INTERMITTENT AND VARIABLE RIFT PROPAGATION RATES IN THE AMERY AND RONNE ICE SHELVES, 2002-2012

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Abstract

Although Antarctic ice shelves are potentially good indicators of climate change, little is currently known about the underlying mechanisms causing their rifting and breakup. I used hundreds of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images to observe five rifts in the Amery Ice Shelf and two rifts in the Ronne Ice Shelf in Antarctica from 2002-2012. I measured the lengths of these rifts over time to discover that although most of the rifts were actively propagating during this time series, the rift propagation rates vary between rifts in the same ice shelf as well as between ice shelves. The differences in rift propagation rate indicate that a single environmental factor is not the driving force behind rift propagation, although sea ice concentration seems to inversely correlate with rift propagation of at least one rift in the Amery Ice Shelf. The propagation of one rift may impact the propagation of another in the same ice shelf, as internal stress within the ice seems to be an important factor regarding rift propagation. Interestingly, one rift changes direction to propagate parallel to a suture zone joining two flow bands, then curves to rift across the suture zone, indicating the importance of internal ice shelf stress. Overall, more long-term monitoring of rift propagation and local environmental conditions is needed to determine the ultimate cause of rift propagation.

Introduction

The disintegration and retreat of Antarctic ice shelves has been of significant interest to those who study global climate change (Skvarca, Rack, Rott, & Ibarzábal, 1999). Ice shelves are the seaward extensions of ice sheets, protruding off the coast and floating on the surface of the ocean. The surface of an ice shelf remains in contact with the atmosphere while the bottom is in contact with the ocean. The large surface area exposed to both air and water has been hypothesized to make ice shelves more susceptible to changes in oceanic and atmospheric temperatures, suggesting that the breakup of ice shelves could be an early indicator of increased global temperatures (Doake and Vaughan, 1991). In particular, the catastrophic breakup of the Larsen B ice shelf over just six weeks in 2002 provides strong evidence that ice shelves are not only sensitive to climate change, but may respond much faster than previously thought as a series of very warm summers in the 1990s was closely followed by ice shelf disintegration events in 1995 and 2002 (Scambos *et al*., 2003).

However, little is currently known about the actual mechanisms of the calving (breaking-off) of icebergs—there is not much evidence at present to say that increased calving is solely the result of increased atmospheric temperatures. Iceberg calving is preceded by the rifting of ice shelves (a rift being defined here as a crevasse or crack that severs the entire ice shelf thickness). As the ice flows toward the ocean, these rifts become the boundaries at which icebergs separate from their parent ice shelf (Joughin & MacAyeal, 2005). The rifting of ice shelves and calving of icebergs may be the cumulative result of many environmental factors, and more research into this topic can help clarify the role of ice shelves as climate change indicators, as little is known about the background rate of rift propagation when bergs are not separating.

Previous studies have examined some of the potential influences of environmental conditions on ice shelf rift propagation. For example, Bassis, Fricker, Coleman, & Minster (2008) studied the Amery Ice Shelf (AIS) in East Antarctica. In three field seasons from 2002/03 to 2005/06, they observed wind speed, ocean swell, and atmospheric temperature to see if any of these environmental factors correlated with rift propagation. They concluded that none of these factors had significant impacts on the rift propagation rate in the ice shelf. The most important aspect appeared to be internal stress within the ice. However, their results did suggest that environmental factors may become more important as the time at which an iceberg calves approaches. It is important to note that this study observed only two rifts in one ice shelf over the course of three summer seasons. Due to the limited nature of the data, it is difficult to extrapolate these conclusions to all Antarctic rift systems.

Furthermore, a study of the AIS by Fricker, Young, Coleman, Bassis, & Minster (2005) indicates that there may be a relationship between rifting rates and season; the rifts propagated faster in the summer (September—April) than in the winter (April—September). Whether this change in propagation rate was due to changes in the temperature of oceanic currents under the ice shelf, the thawing and freezing of ice mélange (the broken fragments of ice and fallen snow which fill the rifts), or other factors is uncertain.

Both of these studies have focused on one rift system within the AIS. Though they can provide some insights, a more comprehensive study comparing several rifts in the same ice shelf and comparing ice shelves in different parts of Antarctica over a longer time period may demonstrate whether or not environmental factors are influencing the rate of rift propagation. This study furthers previous work by examining the propagation rates of five rifts in the AIS and two rifts in the Ronne Ice Shelf (RIS) over the course of a decade by measuring the rifts in hundreds of satellite images taken in the summers of 2002—early 2012.

Methods

I analyzed MODIS satellite images of five rifts in the AIS and two rifts in the RIS from the summers of 2002 to early 2012 (Fig. 1). Images were from the Austral summer as the imagery relies on visible solar radiation that is absent during the Austral winter. The images used in this study are archived at nsidc.org, the website for the National Snow and Ice Data Center sponsored by the University of Colorado. Images were selected based on the visibility of the rifts. Using Adobe Photoshop CS5, the images were adjusted for contrast and brightness to

