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Monitoring the Amery Ice Shelf front during 2004−2012 using ENVISAT ASAR data

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Abstract The Amery Ice Shelf is the largest ice shelf in East Antarctica. It drains continental ice from an area of more than one million square kilometres through a section of coastline that represents approximately 2% of the total circumference of the Antarctic continent. In this study, we used a time series of ENVISAT ASAR images from 2004–2012 and flow lines derived from surface velocity data to monitor the changes in 12 tributaries of the Amery Ice Shelf front. The results show that the Amery Ice Shelf has been expanding and that the rates of expansion differ across the shelf. The highest average annual rate of advance from 2004–2012 was 3.36 $m \cdot d^{-1}$ and the lowest rate was 1.65 $m \cdot d^{-1}$. The rates in 2009 and 2010 were generally lower than those in other years. There was a low correlation between the rate of expansion and the atmospheric temperature recorded at a nearby research station, however the mechanism of the relationship was complex. This study shows that the expansion of the Amery Ice Shelf is slowing down, reflecting a changing trend in climate and ice conditions in East Antarctica.

Keywords **Amery Ice Shelf, change detection, ENVISAT ASAR, coastline detection, Antarctica**

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1 Introduction

The Antarctic ice sheet holds approximately 90% of the world's ice so even a small imbalance between snowfall and the discharge of ice and melt water into the ocean could significantly alter global sea level[1]. Antarctic ice shelves are important components of ice sheets because of the ice-ocean-atmosphere interface and vulnerability to regional and global changes in atmospheric and oceanic temperatures[2-4]. Ice shelves are more sensitive to climate change than ground-based ice sheets or continental glaciers. Many studies have been conducted to estimate the mass balance of the entire Antarctic ice sheet[5-7] and individual drainage systems[8-9]. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change suggests that mass losses from the Antarctic ice sheet have contributed to sea-level rise over the past 30 years. However, there is still much uncertainty about the magnitude of mass loss and the related sea-level rise. Studies of Antarctic ice sheet mass balance are increasingly important in the context of global warming[10]. Most of the mass loss from the Antarctic ice sheet occurs at the ice shelves as a result of iceberg calving (break-off of icebergs from the ice shelf) or basal melting (melting of ice at the bottom of the ice shelf as a consequence of warmer ocean temperatures or increased pressure)[11-12]. Understanding the dynamics of ice shelves and their interaction with the ocean is therefore fundamentally important for predicting the contribution of the Antarctic ice sheet to future global sea-level rise[13].

The Lambert Glacier—Amery Ice Shelf system is the

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Earth's largest glacier system. Approximately 16% of the ice in this region of the Antarctic continent drains through the Amery Ice Shelf[14-15]. The Amery is a broad ice shelf located at the head of Prydz Bay, between the Lars Christensen Coast and the Ingrid Christensen Coast (Figure 1)[16]. It is the third largest embayed ice shelf in Antarctica, and it forms the floating portion of the Lambert Glacier system, a system that drains continental ice from an area of about 1 380 000 km^2 through a section of coastline that represents approximately 2% of the total circumference of the Antarctic continent[17-18]. The main tributary glaciers that flow into the Amery Ice Shelf near the grounding line are, from east to west, the Lambert, the Mellor, and the Fisher Glaciers (Figure 1)[19]. The Charybdis Glacier joins the western part of the ice shelf downstream of Jetty Peninsula.

To better understand the complex process of ice shelf mass balance, and to interpret the interactions between the atmosphere, oceans, and ice, it is necessary to monitor ice shelf dynamics over an extended period of time.

