rack and Rott (2004)
	Larsen A (between Prince Gustav channel and Sobral Peninsula)	1995 2000	984 km^2	Retreat Retreat	- Disappeared almost completely - 34 km^2 of grounded ice lost	Rott et al. (2002)
	Larsen B (Between Jason Peninsula and Seal Nunataks)	1963-1995 1995 1998 1998- 2000 2002-2003	 Area decreased 2320 km^2 110 km^2 calved Area decreased 1000 km^2 Ice shelf decreased from 3463 km^2 in March 2002 to 2667 km^2	Advance Retreat	- Ice Shelf advanced steadily - Iceberg A-32 calved 1720 km^2 - Calving in November along the ice front between Jason peninsula and Robertson Island -Position is now in irreversible retreat - Main loss on the northern half of the ice shelf This coincided with a temperature increase -See appendix 3 - Over one week in march the ice shelf broke up into many small icebergs - Exceptionally warm summer	Rott et al. (2002), Skvarca et al. (1999), Rack and Rott (2004), Skvarca et al. (1999a))

			in April 2003		- Similar pattern of break up to 1995 - Unusually warm summer was the reason for these calving events during a period of constant and pronounced warming - See appendix 4	
	Wordie Ice Shelf	1966-1989	1300 km^2	Retreat	- Rapid disintegration was triggered by climate warming that increased ablation and the amount of melt water. - Still unsure about the mechanism that are at work during the ice shelf retreat -First ice shelf to suffer - Retreat has continued	Vaughan and Dorke (1996), Skvarca et al. (1999a))
	Wilkins Ice Shelf, George VI, Wordie Ice Shelf	Since mid 1960s	10,000 km^2	Retreat	- Retreat is related to climatic warming - Wilkins, previously though stable, is reported to have started retreating at its northern margin -George VI –loss 993 km^2 from 1974-1995 and 1360 km^2 between 1900-1995	Skvarca et al. (1999a))

Rott et al. (1998) argues that to understand the ongoing changes on the Antarctic Peninsula, it will be important to know in detail the present climatic conditions, as well as the pattern of temporal changes during the last decade. Yet, continuous meteorological data is not always available for all regions, for example the Matienzo Station on the Larsen Nunatak, Antarctic Peninsula. Temperature data analysis from the mid 1940s indicates a slight warming trend for Antarctica and the surrounding oceans associated with the reduction in sea ice extent (Jacka and Budd, 1998). The increases in surface air temperatures are particularly evident around the Antarctica Peninsula. Climate change data was downloaded from the British Antarctic Survey (BAS) website and graphed (Figure 3). It illustrates the recent increasing temperature trends at four stations in the West Antarctic region. These results strongly correlate to that of Hoffman et al. (1997), Van den Broeke (2000), Turner at al. (2005) and the IPCC (2008).

The longest temperature record from Antarctica shows that the last two decades were the warmest in this century (Hoffmann et al., 1997). This record started at the meteorological station Orcadas in the South Orkney Islands in 1903. It shows a mean cooling trend of 0.4°C per decade for the period 1904-1930, which was followed by a warming trend of 2.1°C between 1930 and 1990 (Hoffmann, 1997). Between 1971 and 1997 the trend at Marambio Station was a 1.4°C temperature increase. A statistically significant temperature trend of +0.56°C per decade was found on Vernadsky (renamed Faraday) Station on the Antarctic Peninsula from 1951 to 2000 (Turner et al. 2005). The greatest warming outside the Antarctic Peninsula occurred at Scott Base, where temperatures had risen +0.29°C per decade (Turner at al., 2005) (appendices 5 and 6).

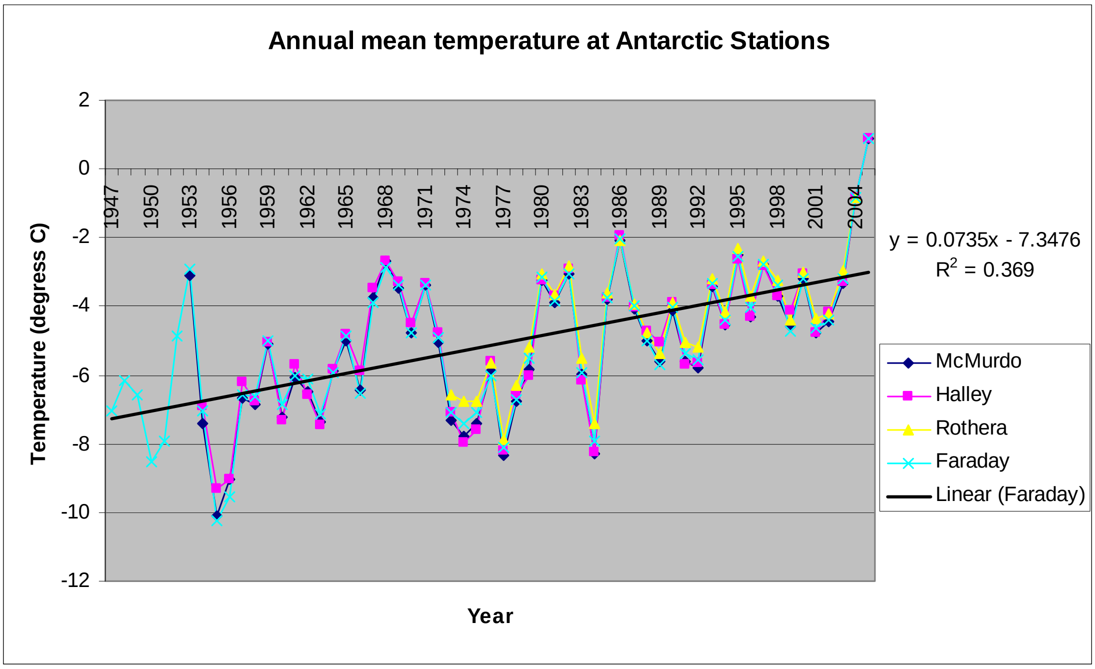


Figure 3: Climate change at selected stations around the Antarctic Coastline

Patterns of sea ice are continuously changing on a seasonal, annual and decadal scale. Figure 4 highlights the sea ice extent over the last 25 years and in particular the seasonal advance and retreat cycle in the summer and winter months. The Southern Ocean is the only ocean domain encircling the globe. It contains the strong eastward flow of the Antarctic Circumpolar Current (ACC), and its unifying link for exchanges of water masses at all depths between the world's major ocean basins. These exchanges are an important control on mean global climate; the Southern Ocean is expected to play an important role in transmitting climate anomalies around the globe (White and Peterson, 1996). Between 1988 and 1991 a strong poleward anomaly near 90° W persisted and resulted in an extraordinary retreat in sea ice reported for the west Antarctic Peninsula (Bellingshausen Sea). This was especially intense during the summer months and was preceded by two years of exceptionally heavy ice conditions (White and Peterson, 1996). This example highlights the local fluctuations in sea ice extent.

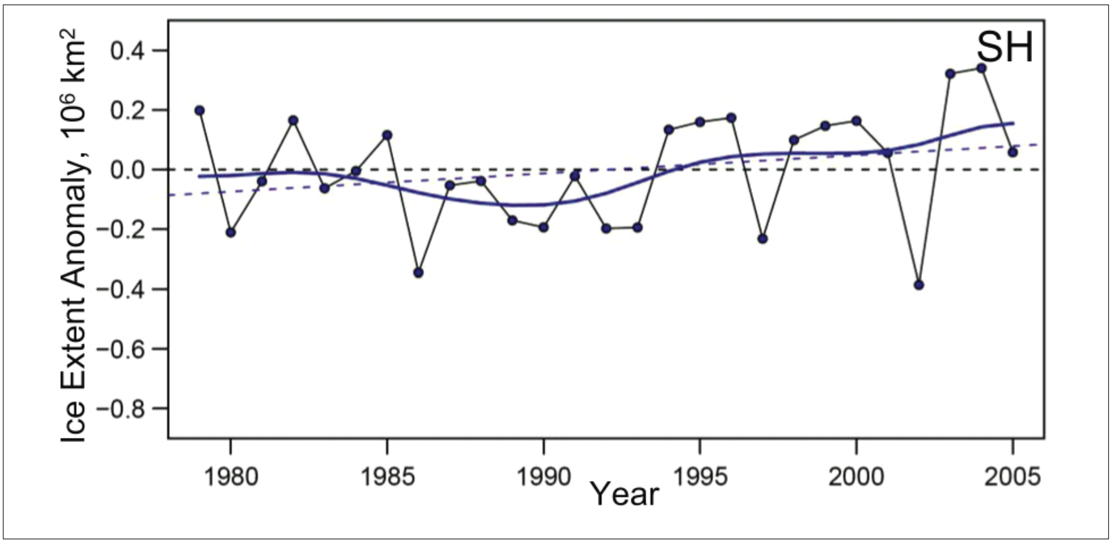


Figure 4: Sea ice extent anomalies for the Southern Hemisphere, based on passive microwave satellite data. Symbols indicate annual mean values while the smooth blue curves show decadal variations. Linear trend lines are indicated. The trend for the Antarctic result shows a small positive trend of 5.6 ± 9.2 × 103 km2 yr^{-1}, however this is not significant. Source: IPCC (2008)

It is clear from the above discussion that a gap exists in the literature of data existing from 2000 onwards.

Aim

To detect changes along the West Antarctic coastline between 1997 and 2001, including changes in glacier tongue extent; sea ice extent; and ice shelf extent boundary before and after calving events.

Sources of primary data

Mapping of Antarctica using the real photographic method is extremely difficult and costly, due to its remote location, snow and ice covered surface, extremely cold and windy climatic conditions and lack of sufficient established geodetic control. Until recently the Antarctic coastline remained poorly charted (Lui and Jezek, 2004). Technological advances in the twentieth century have enabled scientists to undertake research on virtually every location on the Earth. Parallel advances in space technology have provided a rapidly increasing number of satellite platforms that can be used to study complex physical processes in the Earth-atmosphere system and remote sensing technology, especially space-borne imaging radar, provides an efficient means for mapping the Antarctic. Figure 5 outlines the basis of remote sensing, this is the electromagnetic spectrum. Satellite sensors can see a wider spectral range than humans. Different instruments measure the different parts of the spectrum. Unlike optical and infrared imaging sensors, which are inherently passive, that is they rely on reflected or radiated energy, radar is an active sensor, which provides its own illumination in the form of microwaves.