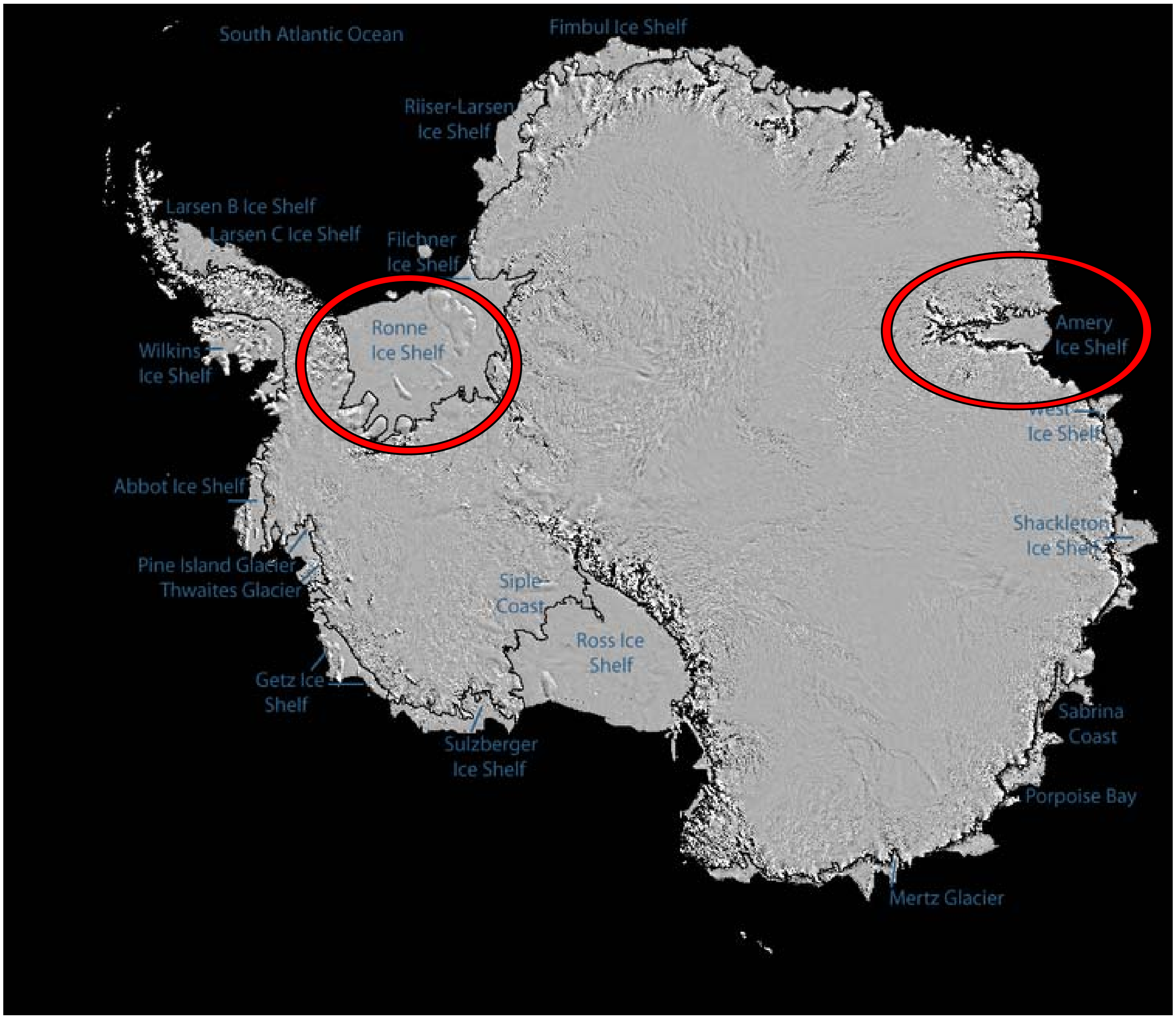

Fig. 1: Map of Antarctic Ice Shelves, with the two ice shelves observed in this study circled in red. The Amery Ice Shelf (AIS) is located in East Antarctica, whereas the Ronne Ice Shelf (RIS) is located in West Antarctica. *Images of Antarctic Ice Shelves,* nsidc.org

enhance the visibility of the rift tip. To measure rift length, I used Photoshop to count the number of pixels that make up each rift, with each pixel being equal to 250 meters. I measured down the center of each rift from the rift origination to the rift tip, defined here as the pixel at which the rift could no longer be distinguished from the background ice shelf. As ice flows, some of the rifts become distorted. To compensate for these changes, I divided the rifts into segments to examine changes in the integrated segment lengths over time.

Five rifts across the AIS were examined (Fig. 2). Of these rifts, two were longitudinal (parallel-to-flow) rifts on the western edge of the AIS, and are named W1 and W2. Rifts were present in these locations in 2002 in the earliest MODIS images, but they later were undetectable as the front of the ice shelf broke apart in that locale. I measured two rifts that reformed in the same locations in 2006 (W1) and 2005 (W2). I analyzed W1 in sixty-six clear images from October 3, 2006 to January 1, 2012, and I measured W2 in seventy-seven images from October 3, 2005 to January 1, 2012. A third longitudinal rift was examined on the eastern edge of the AIS, to be referred to as E1. I measured rift E1 in 106 images spanning November 28, 2002 to January 1, 2012. The other two rifts are transverse (perpendicular-to-flow), and constitute part of the same rift system at the center of the AIS front. This system consists of a longitudinal rift, which stopped propagating and split into two transverse rifts, T1 and T2. I analyzed 118 clear images of T1 and T2 from March 9, 2002 to December 20, 2011, which cover nine and a half field seasons. T1 and T2 comprise the rift system examined by Bassis *et al.* (2008) and Fricker *et al.* (2005).

