Velocities of Pine Island and Thwaites Glaciers, West Antarctica, From ERS-1 SAR images

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Abstract

Average velocities of Pine Island and Thwaites Glaciers were measured for the time periods between 1992 and 1994 by tracking ice-surface patterns. Velocities of the central flow of the Pine Island Glacier range from 1.5 km/yr above the grounding line (separating the grounded from the floating parts of a glacier) to 2.8 km/yr near the terminus; velocities of the central Thwaites Glacier range from 2.2 km/yr above the grounding line to 3.4 km/yr at the limit of measurements on the tongue. Both glaciers show an increase in velocity of about 1 km/yr where they cross their grounding lines. The velocities derived from ERS-1 images are higher than those previously derived from Landsat images, perhaps reflecting acceleration of the glaciers. Both glaciers are exceptionally fast. The high velocities may be due to high precipitation rates over West Antarctica and the lack of a major buttressing ice shelf.

Keywords: ERS-SAR images, Pine Island Glacier, Thwaites Glacier, glacier velocity, glacier tongue, glacier terminus

Introduction

The polar regions play an important role in the global environment. Melting of the marine West Antarctic ice sheet alone could raise sea level by 5 m (Ref. 1), severely impacting densely populated coastal regions of the world. Hypothetically, the ice sheet could disintegrate within the next 100 years (Ref. 2). Yet, little is known about its mass balance (the net gain or loss of ice). An important variable in the study of mass balance is velocity. Velocities for the West Antarctic ice sheet are well known for the ice streams draining into the Ross and Ronne Ice Shelves; less is known about velocities of ice draining through the Pine Island and Thwaites Glaciers into the Amundsen Sea, even though these glaciers drain about one fifth (Ref. 3) of the West Antarctic Ice Sheet. Both glaciers are grounded well below sea level (Ref. 4), making them susceptible to grounding line instabilities (Ref. 1) and sensitive to climate change. This study provides new data concerning the velocities of these glaciers.

METHOD

Crevasses or other surface patterns on glaciers may remain visible for many years. Using sequential satellite images, average velocities (for the time interval between image acquisitions) can be calculated from the displacements of such features. ERS-1 SAR images, used in this study, have 25 m resolution (12.5 m/pixel) and enable identification of crevasses both above and below the grounding line. The European Space Agency (ESA), through the German DLR (Deutsche Forschungsanstalt fuer Luft und Raum), furnished CCTs of ERS-1 images in geocoded format (images placed in Universal Transverse Mercator map projection using the WGS 1984 ellipsoid). The DLR also provided similar reference elevations for repeat images that have similar orbit and frame locations (Table 1), thus eliminating major range-displacement errors. (Range displacements within frames are 2.3 times the elevation difference between the actual elevation of a point and the reference elevation; Ref. 5). In addition, layover problems on ice streams and ice shelves are minor because slopes are low. Thus, small elevation differences between displaced measured points cause errors of less than 1%. To reduce speckle, we compressed the images to 25 m/pixel by averaging squares of four pixels. On some images we removed noisy data with adaptive box filters described in Eliason and McEwen (Ref. 6).

We coregistered image pairs by matching a minimum of three well-dispersed fixed points, such as nunataks (outcrops) or coastline features, or by using furnished latitude and longitude coordinates based on orbital parameters. Previous investigations (Ref. 7) showed that images coregistered by nunataks have essentially no residual errors on other fixed points; images coregistered by furnished coordinates may have maximum ground location errors of 50 m (Ref. 5). A hypothetical 50 m error in nominal location of two images would result in a ± 5% error in measured displacement of a tracked point that moved a distance of 1 km.

An automated cross-correlation method, developed by Bindschadler and Scambos (Ref. 8) and Scambos et al. [Ref. 9], was applied to the sequential images. Then we plotted vectors, representing the offsets of recognized patterns, on the images. To obtain the distribution of average velocities over the length of the glaciers, the distance from the midpoint of each vector to the approximate position of the grounding lines was portrayed on graphs (see figures). Dividing the wide Thwaites Glacier into separate parallel paths served to record velocity variations in a cross-flow direction.

RESULTS

PINE ISLAND GLACIER

The Pine Island Glacier drains part of the northeastern segment of the West Antarctic Ice Sheet (Fig. 1) and near its mouth occupies a subglacial trough with floor elevations more than 1000 m below sea level [Refs. 10, 4]. Images were coregistered using nunataks. Average velocities for the grounded and proximal floating parts of the glacier were reported in Lucchitta et al. [Ref. 7]. For this report, we added velocities for the distal, floating part of the glacier and for a later time period (Figs. 2 and 3). The fast-moving central part of the glacier flows at approximately 1.5 km/yr above the grounding line, at an interpolated 1.9 km/yr at the grounding line as inferred by Crabtree and Doake [Ref. 10], and at about 2.6 km/yr below the grounding line. At the terminus, velocities are as high as 2.8 km/yr. Remarkable is an increase of about 1km/yr across the grounding line (Fig. 3). The scatter of points in the graph is due to the low velocities recorded at the glacier margin.