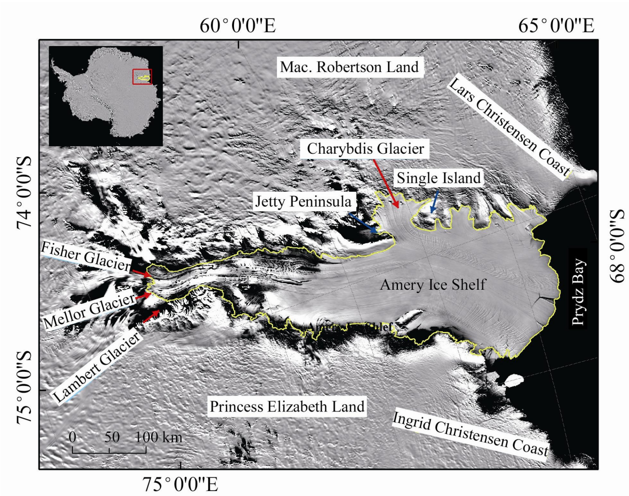

Figure 1 Location map of the Amery Ice Shelf in East Antarctica, with major ice flows indicated by solid red arrows, and key features annotated. The yellow line is the outline of the Amery Ice Shelf. The background image is the MODIS Mosaic of Antarctica (MOA) image map derived from composites of 260 MODIS orbit swaths acquired between 20 November 2003 and 29 February 2004. MOA data was downloaded from the NSIDC.

2 Data and methods

2.1 Data

Satellite remote sensing has played an important role in the advancement of polar science by enabling the systematic collection of data across broad temporal and spatial scales. In particular, remote sensing technology is not limited by weather or darkness, therefore it can be used to monitor changes in the Amery Ice Shelf front over long time periods. Antarctic sea ice peaks in September (at the end of the austral winter) and retreats to a minimum in February, therefore we used ENVISAT ASAR images acquired in February each year from 2004–2012 for this research.

ENVISAT is an earth-observation satellite that operated from 2002–2012. ENVISAT was launched to contribute to the continuity of European Remote-Sensing Satellite missions, providing additional observational parameters to improve environmental studies. ENVISAT orbited the Earth in about 101 min with a repeat cycle of 35 d, and it covered the study area consistently and reliably. The Advanced Synthetic Aperture Radar (ASAR) on board ENVISAT, operating at C-band, ensured continuity with Synthetic Aperture Radar (SAR) imaging and the European Remote Sensing-1/2 Active Microwave Instrument (ERS-1/2 AMI) wave mode mission. It featured enhanced capability in terms of coverage, range of incidence angles, polarization, and modes of operation.

For this study, we selected Wide Swath Mode (WSM) image data with a width of approximately 3.6 km over the Amery Ice Shelf front (Figure 2). The WSM data enabled coverage of the ice shelf front in one scene, and avoided the errors caused by mosaicking different scenes acquired on different days. With the ENVISAT ASAR sensor, the wide-swath observation mode could cover a maximum width of about 400 km.

The Amery Ice Shelf is composed of several longitudinal portions fed by surrounding tributary ice sheets. The different portions move at different velocities, therefore it is possible to divide the ice shelf into several tributaries using surface velocity data. The latest surface velocity data was downloaded from the National Snow and Ice Data Center (NSIDC) and provided by Rignot et al.[20].

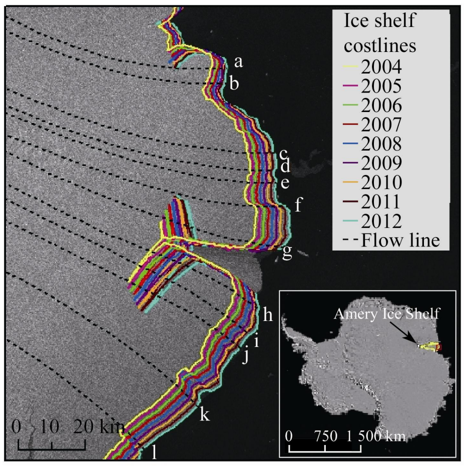

Figure 2 The Amery Ice Shelf front and the 12 tributaries shown in an ENVISAT ASAR image acquired on 17 February 2012. The solid colored lines are the derived coastlines of the ice shelf front for each year of the study period.

2.2 Methods

The ASAR images were processed with precise orbits and geometric correction using ENVI 4.7 software following the flowchart shown in Figure 3, and the registration accuracy was estimated to be within one pixel (75 m). Each image was linearly stretched to enhance the quality and then filtered according to an efficient image denoising scheme using principal component analysis (PCA) with local pixel grouping (LPG)[21]. We then extracted the coastlines semi-automatically by combining an artificial drawing method with an improved watershed algorithm[22]. The 12 tributaries were determined according to the ice flow lines derived from surface velocity data. We then calculated the displacement differences for pairs of consecutive years in each test area along the ice flow lines.