The examined rifts in the RIS consist of two rift systems (Fig. 3). The first system is located at the center of the RIS front and consists of two longitudinal rifts. The western rift (RW) is propagating, and I measured it according to the same standards as the rifts in the AIS. I analyzed forty images of RW from December 3, 2002 to December 21, 2011. The eastern rift in this system had already turned and intersected with the first rift and was not actively propagating during the measurable time period. I measured another rift at the eastern margin of the RIS (RE). Though the eastern margin of the RIS contains a rift system which includes several small rifts, only the major component (RE) was measured. I measured RE in thirty-five satellite images during the same time period as RW. Even though available images of RW and RE covered the same number of field seasons as those of T1 and T2, I measured fewer images of the

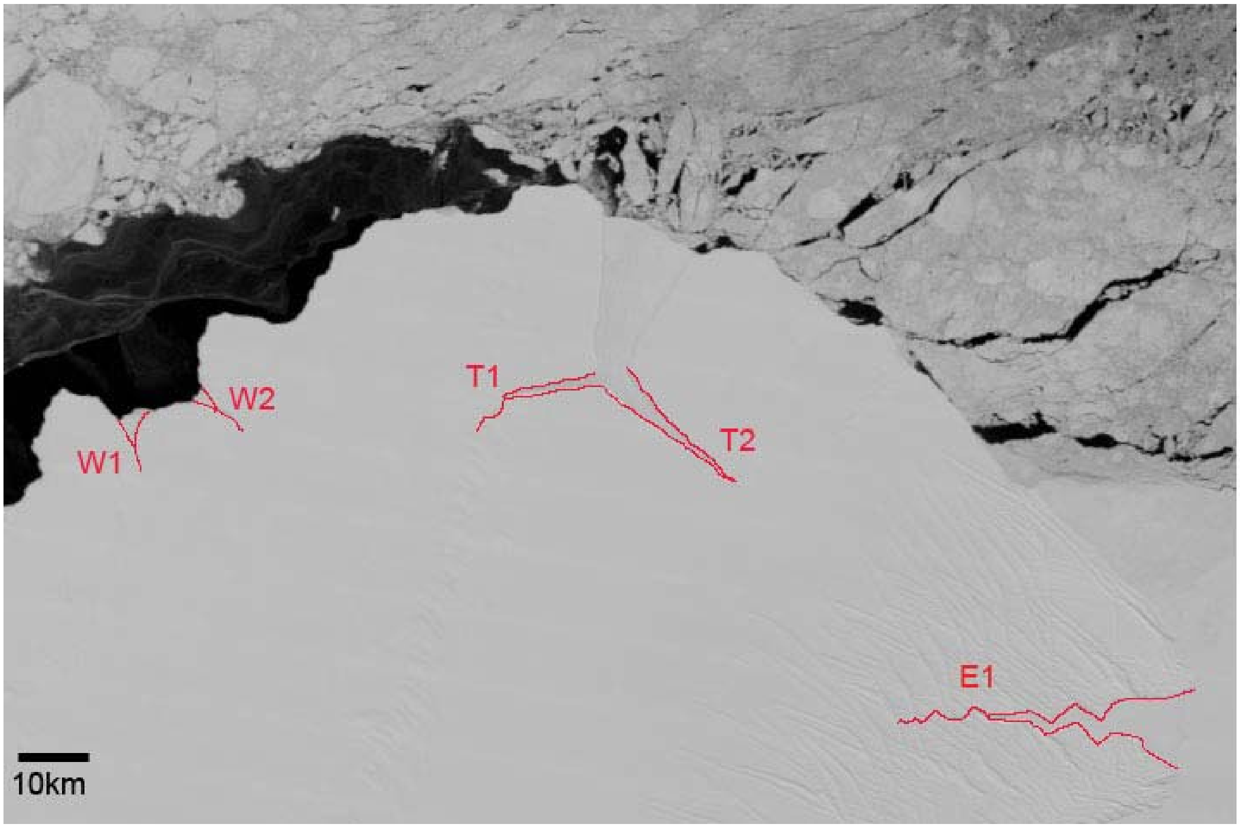

Fig. 2: Diagram of the rifts examined in the Amery Ice Shelf, highlighted in red. From left to right: W1, W2, T1, T2, and E1. MODIS *Images of Antarctic Ice Shelves*, November 21, 2011.

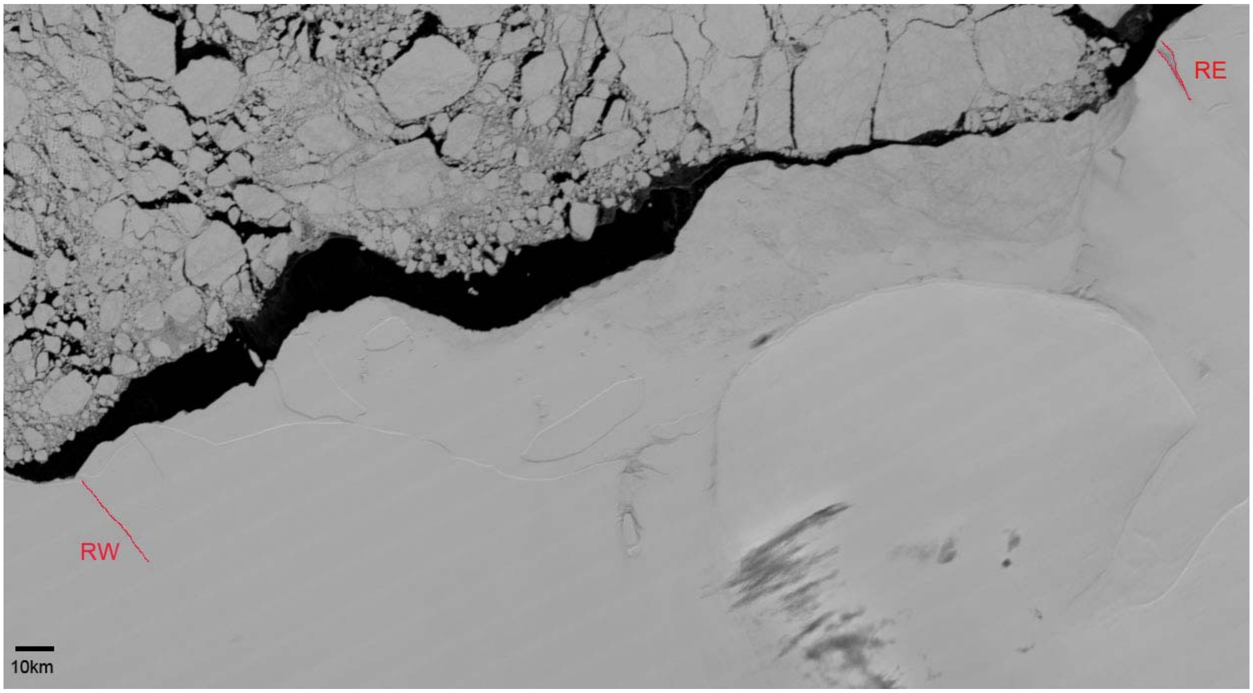

Fig. 3: Diagram of the rifts examined in the Ronne Ice Shelf, highlighted in red. From left to right: RW and RE. MODIS *Images of Antarctic Ice Shelves*, December 21, 2011.