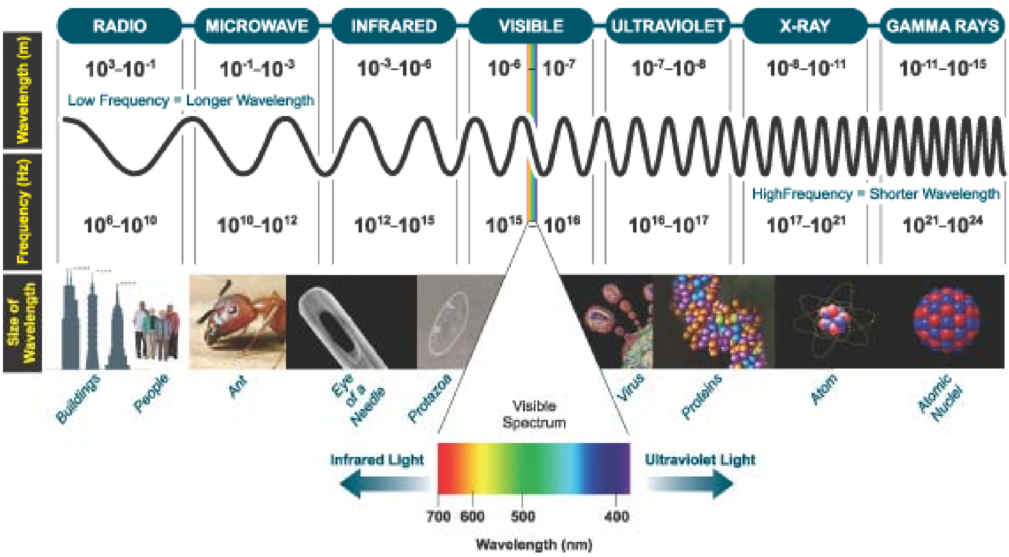


Figure 5: The electromagnetic spectrum. Source: www.andor.com/library/

Two satellite images were analysed in this project: Radarsat Image Mosaic of Antarctica (1997) and Landsat Image Mosaic of Antarctica (LIMA) (2007).

Radarsat Satellite Image Mosaic of Antarctica

The 200 m pixel resolution Radarsat Image Mosaic of Antarctica (1997), complied by the Ohio State University's Byrd Polar Research Centre (BPRC) was used in this project (Figure 6). It was a joint National Aeronautics and Space Administration (NASA) and Canadian Space Agency (CSA) project to map Antarctica. The image was generated from Synthetic Aperture Radar (SAR) collected by the RADARSAT-1 satellite. The Radarsat Image Mosaic is composed of data recorded from 9th September to 20th October 1997 (Jezek, 1998). Over 400 individual images were used to build the mosaic at a 25 m resolution. The geodetic accuracy of the Radarsat Image Mosaic of Antarctica is $\pm$ 150 m (Noltimier et al., 1999). Orthorectification of the mosaic was accomplished using a Digital Elevation Model (DEM) generated by the BPRC specifically for the production of the mosaic. From this Lui and Jezek (2004) derived a complete, high-resolution coastline of Antarctica, through a sequence of automated image processing algorithms. This radar-image-derived coastline gives an accurate description of geometric shape and glaciological characteristics of the Antarctic coastline and also provides a precise benchmark for future change detection studies.

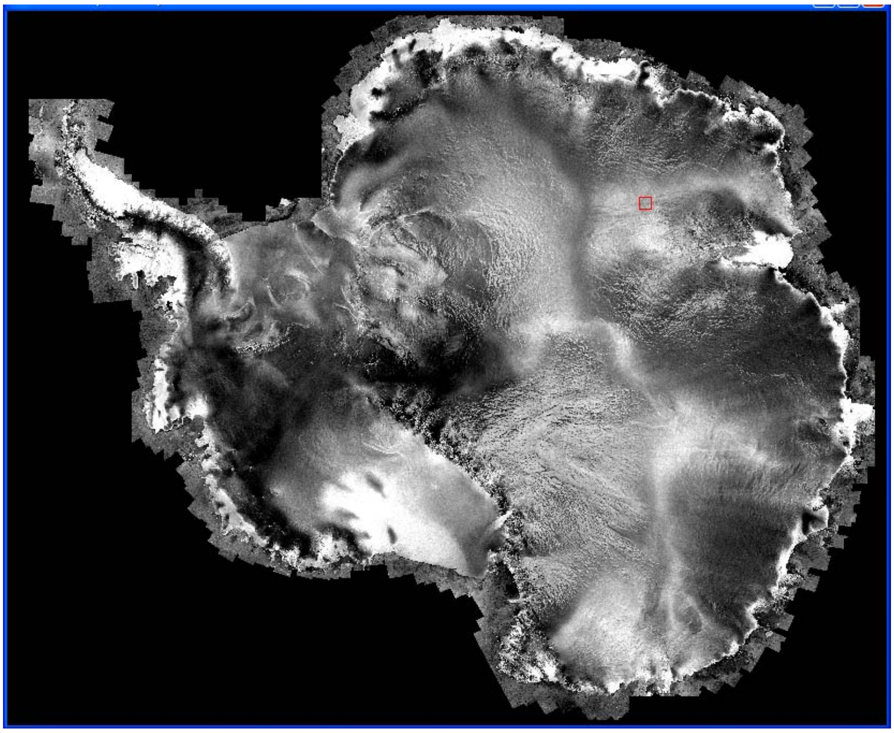


Figure 6: Radarsat Image Mosaic of Antarctic (1997)

Landsat Image Mosaic of Antarctica (LIMA) 2007

In support of the International Polar Year (IPY), LIMA (2007) was composed in conjunction with the United States Geological Survey (USGS), NASA and BAS and with funding from the National Science Foundation (NSF). The comprehensive view of Antarctica is at a 15 m resolution (USGS, 2008). The producers of the map used 1,073 scenes from the 8000 scenes taken by the ETM+ sensor on LANDSAT 7 which was launched in 1999. Each Landsat scene is 184 km by 170 km. They were produced with elevation data and sun angle correction to ensure surface features were accurately represented. These senses were then merged together. The scenes were acquired between 1999 and 2001 (USGS, 2008). The exact date of each scene is currently unavailable, but NASA intends to include an index map that shows exactly how much of each image was used and additional information, such as the time each scene was taken, on the LIMA website (Bindschadler, 2008). The final image was completed and made available in 2007 (Figure 7).

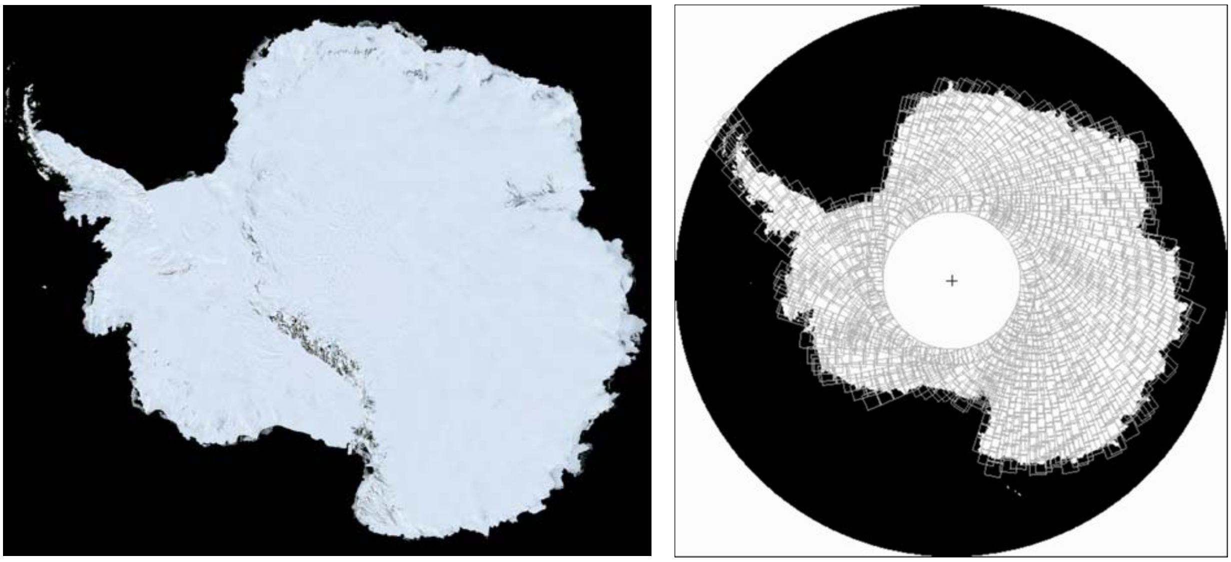


Figure 7: Landsat Image Mosaic of Antarctica (2007). Source: USGS (2008)

Methodology

Obtaining the data

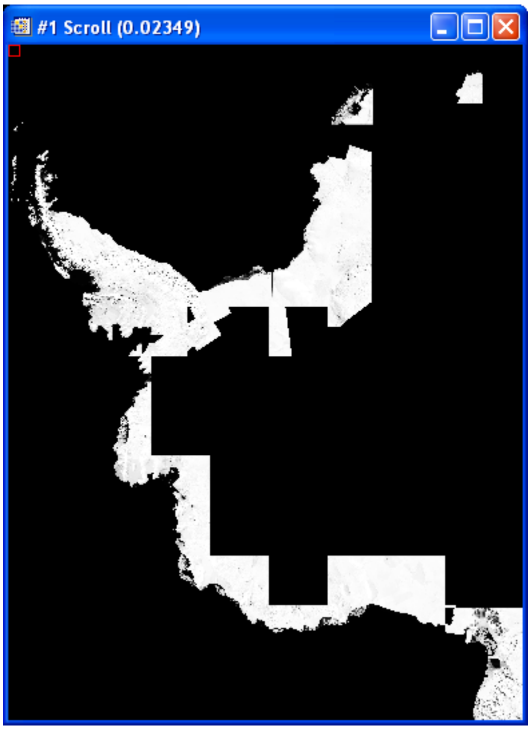
The LIMA (2007) data was downloaded from the BAS website on the ‘anta-lab 3’ computer which uses the Fedora operating system in the Antarctic Studies Geographical Information Systems (GIS) laboratory. Because the University of Canterbury is a member of the Kiwi Advanced Research and Educational Network (KAREN) the data was relatively quick and inexpensive to download. Each scene around the West Antarctic coastline was downloaded and copied to the ‘anta share directory’ so they could be accessed on the ‘anta-phd 6’ computer using the Microsoft Windows operating system. Gateway Antarctica had previously acquired the Radarsat image (1997) and this was made available. The LIMA (2007) scenes were copied into a personal directory on the hard drive. As they were downloaded in the compressed format they were uncompressed by ‘extracting all’ the data.

Processing the data

Two software packages were used to process the spatial data. The first was ENVI, which is a remote sensing image program which analyses geospatial data. Three days were spent undertaking the ‘quick ENVI tutorials’ to become familiar with the software. The scenes were downloaded in raster format. Raster data consists of a matrix or cells or pixels organized into rows and columns (or a grid) where each cell contains a value representing information. Imagery from satellites and aerial photographs are typically rasters. Storing data as raster is useful because it is a powerful format for spatial analysis, it has ability to perform overlays and it is a simple data structure.