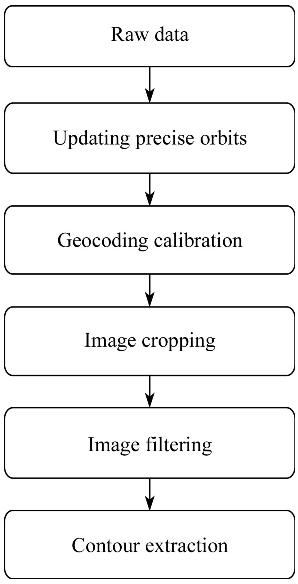

Figure 3 ENVISAT ASAR data processing flowchart.

3 Results and discussion

The results presented in Figure 4 show that the Amery Ice Shelf has been expanding and that it advanced approximately 8.142 km from 2004–2012. The average annual rate of advance was 2.79 $m\cdot d^{-1}$, and the rates were different at different locations (Figures 4c, 4d). Among the 12 tributaries, the highest average rate of advance was 3.36 $m\cdot d^{-1}$ and the lowest rate was 1.65 $m\cdot d^{-1}$. The rate of advance in the middle portion of the Amery Ice Shelf front was higher than that on both sides of the ice shelf front (Figures 4c, 4d). The ice shelf is in contact with both the atmosphere and the ocean, therefore many environmental forces could affect the surface ice flow rate, in addition to the glaciological stress caused by gravitational spreading of the ice[23]. Furthermore, the presence of glaciers and exposed rocks on both sides of the Amery Ice Shelf will exert a drag force that could block forward ice flow. The rates of advance for tributaries c, d, and e were lower than the rate for tributary f (Figures 4c, 4d). This finding could be explained by blockage of the thick marine ice band beneath the ice shelf. According to Fricker et al.[24], the thickest marine ice in the Amery Ice Shelf occurs in two longitudinal bands, oriented along the direction of the ice flow. These bands are located each side of the Charybdis Glacier inflow where this stream merges with the Amery Ice Shelf downstream of Jetty Peninsula, and with an unnamed stream north of Single Island (Figure 1). The different terrain, the basal melting and refreezing rate, and the distribution of crevasses and rifts in the ice flow route may also influence the ice spread.

The distance and rate of advance of the Amery Ice Shelf front followed a decreasing trend over our study period (Figures 4a, 4b). King et al.[25] also found a net slowing of about 0.6% for the Amery Ice Shelf during the periods 1968–1970 and 1988–1999. The main contributions of ice to the ice shelf are flow from the ice sheet, snow accumulation, and refreezing at the bottom of the ice shelf. Mass loss is mainly a result of iceberg calving, basal melting, surface runoff, and surface ablation. Of the factors potentially affecting the rate of advance of the Amery Ice Shelf, accumulation rates over the shelf have been increasing since the 1980s[26-27]. The ice shelf elevation increased from 1992–2003[28-29], but little is known about the change in thickness of the shelf over the same period. Wen et al.[30] calculated the spatial distribution of basal melting and freezing rates beneath the Amery Ice Shelf, and we noted that the Amery Ice Shelf front is located in a freezing zone. Atmospheric temperatures have not changed significantly in this region over the past 50 years[31], implying little change in surface melt rates in the long term. Further investigation is therefore required to determine the mechanism of ice shelf velocity change.

The rates of advance for the 12 tributaries during 2009 and 2010 were generally lower than those in other periods. Changes in atmospheric temperatures will influence surface accumulation and sea ice distribution, which could alter seawater salinity and ocean circulation beneath the Amery Ice Shelf. In addition to changes in atmospheric temperature, snowfall, wind, tidal effects, and ocean currents might also affect the expansion of the ice shelf.

More data, including meteorological data, ocean data, and ice flow data, are needed to simulate and analyze changes in the ice shelf.