rifts in the RIS because these satellite images had noticeably more cloud cover which blocked the rifts from view.

The satellite imagery provides a time series of rift length as a function of time. Plotting rift length versus time and calculating the slopes of these lines yields $^{dL}/_{dt}$, the change in rift length over time, or rift propagation rate. Understanding the speed at which rifts propagate and what conditions affect rift propagation rate will help clarify the role of iceberg calving as a possible indicator of climate change.

Results

The images reveal that each of the examined rifts in the AIS and the RIS lengthened over the course of the time series, with perhaps the exception of W2 (Table 1; Figs. 4 & 5). The rates of rift propagation varied drastically among the rifts and over the course of a decade (Fig. 6; Table 2). W2 did not lengthen much over the time series, with an overall rift propagation rate of -0.1±0.2 meters day^{-1}. W1 was propagating rather quickly in the 2006/07 season (14.5±0.4 meters day^{-1}), but it slowed propagation drastically such that negligible propagation occurred between 2008 and 2012. T2 was rifting at an intermediate rate in 2002/03 (8.3±0.4 meters day^{-1}) but decelerated in the following season until 2004/05 when it appeared to have completely arrested. It resumed propagation in 2005/06 but again slowed to a near halt in the years from

Table 1: Length of each rift at the beginning and end of the time series (km)

Rift	**W1**	**W2**	**T1**	**T2**	**E1**	**RW**	**RE**
Rift length at beginning of time series (km)	3.6	10.5	4.6	15.7	33.0	15.1	7.3
Rift length at end of time series (km)	7.8	10.7	18.2	22.6	47.5	27.9	17.0

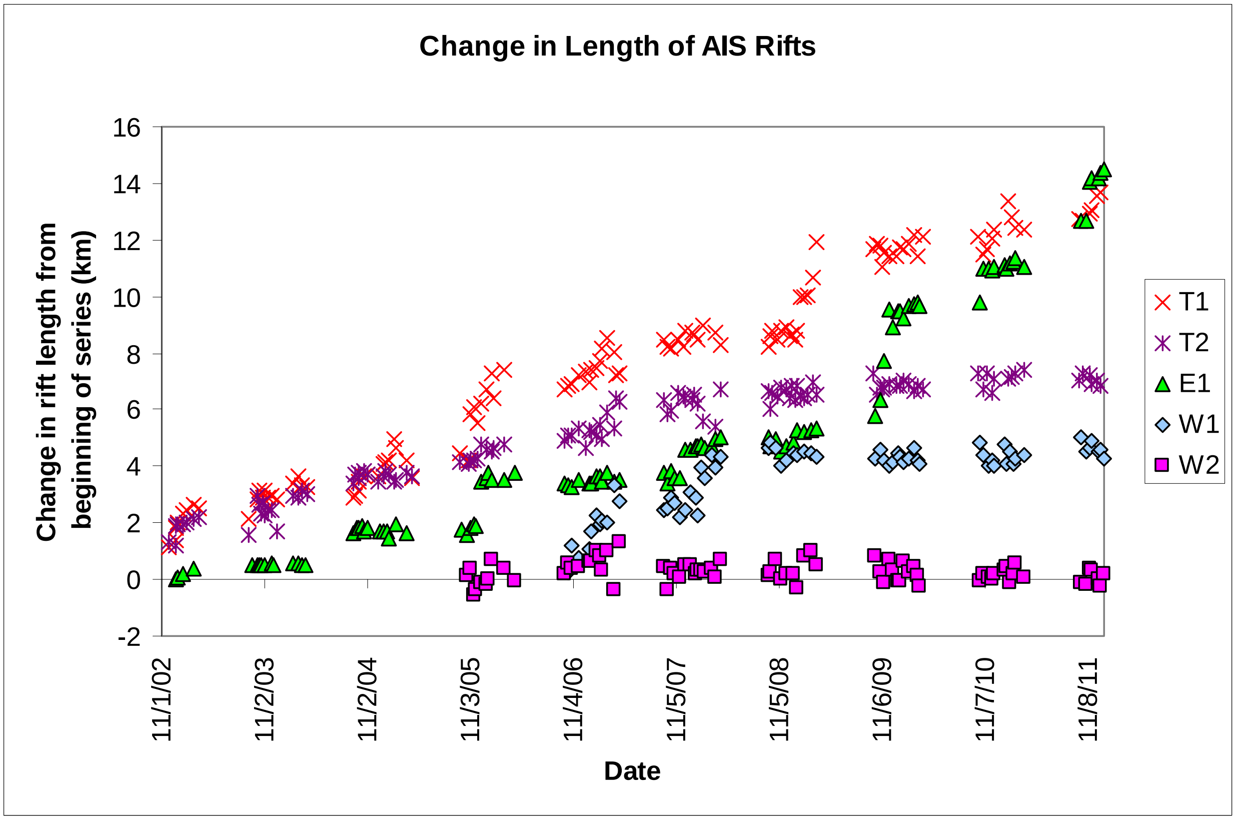

Fig. 4: Change in length of each rift in the AIS over the course of the time series. Calculated by subtracting the length of the rift at the beginning of the time series from the length of the rift on the day measured.