Fortunately the LIMA scenes were georeferenced. Georeferencing assigns real world coordinates to a number of reference points on the image. This allows two images to be overlaid upon each other with the coordinates of each point directly in line with each other. A map coordinate system is defined using a map projection (a method by which the curved surface of the earth is portrayed on a flat surface). The Polar Stereographic projection was used because it has zero distortion at 71°S. This is the average longitude of the Antarctic coastline. The datum that was used was WGS84 because Antarctica is at the global scale. However if Ross Island, for example, was just being investigated a local scale datum would be used.

The LIMA scenes were opened in ENVI and resized to 200 m pixels. It was crucial to use the images with the same pixel size to ensure accurate georeferencing. Two bands were used to detect change. A mosaic was constructed of all the red band scenes (Figures 5 and 8). The mosaic was then stacked upon the blue band of the Radarsat 200 m image (Figures 5 and 9). The LIMA image was in band one and the Radarsat image was in band two. Using only two bands of the spectral image visually allows for areas of change to be detected.



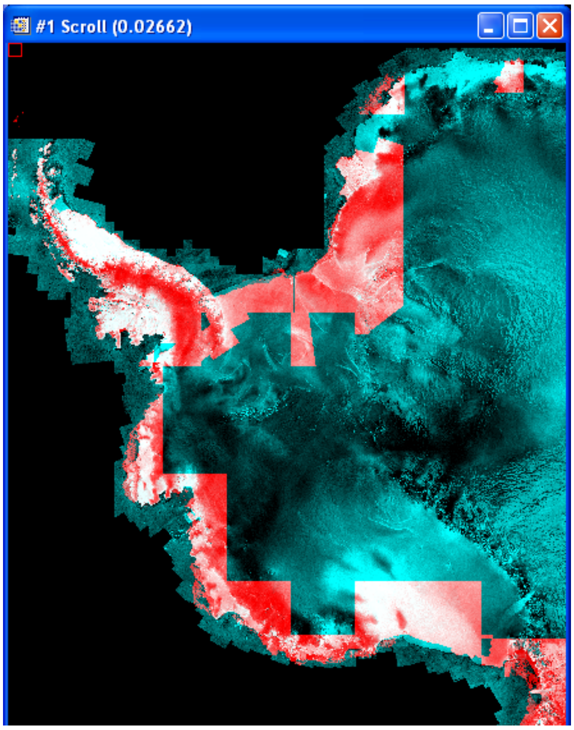


Figure 8: Snap shot of the final mosaic

Figure 9: Snap shot of the stack

Analysing the data

The second software was a GIS package by ESIR called ArcGIS. Within this software, ArcMap and ArcCatalogue are programmes which assisted with change detection measurements. The image stack was saved as a .tif file and opened in ArcMap. Using the zoom and pan functions, areas of change were identified. Blue areas around the coastline were areas of retreat because ice shelf in the overlying image (LIMA in the red band) was no longer present. Red areas were hence areas of advance (Figure 9). The blue and red bands were switched on and off to see the coastline shape before and after calving events. Pink areas were areas of no change.

Shapefiles were prepared in ArcCatalogue. These were polylines using the Polar Stereographic map projection referenced to the WGS84 ellipsoid. The polylines were drawn around the detected areas of change, including icebergs and ice tongues. These features were then measured using the measurement tool in ArcMap and recorded in Table 2. The coordinates of each main vertex were also recorded. Each area of change was named with reference to the Physical Map of Antarctic (Ordnance Survey, 1997). Maps were constructed in the ‘layout view’ and scales, arrows, titles, legends and labels were added.

Climate change data was also downloaded from the BAS website at nearby stations where significant change occurred. These included Varaday, Rothera, Halley and McMurdo Stations. Data from McMurdo station was used because records at Scott Base only extended until 2002, whereas McMurdo held data until 2007/08. Annual means were calculated at each station and these were graphed (Figure 3). Coastline changes were related to sea ice conditions and temperature trends during 1997 and 2001.

Results and discussion

The change around the Antarctic coastline between 1997 and 2001 is illustrated in Table 2.

Table 2: Change detection around the West Antarctic Coastline 1997-2001

Region	Area	Coordinates of the main vertices	Change	Area (km^{2})	Notes
Antarctic Peninsula	Northern Larsen Ice Shelf (between Robertson Island and Seal Nunataks and Cape Disappointment	(-2356634.394, 138270.366), (-2310096.392, 1300114.455), (-2372086.159, 1283406.35), (-2418154.344, 1317728.990)	Retreat	4,820.15	
Antarctic Peninsula	Wordie Ice Shelf	(-2128877.572, 891615.92), (-2132218.280, 87576.113), (-2123131.450, 873843.70)	Retreat	99.71	
Antarctic Peninsula	Trinity Peninsula	(-2454199.32, 1591052.55), (-2405000.86, 1573674.08)	Advance	207.41	Likely to be fast ice protected from the climatic in the bay (fast ice = sea ice attached to either land or land-bound ice)
Antarctica Peninsula	Wilkins Ice Shelf	1. (-2133461.19, 705213.086), (-2139116.553, 685162.251) 2. (-2149399.033, 656371.308), (-2138602.429, 536066.299) 3. (-2079992.296, 577196.216), (-2058913.213, 549947.646), (-2055828.47, 587992.82) 4. (-2020353.915, 593134.06), (-1961743.782,	Advance	222.199 4,085.26 757.26 748.668	Four separate areas around the ice shelf and island of advance/ sea ice

		584908.076)		Total - 5,813.39	
Antarctic Peninsula	George VI Ice Shelf	1. (-1780099.671, 565461.09), (-1758133.345, 549817.175) 2. (-1771669.79, 530606.772), (-1738031.32, 547628.648) 3. (-1721366.093, 530282.546), (-1710990.854, 539533.993)	Retreat	92.260 234.55 46.48 Total - 373.25	On the ice front At ice front extending into the ice shelf Inside ice shelf Three areas
Antarctic Peninsula	George VI Sound	(-209492.91, 819514.19), (-204609.88, 781155)	Advance	1,342.83	Advance or sea ice in the bay
Antarctica Peninsula	Cape Jeremy (below Wordie Ice Shelf)	(-2120752.82, 801795.5), (-2108905.37, 845942.35), (-2125886.72, 842782.02)	Advance	267.28	- Iceberg nearly completely broken off Probably sea ice
Antarctica Peninsula	Charcot Island (northwest of the island – Wilkins Ice Shelf)	(-2099264.186, 574011.219), (-2087265.222, 574299.194)	Retreat	20.51	
Ellsworth Land	Bryan Coast	1. (-178997.92, 188915.62) 2. (-1767593.53, 219599.65), (-1764403.64, 223234.36)	Advance Advance	1,513.98 1.82 Total – 1,514.80	
Ellsworth Land	Bryan Coast iceberg	(-1794038.78, 216002.79), (-1788000.933, 210096.38), (-1780958.67, 216835.747)	Iceberg	68.15	South Eltain Bay
Ellsworth Land	Eights Coast (between Flechter Peninsula and Thursston Island)	(-811775.93, 119639.97), (-1928030.166, -416015.25)	Iceberg	14,118.91	
Amundsen Sea	Pine Island Bay – advance (between Canisteo peninsula and Pine Island Glacier)	(-1713640.097, -350056.02), (-1683258.91, -34028.21), (-1670445.894, -373040.05)	Advance	891.45	
Amundsen Sea	Pine Island Bay iceberg (south of Pine Island Bay advance)	(-1689335.153, -360171.26) (-1672823.64, -389419.466)	Iceberg	136.32	

Amundsen Sea	Pine Island Glacier Iceberg (Walgreen Coast)	(-1637179.62, -339645.73), (-1625339.50, -359535.67)	Iceberg	253.11	
Amundsen Sea	Pine Island Bay retreat	1. (-1640245.508, -325614.84), (-1591151.43, -337060) 2. (1652774.695, -364821.04)	Retreat	34.36 235.83 Total – 270.19	Two areas
Amundsen Sea	Thwaites Glacier iceberg	(-1605896.942, -475316.622), (-1597444.212, -522035.127)	Iceberg	2,055.35	- Many small icebergs scattered in bay - Also smaller broken up icebergs counted so likely to be overesti-mated
Amundsen Sea	Thwaites Glacier-area lost	1. (-1613672.507, -477382.312), (-1607582.566, -540911.572) 2. (-1595679.47, -469077.833), (-1546959.863, -526932.367)	Retreat	3,890.13 329.986 Total – 4,220.11	Two areas with iceberg in the middle
				Total iceberg and area lost = 6275.46	
Amundsen Sea	Thwaites Glacier advance	(-1582115.488, -388358.302), (-1599278.077, -457700.698), (-1625990.816, -434032.943)	Advance	1,643.07	Or sea ice
Amundsen Sea	Smith Glacier	(-1563430.412, -519112.316), (-1600385.341, -587762.672)	Advance	1,488.41	
Amundsen Sea	Smith Glacier	(-1605091.212, -552191.822), (-1624883, -595790.334)	Iceberg	438.99 Total- 1,927.4	- Two big icebergs and many smaller scattered ones - Most likely to be sea ice
Marie Byrd Land	Getz Ice shelf	1. (-1517229.83,	Advance	7,211.84	- Iceberg

		-924011.006), (-1476261.069, -1078239.013) 2. (-1480966.94, -1084052.147), (-1565063.626, -873588.981), (-1576274.672, -1032079.953)	Icebergs	8297.77	overesti-mated as many small icebergs in area. - Likely to be sea ice
Marie Byrd Land	Wrigley Gulf iceberg	(-1348455.145, -1079540.048). (1291984.691, -1144868.612)	Iceberg	1,868.68	Many icebergs floated away or have disintegr-ated
Marie Byrd Land	Hull Bay (Between Cape Burns and Land Bay	(-12000651.635, -1183233.389), (-1003169.501, -1358280.30)	Advance	15,426.30	Sea ice
Marie Byrd Land	Wrigley Gulf advance	(-1260139.28, -1148240.89), (-1280778.89, -1117111.4), (-1280838.233, -114159.841)	Advance	264.49	Sea ice
Marie Byrd Land	Dean Island (Wrigley Gulf)	(-1393076.64, -1068079.007), (-1340200.998, -1064756.977)	Retreat	91.687	
Marie Byrd Land	Nickerson Ice Shelf (Ruppert Coast)	(-921632.769, -1325717.713), (-593701.509, -1278457.032)	Advance	13, 639.35	Sea ice
Ross Sea Dependency	Okuma Bay	(-467628.18, -1226762.73), (-330157.955, -1202460.220	Retreat	1,560	Icebergs breaking up in the area
Ross Sea Dependency	Ross Ice Shelf	(-350317.170, -1208492.540), (1888549.464, -1376287.783)	Retreat	10,800.92	- Four areas - There is not complete coverage for one area (possibl-y due to cloud cover so it was estimated from the LIMA map), so this area was estimated
Ross Sea Dependency	Scott Coast	(306523.501, -1288324.641),	Advance	8,294.92	Sea ice

		(466187.751, 150429.066)			
Ross Sea Dependency	Ross Island	(201433.211, -1345981.154), (300610.072, -1396984.993)	Advance	1, 392.709	Sea ice
Ross Sea Dependency	Drygalaski Ice Tongue	(386356.184, -1526679.135), (405241.87, -1544100.814), (420467.539, -1542636.807), (437010.814, -1542344.006), (443745.245, -1546443.225)	Advance	Total – 106.16	- Five small bits of fast ice surround -ing the tongue - Sea ice formed after 1997 and many icebergs on the coast
Oates Land	Borchgrevink Coast	(390051.586, -1548074.625), (327959.956, -1938364.867)	Advance	15,509.766	- Sea ice - Crack starting to form and break away
Weddell Sea	Ronne Ice Shelf	(-1471482.088, 803015.882), (-995751.909, 912574.432)	Retreat	13,029.97	
Weddell Sea	Filchner Ice Shelf	(-908222.244, 930503.195), (-765854.715, 1108022.2)	Advance	5,428.59	Fast ice
Weddell Sea	Luitpold Coast	(-771127.586, 1128527.811), (-712540.126, 1317530.959)	Advance	3,136.37	Fast ice, likely to be overesti-mated due to icebergs

The following Figures illustrate the results of change detection (Figures 10 to 16).