4 Conclusions

Remote sensing enables the measurement and monitoring of elements of the cryosphere on a continuous basis, and with broader spatial coverage than field or *in situ* measurements. The WSM of ENVISAT ASAR data is a high-resolution mode with a wide swath, and just one scene provided full coverage of the study area, helping to avoid the errors caused by the use of image mosaics. A disadvantage of relatively low-resolution coverage of 150 m is that some tiny rifts, equal to or less than 150 m in width, cannot necessarily be extracted automatically by detection algorithms. By detecting and analyzing the changes of the Amery Ice Shelf front accurately derived from the ENVISAT ASAR data for 2004–2012, we found that the Amery Ice Shelf has been expanding, with a highest annual rate of advance of 3.36 $m\cdot d^{-1}$ and a lowest rate of 1.65 $m\cdot d^{-1}$. If large iceberg calving events occur in the future, there would be more mass loss in the Lambert Glacier—Amery Ice Shelf system, which could accelerate global sea-level rise.

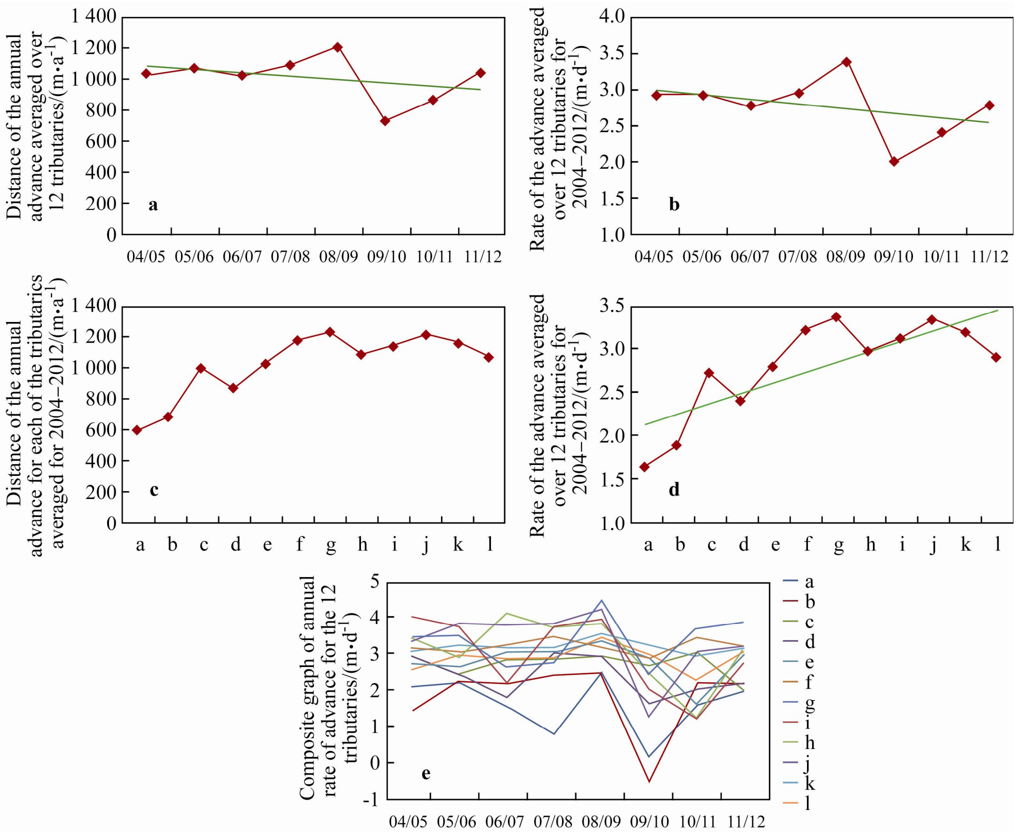

Figure 4 Distance of the annual advance of the ice shelf (**a**) and rate of advance averaged over 12 tributaries in the Amery Ice Shelf for 2004–2012 (**b**), distance of annual advance (**c**) and rate of advance for each of the 12 tributaries (a–l) averaged for 2004–2012 (**d**), composite graph of annual rate of advance for the 12 tributaries (**e**). The green line is the linear trend line.

The rate of expansion of the Amery Ice Shelf front followed a downward trend over our study period, similar to the trend in surface temperature change. To simulate the changes of the ice shelf front quantitatively, and to precisely model the ice shelf, more information on environmental forces from atmospheric and oceanic data is required. This would enable a better understanding of the ice—ocean—atmosphere system underlying the dynamics of the Amery Ice Shelf.

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