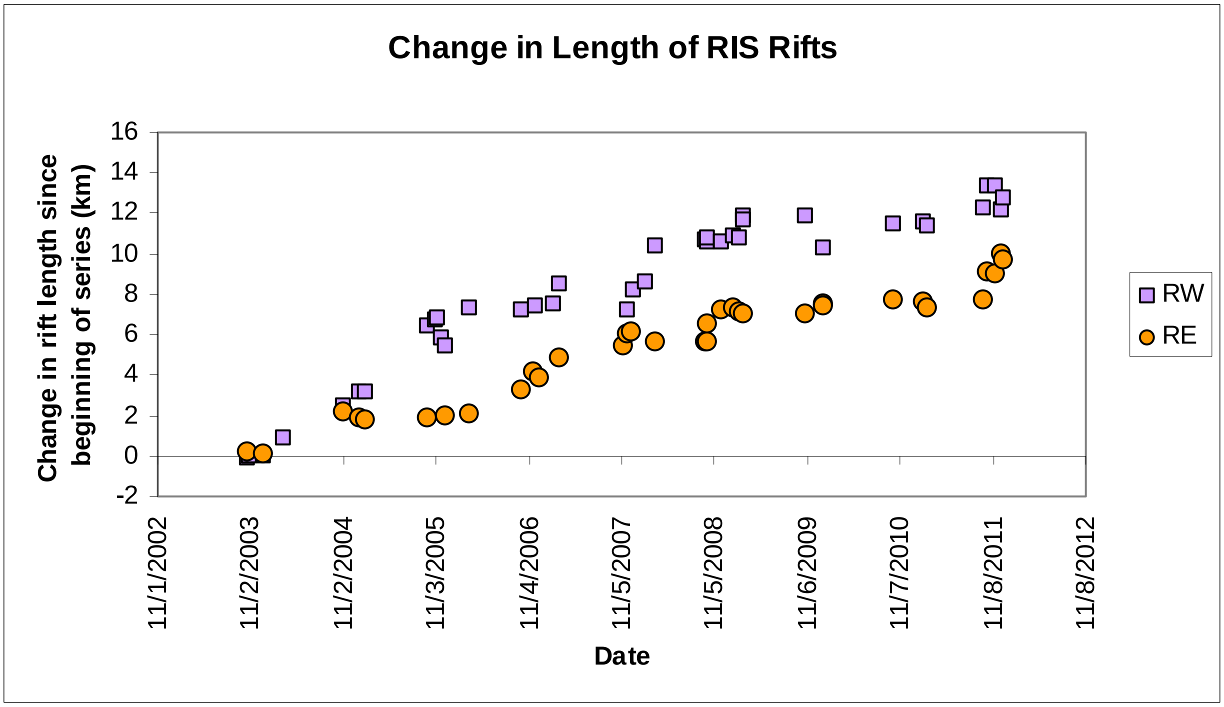

Fig. 5: Change in length of the two rifts in the RIS over the course of the time series.

2007-2010. T2 began propagating again in 2010/11 and increased rift propagation rate in 2011/12. T1 and E1 show correlated rates of propagation early in the time series, being relatively high in 2002/03 (13.5±0.4 meters day^{-1} and 5.0±0.5 meters day^{-1}, respectively), slowing down in 2003/04 and then suddenly spiking in the 2005/06 season (19.6±0.4 meters day^{-1} and 13.9±0.4 meters day^{-1}). In 2006/07, both rifts decrease in rift propagation rate once again, but after that, the correlation seems to dissolve as T1 continues to slow down and as E1 increases its rate of propagation.