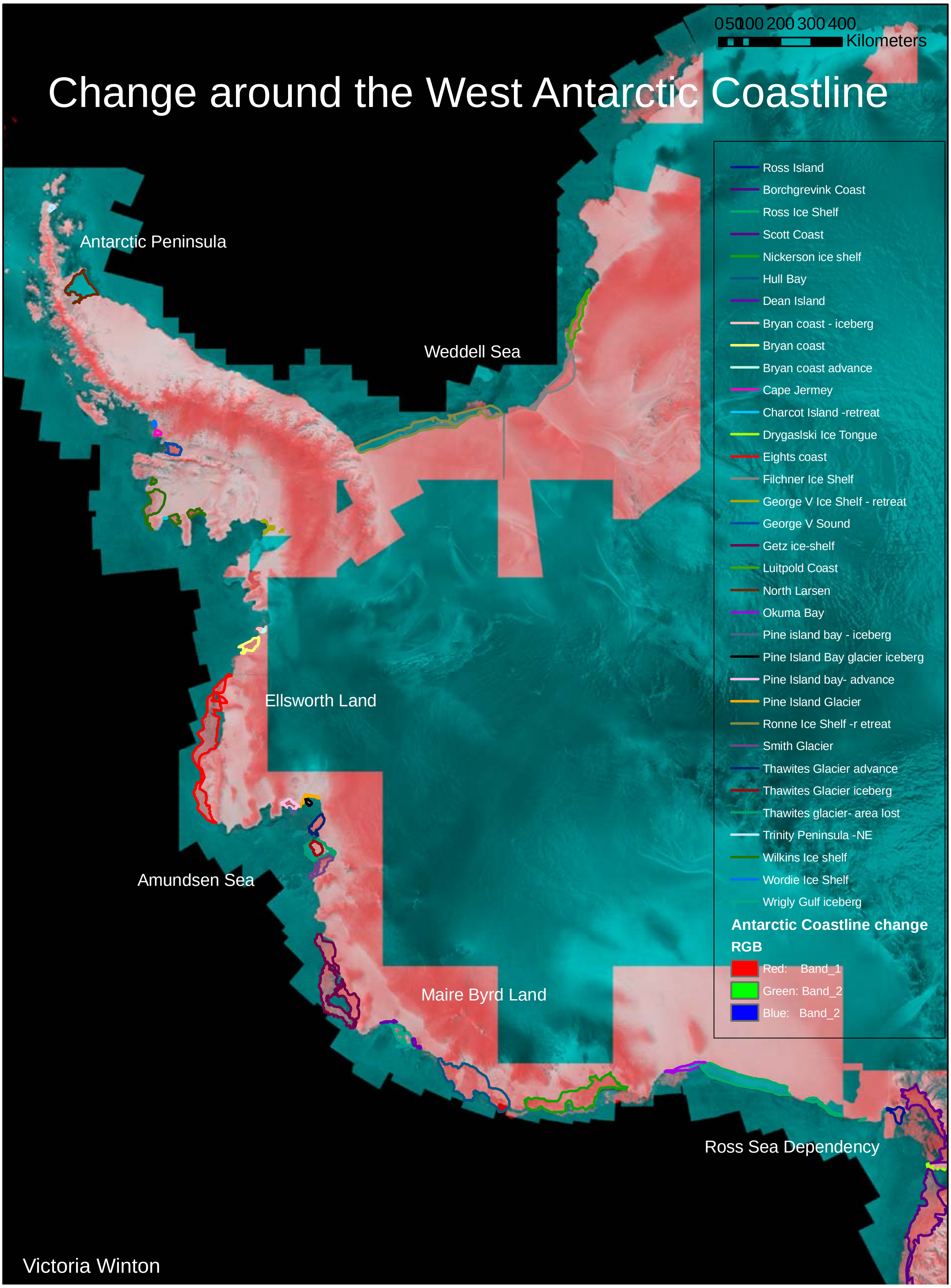


Figure 10: Change around the West Antarctic Coastline 1997 to 2001

Antarctic Peninsula

The warming on the Antarctic Peninsula is the greatest of all regions on the continent and this is the area with great snow and ice retreat. It is not, however, the area with the greatest change as expected. There were five areas of retreat in the Antarctic Peninsula (Northern Larsen Ice Shelf (LIS), Wordie Ice Shelf, Wilkins Ice Shelf northwest of Charcot Island and George VI Ice Shelf) totalling 5,313.62 km^2 (Figure 11). The LIS is located close to the climatic limit for the existence of ice shelves. In accordance with the small ice shelves on the west coast of the Antarctica Peninsula, the northern LIS has retreated and continued to decrease during recent decades which are characterised by increasing temperatures. Rott et al. (1998) predicted that if the warming trend continues, major retreat is likely within the next few years for the section of LIS north of Jason Peninsula. This in fact became true and the disintegration of the northern LIS in October 2000 can be seen in Figure 11. Northern LIS had the fourth greatest area of recession amounting to 4,820.15 km^2 between 1997 and 2001 on the Antarctic Peninsula.

The other four areas (Trinity Peninsula, Wilkins Ice Shelf, George V Sound and Cape Jeremy) all experienced sea ice presence in 2001 that was not present in 1997. The sea ice extent totals 7,630.91 km^2 in the region. The greatest amount of sea ice accumulated around the Wilkins Ice Shelf. The fast ice in the bay at Trinity Peninsula is protected from climatic variables.

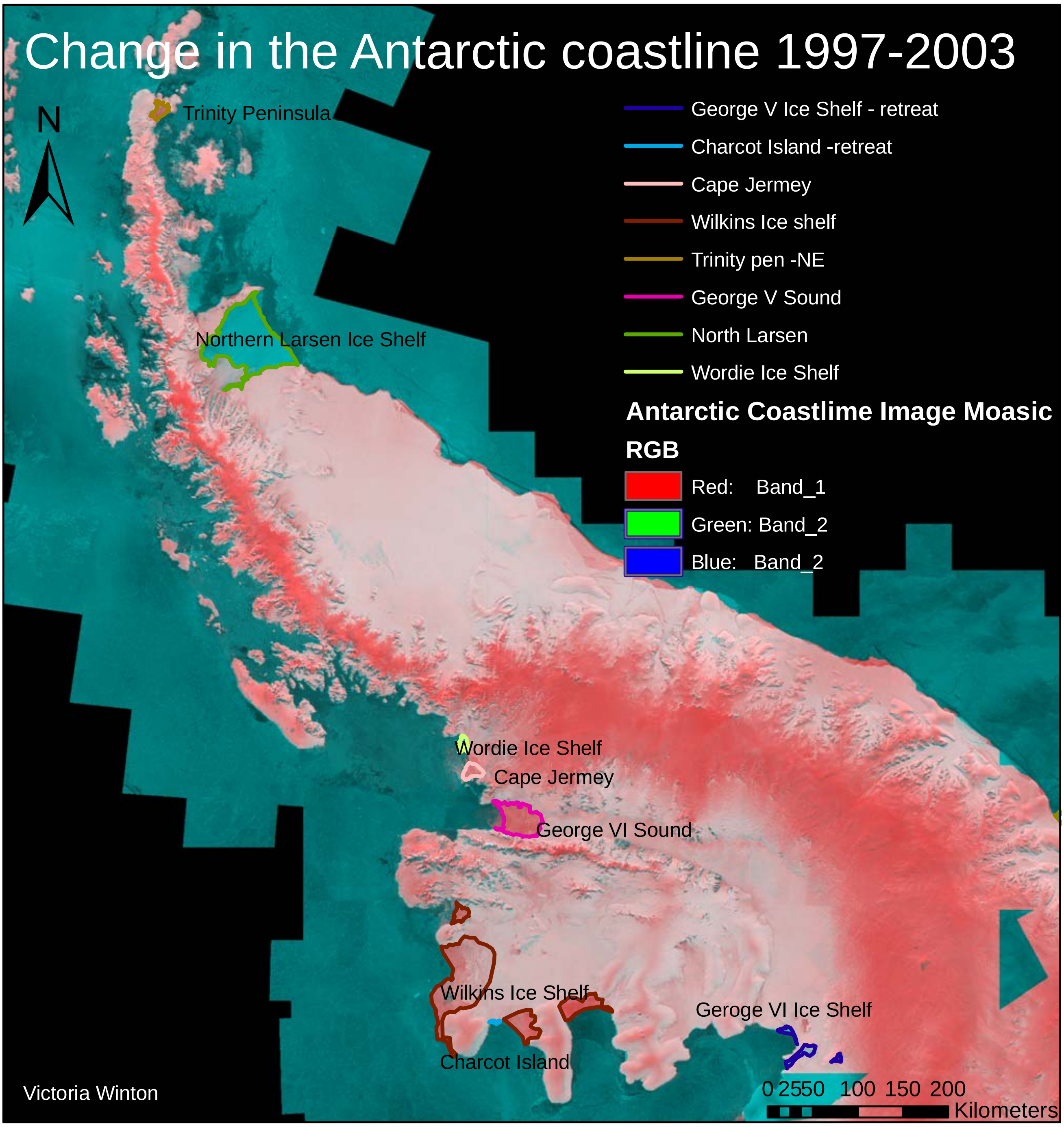


Figure 11: Change around the Antarctic Peninsula 1997-2001

Ellsworth Land

The only change that has occurred since 1997 around the Ellsworth Coastline was sea ice advance and sea iceberg presence (Figure 12). This totalled 1,514.80 km^2 of sea ice and 14,249.21 km^2 of icebergs. The total area of sea icebergs is likely to be overestimated because the whole perimeter of the iceberg area was made into a shapefile and the area was measured from this. The justification for measuring this whole area was that the resolution was not great enough to individually measure each iceberg.