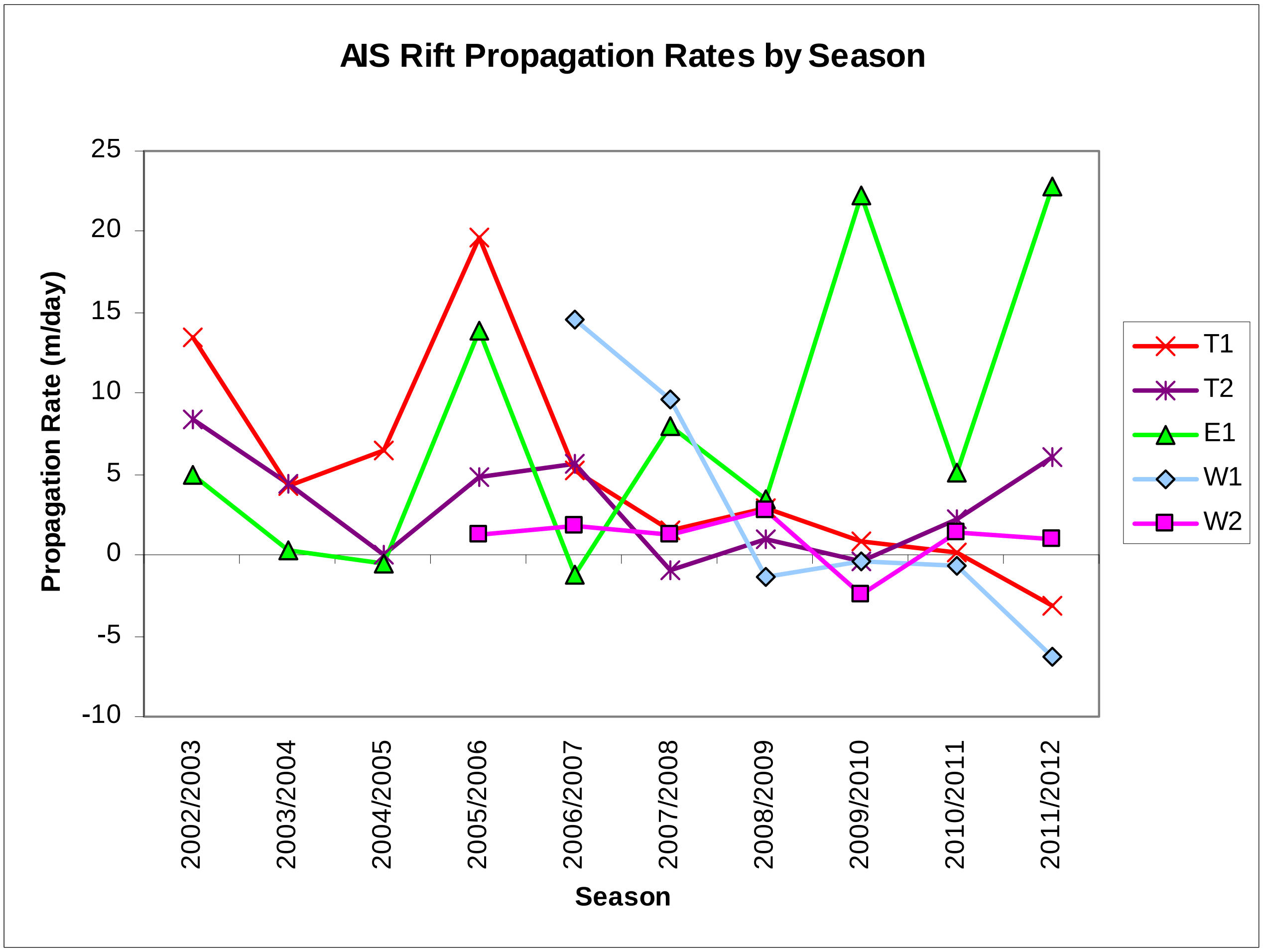

Fig. 6: Rift propagation rates by season (meters day^{-1}) for each examined rift in the AIS

Table 2: Rift propagation rates (meters day^{-1}) for each rift by season and overall. Negative values are attributed to error in the measurement process and likely do not reflect rifts shortening over time, but rather stable non-propagating rifts.

Season	**W1**	**W2**	**T1**	**T2**	**E1**	**RW**	**RE**
2002/2003	N/A	N/A	13.5	8.3	5.0	N/A	N/A
2003/2004	N/A	N/A	4.2	4.3	0.2	6.3	-12.5
2004/2005	N/A	N/A	6.4	0.1	-0.4	7.5	-4.8
2005/2006	N/A	1.2	19.6	4.8	13.9	4.4	37.5
2006/2007	14.5	1.8	5.3	5.5	-1.2	6.4	9.9
2007/2008	9.6	1.2	1.5	-0.8	8.0	26.1	-0.8
2008/2009	-1.4	2.7	2.8	0.9	3.3	5.6	8.6
2009/2010	-0.3	-2.4	0.8	-0.4	22.2	-53	5.2
2010/2011	-0.7	1.4	0.1	2.1	5.0	-0.2	-2.2
2011/2012	-6.3	0.9	-3.1	6	22.7	-1.8	22.8
Overall	**1.6**	**-0.1**	**3.6**	**1.81**	**3.9**	**4.0**	**2.9**

The correlation between T1 and E1 appears to end in 2007/08. In the following season (2008/09), T1 underwent major structural changes. In the interval between January 4, 2009 and January 8, 2009, when consecutive clear MODIS images were taken, T1 continued to propagate but changed direction of propagation. As opposed to propagating perpendicular to ice flow, it began propagating southward, parallel to a suture zone where two ice flows had joined together farther upstream. A high resolution image (Fig. 7) was taken from a different satellite in January 2012, showing that the tip of T1 meanders, turning south when meeting the suture zone, then curving westward, and abruptly turning south once again.

Overall in the AIS, T1 generally propagated at the fastest rate in the first half of the time series, although E1 seems to have made significant increases in propagation rate in the 2007/08 summer and had the greatest increase in rift length over the course of the time series. E1 is different from the other rifts in that it does not rift straight in one continuous line but frequently changes direction of propagation forming a sawtooth pattern. The amplitude of the sawtooth is greatest near the origination of the rift and becomes smaller near the rift tip towards the interior of the ice shelf.