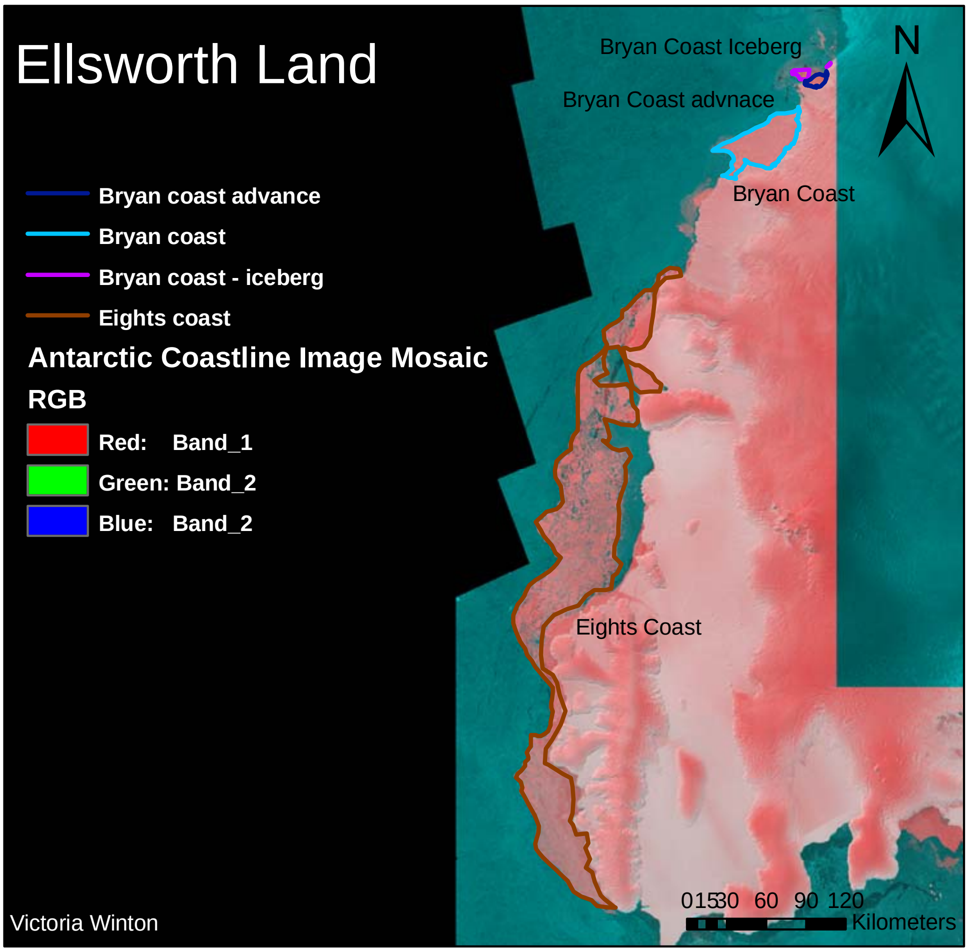


Figure 12: Change around Ellsworth Land Coastline 1997 to 2001

Amundsen Sea

A large amount of change occurred relative to the size of area around the Pine Island and Thwaites Glacier systems (Figure 13). Retreat occurred on the Thwaites Glacier and Pine Island Glacier totalling 7,437.10 km^2. The retreat on the Thwaites Glacier was the third greatest area of retreat during the study period. Sea ice advance totalled 4022.93 km^2 and the area of sea icebergs equalled 4,372.18 km^2. Many smaller icebergs were scattered in the bay and this estimate is likely to be overestimated for the same reason, as the estimate for Ellsworth Land. The iceberg in the middle Thwaites Glacier system is most likely to be calved off from the Glacier.

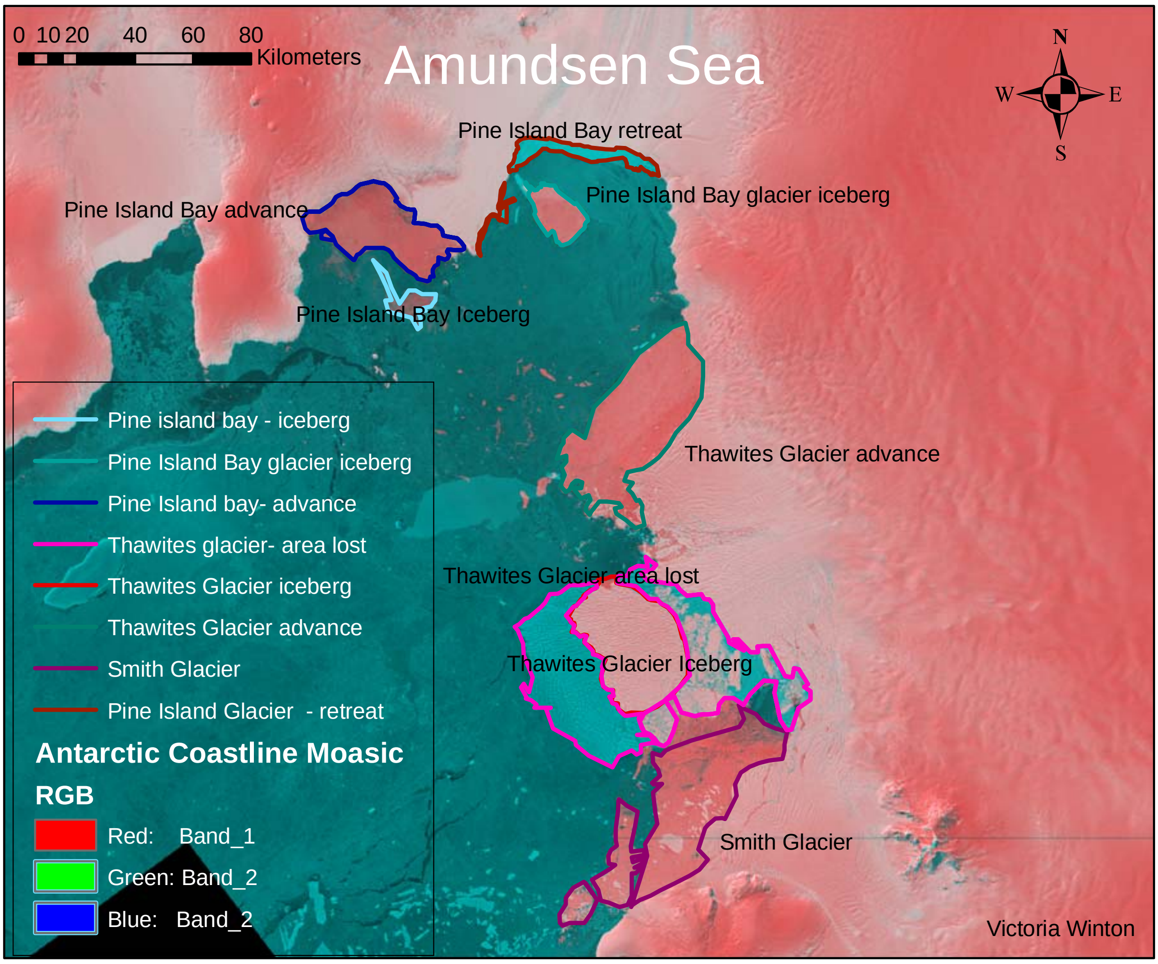


Figure 13: Change around the Amundsen Sea Coastline 1997 to 2001

Marie Byrd Land

Marie Byrd Land was the region with the smallest amount of retreat totalling 91.687 km^2 on the Getz Ice Shelf (Figure 14). However, it was the region with the greatest amount of sea ice advance, totalling 43,768.82 km^2. The iceberg area was 8,297.77 km^2. Again, numbers of these icebergs are likely to be overestimated due to the gaps of sea in the measurements. In Wrigley Gulf, it is clear that many icebergs have floated away or disintegrated since 1997.

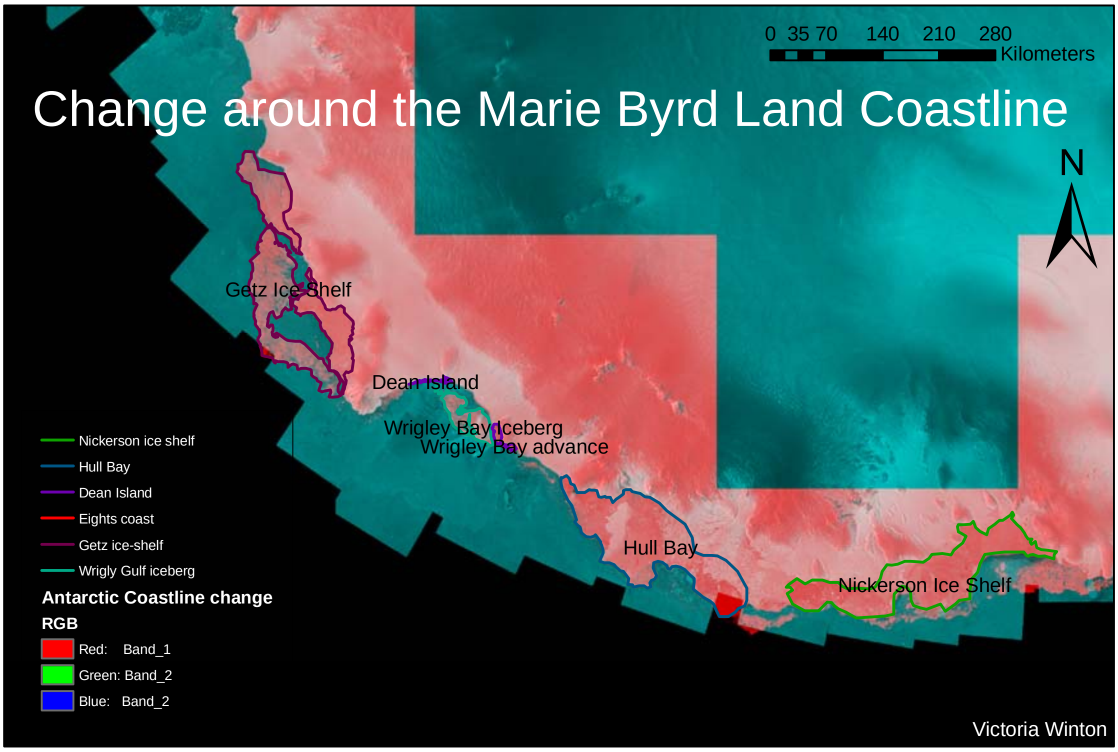


Figure 14: Change around the Marie Byrd Land Coastline 1997 to 2001

Ross Sea Dependency

Recession in the Ross Sea Dependency occurred from the Ross Ice Shelf with an area of 12,360.92 km^2 (Figure 15). This was the second largest area to undergo retreat between 1997 and 2001 in West Antarctica. The Ross Ice Shelf is the largest ice shelf in Antarctica. Sea ice advance was prominent along the Scott Coast equating to 11,292.658 km^2. This sea ice that formed after 1997 is not a new finding; icebreakers have worked their way through this ice cover in recent years. There is a clear disintegration where sea icebergs have calved from the coastline. The icebergs almost fit together like a jigsaw puzzle. Fragments of fast ice have accumulated around gaps in the Drygalski Ice Tongue. Small Sea ice advance (with an area of 15,509.766 km^2) also occurred along the Borchgrevink coastline. There is a clear crack starting to form along the fast ice, which is very likely break off in the near future.

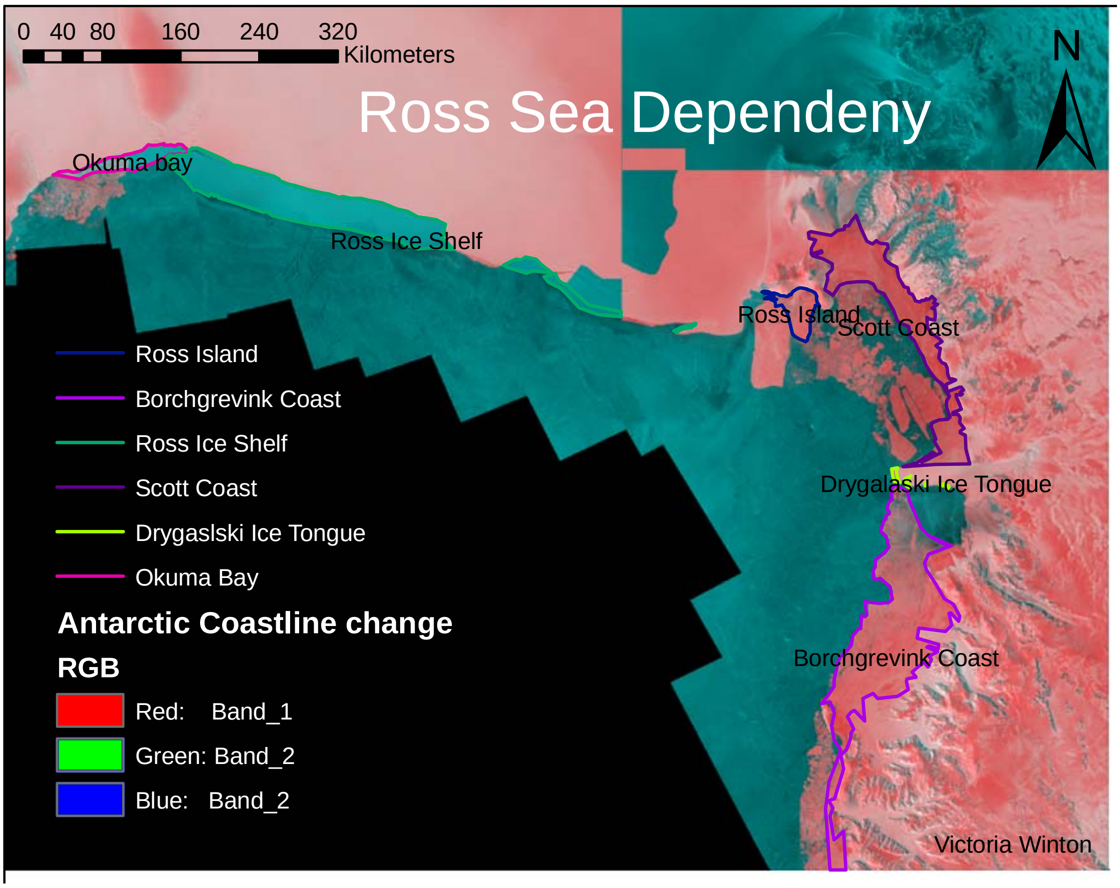


Figure 15: Change around the Ross Sea Dependency Coastline 19997 to 2001

Weddell Sea

The Weddell Sea coastline has been subject to considerable of activity over the four year study period (Figure 16). From the emphasis of the Antarctic Peninsula in the literature, it is expected that the greatest amount of recession would occur in this region over the study period. However, this expectation was defeated as the Ronne Ice Shelf experienced the largest amount of recession (13,029.97 km^2) in West Antarctica between 1997 and 2001. The ice shelf produced icebergs A-43A, A-43B, A-44 and A-38 between 1998 and 2000 (Ferrigano et al. (2005). The only apparent ice shelf advance in the West Antarctic is along the Filchner Ice Shelf and equals 5,428.59 km^2. However, it is not known with certainty whether this is ice shelf advance or sea ice advance. Sea ice advance and smaller icebergs also occurred along the Luitpold Coast, which totalled 3,136.37 km^2. This Figure is likely to be overestimated because the gaps of sea between the icebergs were included in the measurement.

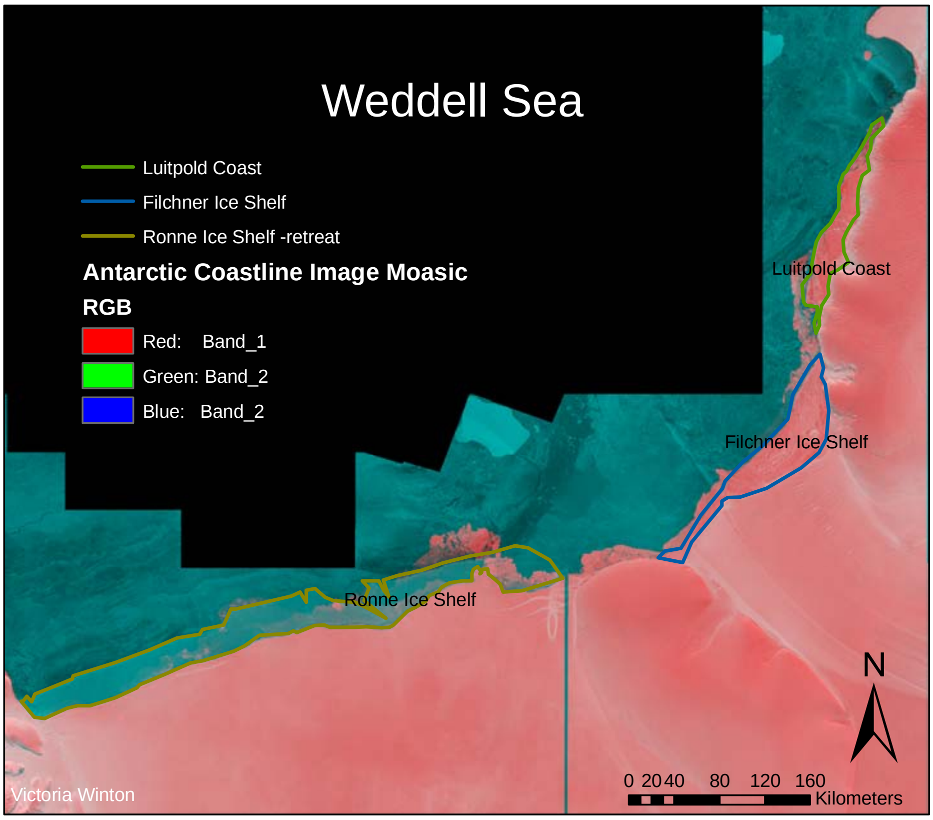


Figure 16: Change around the Weddell Sea Coastline 1997 to 2001

Total change detection

Table 3 summarises the change around the West Antarctic coastline. Ice shelf retreat was the greatest change in extent, followed by sea ice area and iceberg extent (both calved from ice shelves and sea ice). There was a relatively small amount of ice shelf advance on the Filchner Ice Shelf, but there is a probability this may actually be sea ice. The difficulty of separating these two variables is discussed below. These estimates of ice shelf advance and retreat can be used to reduce the uncertainty in mass balance equations.

Table 3: Total Change around the West Antarctic coastline 1997-2001

Total ice shelf retreat	Total ice shelf advance	Sea ice extent	Iceberg extent
37,341.85 km^2	5,428.59 km^2	35,806.78 km^2	20,422.92 km^2

Retreat and climate change

Factors contributing to the polar amplification of climate include; the temperature-albedo feedback associated with the retreat of snow and ice; the breakdown of the shallow but steep near surface temperature inversions; and the trapping of terrestrial radiation by the increased water vapour and cloudiness that accompany this warming (Chapman and Walsh, 1996).

Temperature results show a strong correlation between climate and ice shelf retreat. The temperature trend for all four Antarctic stations is very consistent in Figure 3. Halley Station is used to represent the temperature changes around the Weddell Sea; McMurdo station is used to represent temperature changes around the Ross Sea Dependency; and Rothera and Varaday Stations are used to represent the temperature changes around the Antarctic Peninsula. There is no research station located along the Ellsworth or Maire Byrd Land coastline or the Amundsen Sea coastline. A trendline has been added to the climate graph which highlights the increasing warming trend occurring at these stations. However, this is not indicative of the whole of the Antarctic continent, as only four stations were selected that are geographically in close proximity to areas of significant coastal change. But it is a representative sample for this particular study. The regression value of the trendline is only R^2=0.369. This is not a significant correlation, because the R^2 value is not a good indicator of how well the model fits the data, and the variability of the residual values around the trendline line is too great relative to the overall variability. Yet, between 1997 and 2001 temperature increased by one degree Celsius (Figure 3). This is a considerable change and a large contributing reason behind the 37,341.85 km^2 of ice shelf retreat.

As the climate has warmed in the Antarctic Peninsula region, the melt season duration and extent of ponding have increased (Scambo et al., 2000). Most break up of ice shelf events have occurred during longer melt seasons. Scambo et al. (2000) suggests that this melt water itself and not just the warming that is responsible. Regions that show melting without pond formation are relativity unchanged. Scambo et al. (2000) hypothesises that water filled crevasses are the main mechanism by which ice shelves weaken and retreat. This is evident upon the the LIS on the Antarctic Peninsula. Cracks along the ice front margin on the Ross Ice Shelf are apparent on the two satellite images. Scambo et al.'s (2000) melt water reasoning could well be a force acting on this region as well. The Ross Ice Shelf and the Ronne Ice Shelf are the two largest ice shelves in Antarctic and suffered the largest amount of recession. Smaller ice shelves (Northern Larsen and the Thwaites Glacier system) also experienced significant collapse. A spatial variation is evident with these areas of retreat: the northern LIS is the most northern area of retreat, the Ronne Ice Shelf and the Thwaites Glacier lie approximately on 75°S latitude and the Ross Ice Shelf lies further south at approximately 78°S. The perceptible trend is that change in the coastline is greater the further north the coastline is located. This project combined with other recent work highlights the sensitivity and vulnerability of ice shelves to global warming. The predicted increase in polar precipitation, as a result of climate change (IPCC, 2008), may result in enhanced iceberg calving rates, a process which may be aided by enhanced basal melting.