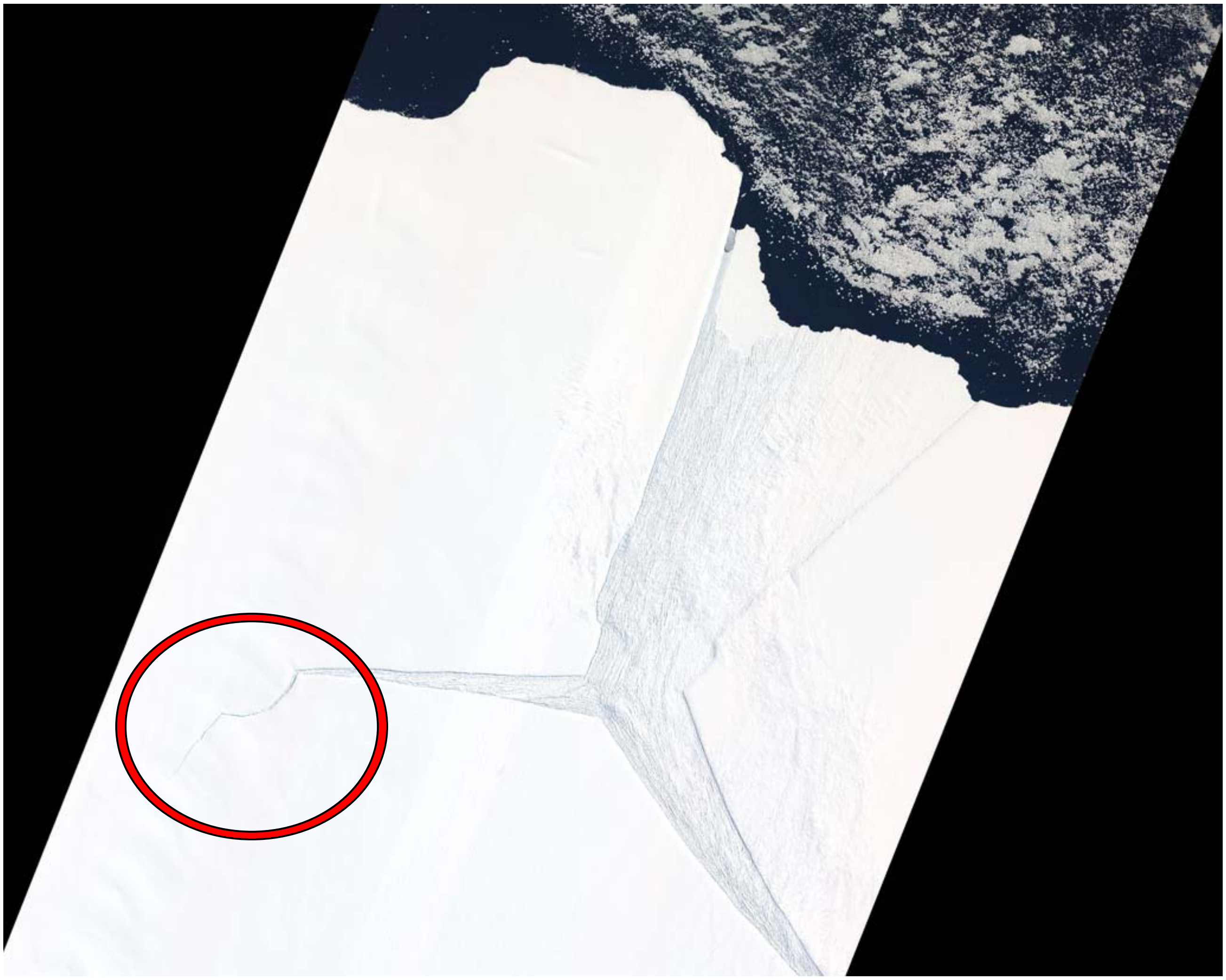

Fig. 7: High resolution image of the meandering rift tip (circled in red) of T1 in the AIS. Image taken January 27, 2012 (Personal Communication with Ted Scambos)

The per-season propagation rates for the two rifts in the RIS are somewhat misleading. As there were few measurable images per season due to cloud cover interference, the per-season rates are based on a very small sample size and are less likely to show an accurate trend. Both rifts are propagating at a fairly steady overall rate, though RW may be slowing down (Fig. 5).

The rate of rift propagation seems to be in line with the results of Fricker *et al.* (2005), in that the rifts propagate faster in the summer than in the winter. Many of the rifts also seem to rift episodically, rifting at a slow background rate and suddenly propagating great distances in a short time span. This episodic rifting seems to be particularly important for E1 in the AIS, though this occurrence may be a result of poor-resolution images preventing me from detecting the switch in direction until the rift has lengthened by a certain amount, as the episodic rift events are correlated with when the rift begins propagating in a new direction.

Discussion

The differences in propagation rate for each of the rifts indicate that rift propagation is a complex phenomenon. If increased rift rate were solely the result of increased atmospheric temperatures, for example, we would expect all five rifts in the AIS to have relatively similar per-season rift rates, rifting faster in some years and decelerating in others, but all following the same general pattern. Additionally, the two rifts in the RIS would be expected to have similar propagation rates, although the rift propagation rates might be different in the two different ice shelves, as the AIS and RIS are located in different parts of Antarctica and at different latitudes. However, I found that the rift propagation rates differ substantially even between relatively close rifts in the same ice shelf.

Despite the unlikelihood of a single environmental factor driving rift propagation, one environmental condition does seem to correlate with rift propagation in the AIS, at least occasionally. This factor is sea ice concentration in front of the ice shelf. It appears that rift propagation is faster when sea ice concentration is reduced. Sea ice concentration is high during the early summer and tends to decrease later in the summer. Within each season, rift propagation rate is slowest at the beginning of the summer and increases as the summer progresses—the exact inverse of sea ice concentration. As sea ice re-forms at the end of the summer, rift propagation rate slows. Sea ice concentration is greatest in the winter months, which might also explain why rifts tend to propagate faster in the summer than in the winter.

The inverse correlation between sea ice concentration and rift propagation is particularly strong for T1, but it also exists with T2 in some years and loosely correlates with E1 in 2006/07. The correlation between sea ice concentration and change in length of T1 is particularly strong in 2006/07—when plotting the two against each other, fitting a line yields an r-squared value of ~0.81 (Fig. 8). The correlation is present but not as strong in the summers of 2002/03 to 2005/06, and it is practically non-existent in 2007/08. (Unfortunately, the data set for sea ice concentration ends in 2008. This lack of data also means that there are too few years to notice correlations between sea ice concentration and propagation of W1 and W2, although the limited available data indicate that the correlation is slight to non-existent.) Though there is an apparent correlation between sea ice concentration and rift propagation, it only exists with a few of the rifts, and only during certain years. Rather than being a clear causal agent, sea ice concentration compounds the complexity of searching for driving forces behind rift propagation.