Sea ice extent

The greatest accumulation of sea ice occurred along the Borchgrevink Coast, closely followed by the Nickerson Ice Shelf, the Scott Coast, the Getz Ice Shelf, the Wilkins Ice Shelf and Hull Bay. The increase in extent of the sea ice from 1997 to 2001 was 35,806.78 km^2. Figure 4 highlights that sea ice anomalies in the Southern Hemisphere increased during the study period and this coincides with the sea ice present in 2001 that was not present in 1997. The Radarsat image was taken in September, which is nearing the end of the winter season and beginning of the summer season. The exact dates of the LIMA (2007) scenes are unknown. It is possible that the increase in sea ice is because of the timing the images were taken.

The rather dramatic warming of one degree Celsius, which is stronger than projected for other parts of the hemisphere, is partly attributed to the temperature-albedo feedback associated with the retreat of snow and ice sea. Many atmosphere-ocean model predictions of amplified polar warming show a substantial retreat of sea ice (Chapman and Walsh, 1993). Chapman and Walsh (1993) argue that there has been no significant trend of sea ice extent in Antarctica during any season over the whole study period between 1973 and 1991. Jacka and Budd (1998) however argue that data extending back to 1945 shows a small significant trend of temperature increase and sea ice cover decrease compatible in magnitude to those expected as a consequence of atmospheric greenhouse gas increase. The seasonal cycle shows a delayed period of autumn-winter sea ice growth with a longer period of open water. They argue that this supports a mechanism for positive feedback between decreasing sea ice cover and increasing temperature.

The absence of a trend (Chapman and Walsh, 1993) or small trend (Jacka and Budd, 1998) or insignificant trend (IPCC, 2008) of sea ice extent reduction appears to be inconsistent with warming trends at Antarctic stations. However, the warming indicated is dominated by measurements taken from coastal stations that are close to the ice edge and ship measurements are unavailable with sufficient coverage to permit meaningful comparisons of sea ice and temperature trends in the Antarctic. A similar trend to that in the Artic, where the sea ice extent is retreating during the summer season, may well be occurring around areas of warming in the Antarctic.

It would be useful to relate the increase of sea ice in 2001 that was not present in 1997 to ship based meteorological measurements taken around the Antarctic Peninsula and the Ross Sea. Moreover, the three-year time difference in LIMA (2007) means that any ice shelves that have retreated and then accumulated with sea ice are not denoted. To overcome this, a series of images with a greater temporal range are needed for continuous and more accurate monitoring of the region.

Limitations

Distortion of the map project:

Unlike a geographical coordinate system, a projected coordinate system has constant lengths, angles and areas across the two dimensions. However, all map projections which represent the earth's surface as a flat map, create distortions in some aspect of distance, area, shape or direction. Even though the Polar Stereographic map projection has been especially designed for the Antarctic, it is still not completely accurate. The central point is the South Pole; the area has a true scale at the centre with distortion increasing with distance.

Use of raster data:

Raster data also has limitations. There can be spatial inaccuracies due to the limits imposed by the dataset cell dimensions. The LIMA (2007) and Radarsat (1997) raster datasets are very large data sets. Resolution increases as the size of the cell decreases, however costs in disc space and processing speeds also increase and this was experienced during the analysis. The LIMA (2007) data was downloaded at the 15 m resolution but had to be resized to 200 m, lowering the accuracy and precision of the data. Moreover, the data contained in each raster cell can only represent one value. If the coastline is in the middle of that cell it is either classed as sea or ice shelf. Using the 200 m resolution pixel size this inaccuracy was likely to be prominent around the coastline.

Difference in imaging techniques:

The LIMA (2007) and Radarsat (1997) images were produced using different imaging techniques. LIMA (2007) is an optical image which essentially takes a photograph of the surface (Figure 17). The sensor is around 800 km in height and looks directly down to the earth's surface. It records reflected radiation form the sun. The whole LIMA (2007) image took two years to complete.

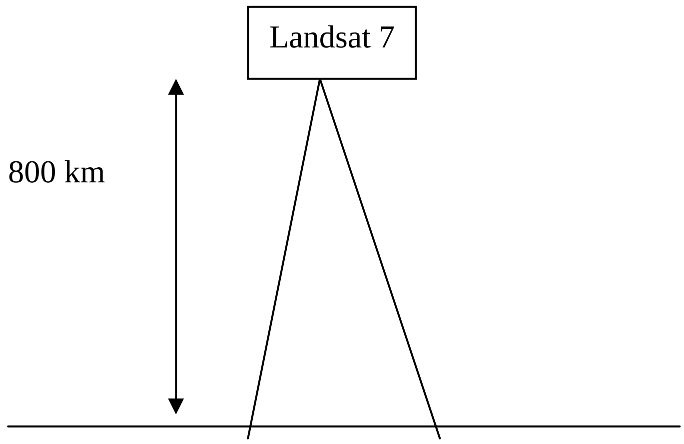


Figure 17: Optical imaging process use in LIMA (2007)

In comparison, the Radarsat (1997) image was acquired using a completely different technique. Synthetic Aperture Radar (SAR) is used (Figure 18). SAR is an active microwave instrument that measures time and power over 100 km. It looks to the side because it has to be unambiguous: elevated features introduce a distortion and have to be orthorectified. In the image bright areas convey high reflective power and dark areas convey low reflective power. Essentially a black and white image is produced. This technique however, has an advantage over optical imaging as it penetrates through cloud cover. The Radarsat (1997) image took 14 days in 1997 to be captured.

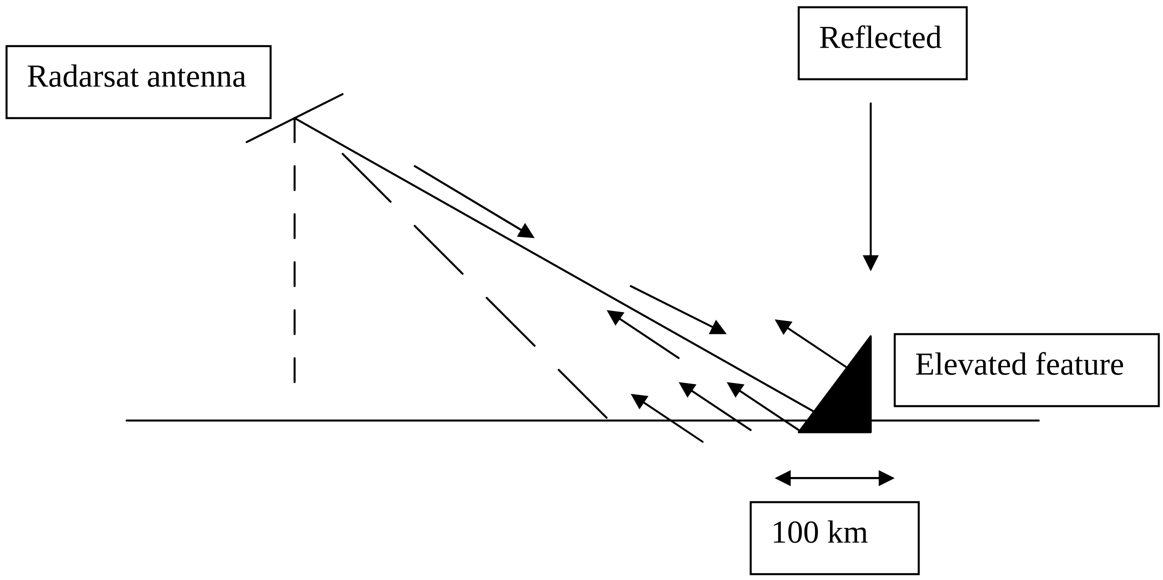


Figure 18: The SAR process used in Radarsat (1997)

These two different techniques affect accuracy when overlaying the images and only ice sheet margins, not elevated features, can be compared using the method in the project. A slight difference in the images can be seen, for example in Figure 11 along the east side of the Antarctic Peninsula where the two images do not overlap exactly. Furthermore, the LIMA images were acquired over a period of two years and much change can take place during this time. The exact date that each scene was taken was unfortunately unable to be obtained.

There are two areas in the mosaic missing LIMA data, one along the Ross Ice Shelf and the other on the bottom west side of the Antarctic Peninsula (Figures 11 and 15). The producers of the map may have not included these scenes because of the presence of cloud cover altering the image pixels. Along the Ross Ice Shelf, this gap in retreat was estimated. Literature suggests that very little exchange along the bottom west of the Antarctic Peninsula occurred during the study period.

Measuring technique and human error:
Uncertainties existed with the measuring technique. Although each area of change was zoomed in, it was very difficult to draw the polyline round the exact area of change. There is potential for human error to occur with free hand. It was also complicated to distinguish the boundaries of some areas, due to the gradual change in colour from blue to red. Moreover, discriminating between sea ice and ice shelf advance was particularly complex. All of the red areas were concluded to be fast ice, but small areas of ice shelf or ice tongue advance are possible within these. The need for field observations to confirm this is essential.

Conclusion

The West Antarctic coastline is extremely dynamic. A large extent of change occurred within four years between 1997 and 2001 and this is attributed to changing climate. The most significant change was recession of the larger ice shelves totalling 37,341.85 km^2. The ice shelves at lower latitudes experienced the greatest retreat. This was most likely because of the increase in melt water and crevassing due to the one degree Celicus temperature increase between 1997 and 2001. The expansion of sea ice was also considerable, equalling 35,806.78 km^2. The extent of icebergs in the area was estimated to be 20,422.92 km^2 in 2001, but this figure is likely to be overestimated. There was no ice shelf advance evident during the study period. The pattern of recession of ice shelves and sea ice extent closely relates to that in the literature. Changes in areal extent of ice shelves are a good indicator of climate change.

Not only does this project further indicate the sensitivity and vulnerability of ice shelves to changes in climate, but also it aids in producing more accurate ablation estimates for mass balance calculations of the AIS through the use of the most up to date satellite imagery. It is exciting to analyse new datasets, such as LIMA (2007). As technology levels continue to advance and imaging techniques become more refined, detection of Antarctic coastline change will become more precise and reflect the changing actions of human activity on the environment through climate change. The degree of change around the coastline echoes the rising temperature trends. What humans do in one region of the world can have severe impacts on other regions of the world.