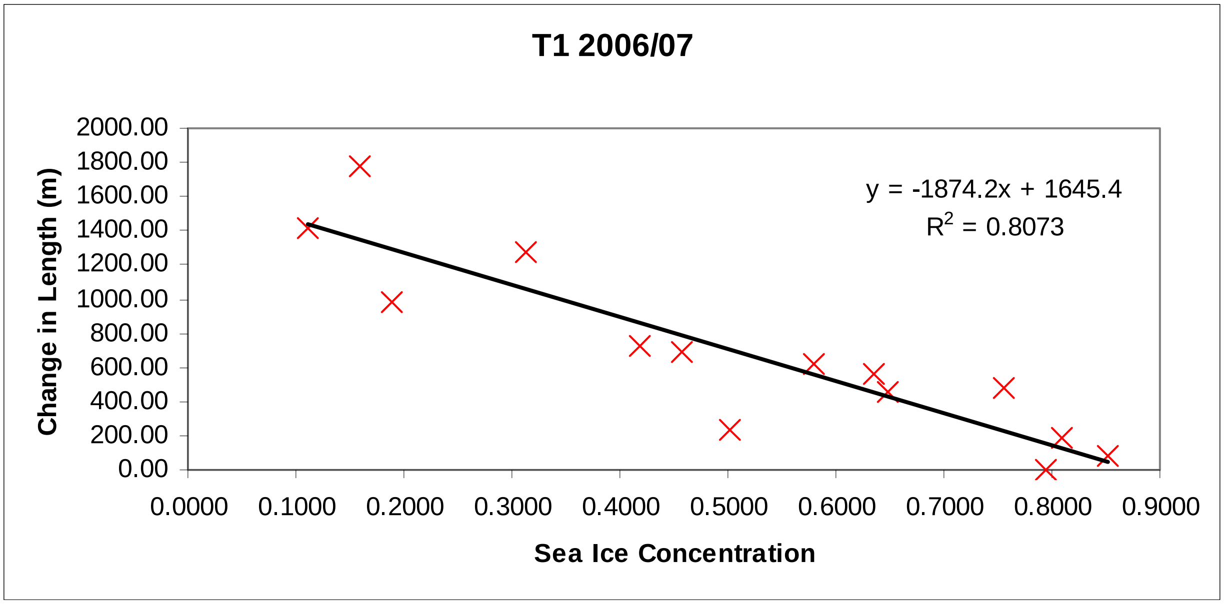

Fig. 8: Change in length of T1 plotted against sea ice concentration in the 2006/07 Austral summer. Note the relatively high R^2 value of 0.8. Sea Ice Concentration from Fetterer *et al.* (2002).

This occasional correlation becomes more complex when one considers that sea ice concentration may not be the driving factor behind rift propagation, but rather an effect of another environmental condition. Sea ice concentration may serve as a proxy for another environmental factor, or potentially several interacting factors, which drive rift propagation. When sea ice is present, it might dampen ocean swell, which would decrease stress on the ice shelf. If rifts propagate to relieve internal stress within the ice shelf, decreased ocean swell as a result of high sea ice concentration might relieve the pressure driving rift propagation. Alternatively, sea ice at the front of the ice shelf may serve as an indicator of fast ice, or ocean water underneath the ice shelf freezing to the bottom of the ice shelf. This fast ice may thicken the ice shelf and help stabilize it, leading to decreased rift propagation rates. Furthermore, the effects of sea ice concentration could be combined with other factors, such as ice mélange, as suggested by Fricker *et al.* (2005). Still yet, sea ice concentration might indicate changes in oceanic temperatures or currents under the ice shelves.

One environmental factor does not appear to control rifting across Antarctica, though a combination of environmental factors may be at work. However, it appears that internal stress within the ice shelf may be a driving factor, as suggested by Bassis *et al.* (2008). As one rift propagates, it may relieve internal stress within the ice shelf, causing other rifts to slow. For instance, the increased propagation rate of E1 in 2007/08 may account for the leveling off of the rift propagation rate for T2 around that same time. A different example of internal structure of the ice shelf affecting rift propagation may be seen in T1. The rift appeared to be propagating in a straight line until it suddenly changed direction of propagation when it met the suture zone, where one would expect the ice shelf to be weaker internally. The rift changed direction to propagate parallel to this supposed weaker area, but as the high resolution image shows (Fig. 7), after a brief period, the rift curved to propagate across the suture zone. Environmental factors are unlikely to control this meandering rift tip, indicating that internal structure of the ice shelf is an important factor impacting rift propagation. Although the direct causes are not yet clear, it appears as though a combination of internal stress within the ice shelf and various environmental factors relating to sea ice concentration may be the driving forces behind rift propagation, but it is important to note that different rifts may be reacting to different stimuli.

Conclusions

I have measured rift propagation of five rifts in the Amery Ice Shelf and two rifts in the Ronne Ice Shelf over the course of ten years. Rift propagation is a complex process and is not controlled by a single obvious environmental condition. Interaction between different rifts in the same ice shelf may be playing a role, as they all affect the internal stress within the ice shelf. Also, sea ice concentration is somewhat correlated with the propagation of at least one rift in the AIS, indicating that increased sea ice may decrease the rate of rift propagation or serve as a proxy for other environmental factors which may impact rift propagation rate. My results indicate that the processes driving rift propagation are complex, and may not be continent-wide, as rift propagation was different in the Amery Ice Shelf in East Antarctica versus in the Ronne Ice Shelf in West Antarctica.

Ice shelves have the potential to be indicators of climate change, but unless the mechanisms controlling their rifting and breakup are better understood, their usefulness is limited. Long-term monitoring of rift propagation across Antarctica and related environmental conditions is necessary to identify which factors have the greatest impact on rift propagation rates. Collecting and analyzing data regarding conditions related to sea ice concentration would be particularly useful, including measuring ocean temperature, ocean swell, and ice mélange thickness to determine the ultimate driving forces behind rift propagation.

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