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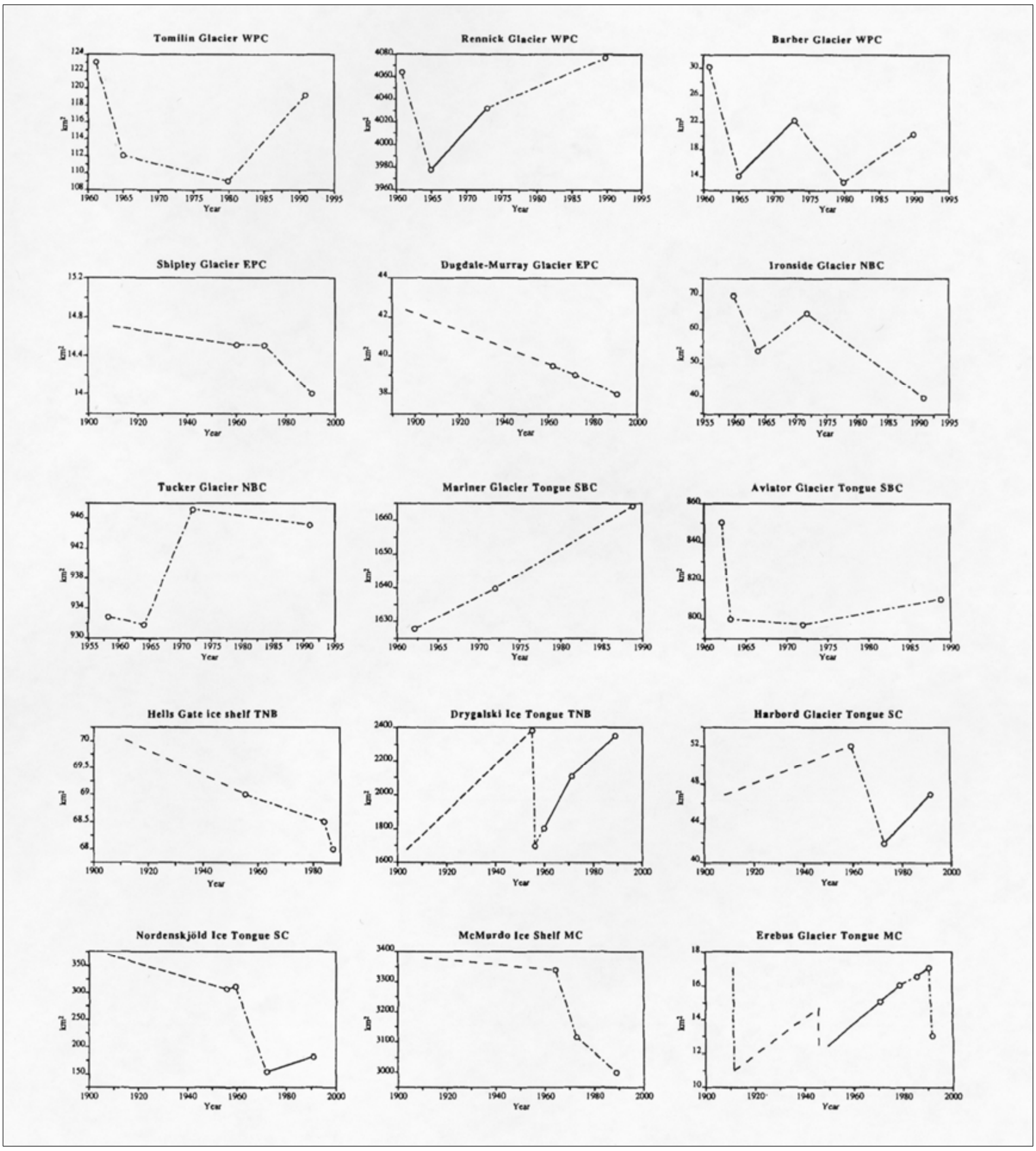
Appendices



Appendix 1: Changes in area of selected floating glaciers with time. WPC is western Pennell Coast, EPC is eastern Pennell Coast, NBC is northern Borchgrevink Coast, SBC is southern Borchgrevink Coast, TNB is Terra Nova bay, SC is Scott Coast, MC is McMurdo Sound. Dashed line is uncertain variation, dashed and doted line is variation with iceberg calving, solid line is increase area without important calving events. Source: Frezzotti (1997)

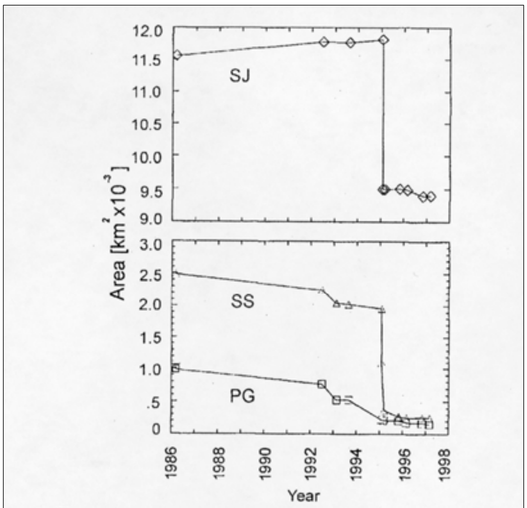
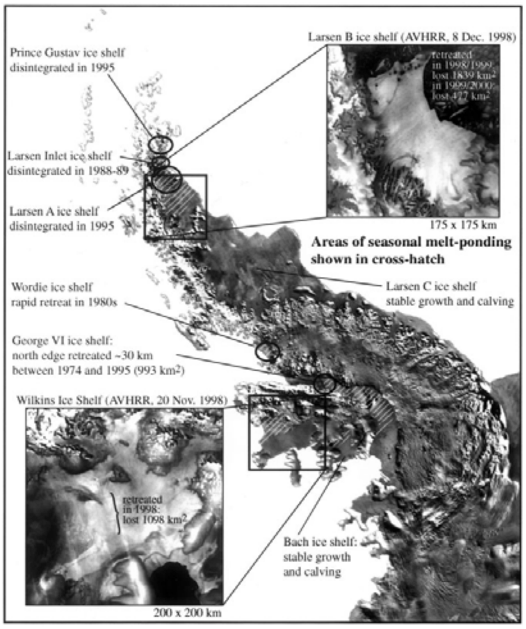


Fig. 2: Areal Changes of the ice shelf section SJ (◇), SS (△) and PG (□) from 1 March 1986 to 2 March 1997.

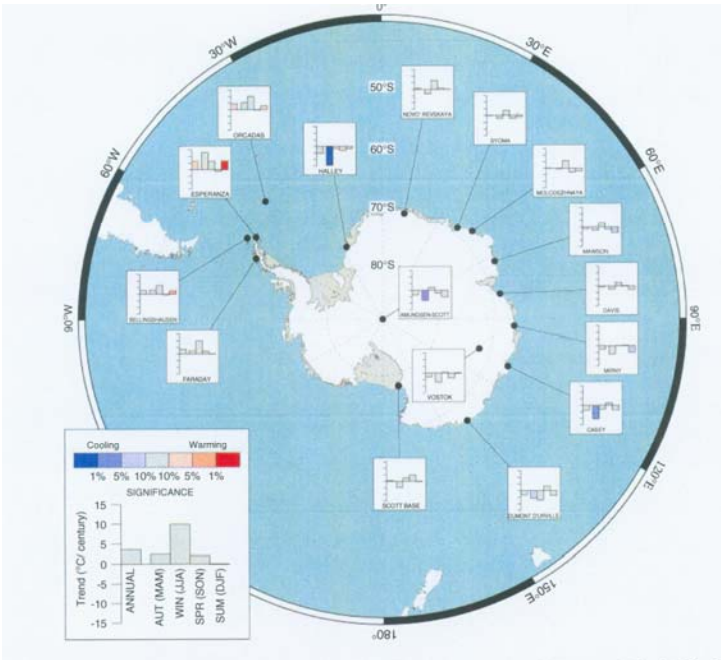
Appendix 2: Areal changes of the ice shelf sections the section between the seal nunataks and the Jason Peninsula (SJ), the section between the Seal Nunataks and Sorbal Peninsula (SS) and Prince Gustav Channel (PG) from march 1 1986 to march 1997. Source: Rack et al. (1998)

Date	*Area* km^2	*Date*	*Area* km^2
29 August 1963	10 936	30 January 1995	9496
3 October 1975	11 329	8 March 1995	9496
1 March 1986	11 560	28 October 1995	9501
19 January 1988	11 628	29 February 1996	9483
8 January 1990	11 695	1 November 1996	9391
2 July 1992	11 775	2 March 1997	9397
26 August 1993	11 770	4 July 1997	9406
28 January 1995	11 816	25 April 1998	9326

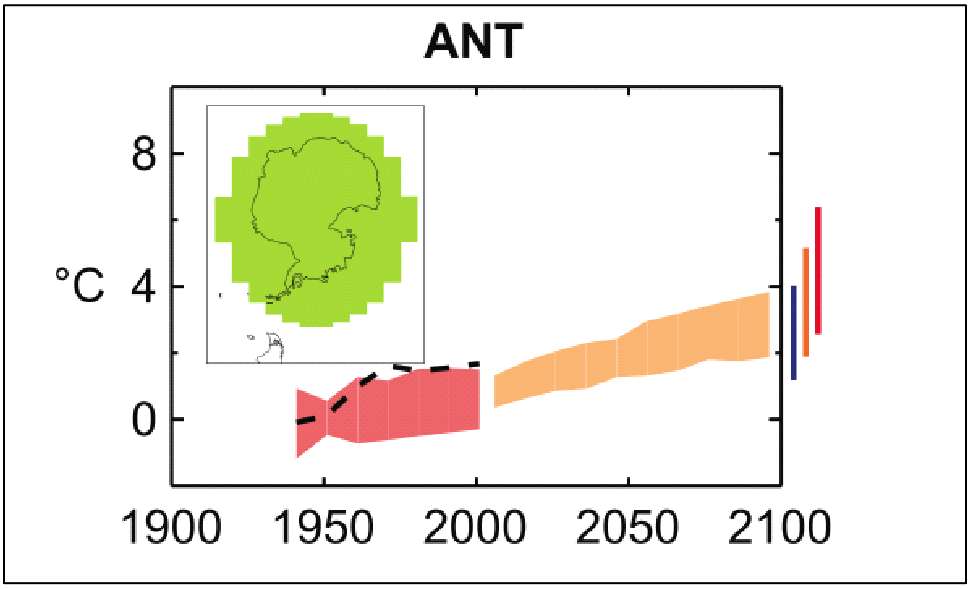
Appendix 3: Areal extent of Larsen B at different dates. Source Skvarca et al. (1999)



Appendix 4: Overview of the Antarctic Peninsula summarising ice shelf activity and its correlation with areas of melt ponding. The base of the image of the Peninsula is an AVHRR mosaic complied from scenes acquired between 1980-1994. Source: Scambo et al. (2000)



Appendix 5: Antarctic near surface temperature trends for 1971-2000. Source: Turner at al. (2005)



Appendix 6: Temperature anomalies with respect to 1951 to 2000 for the whole Antarctic for 1936 to 2005 (black line) as simulated (red envelope) by MMD models incorporating known forcing; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are present for less than 50% of the area in the decade concerned. Source IPCC (2008)