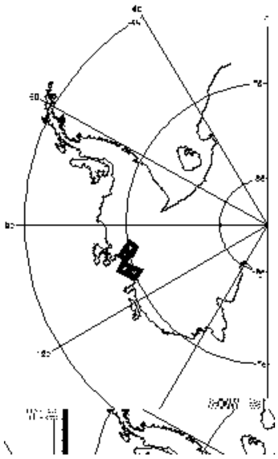

Fig. 1

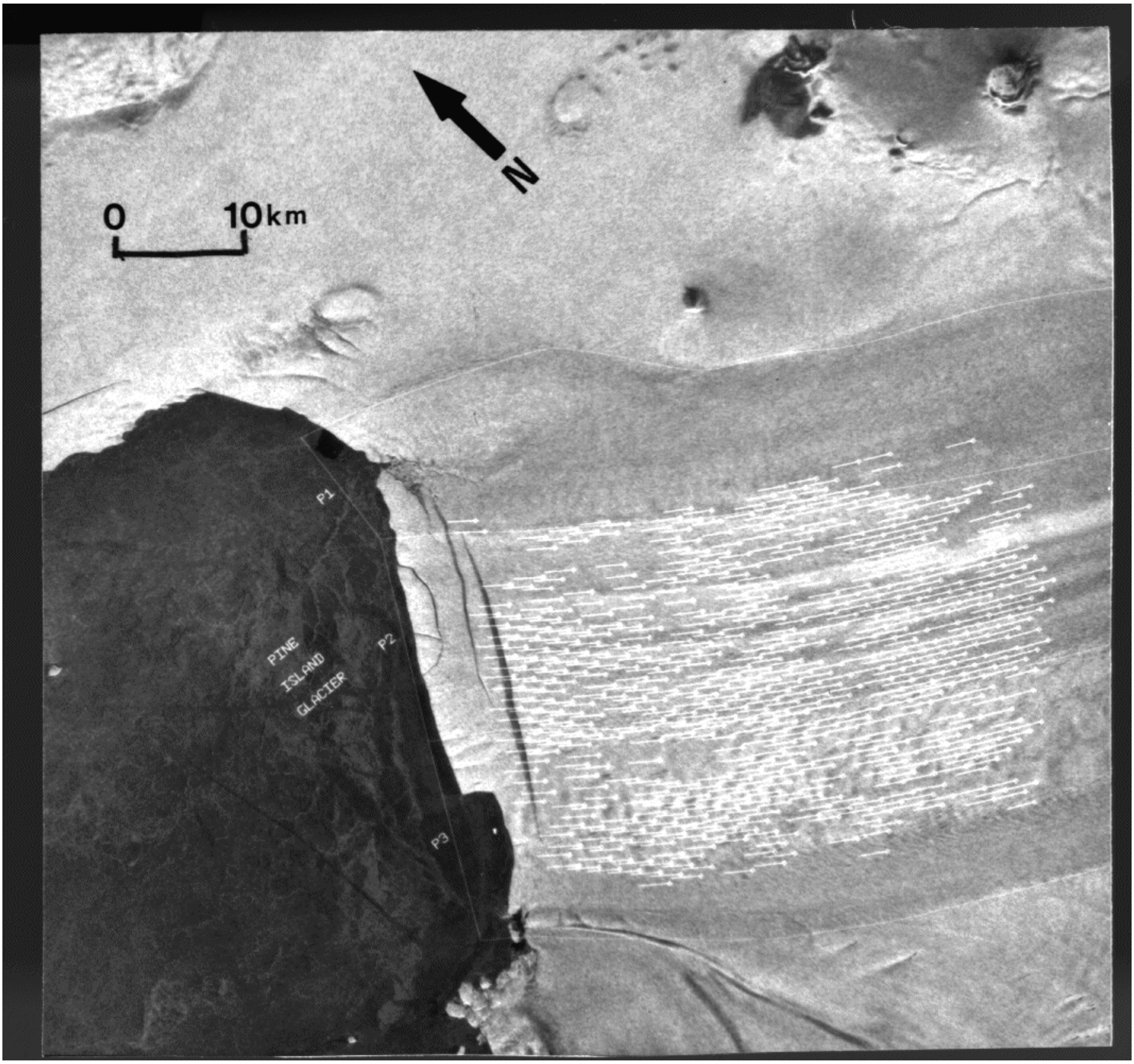

Fig. 2. Lower part of Pine Island Glacier, showing terminus. Movement toward left. Small white lines are displacement vectors for time interval 9 February 1992 to 4 December 1992. ERS-1 image 2970-5607, 9 February 1992.

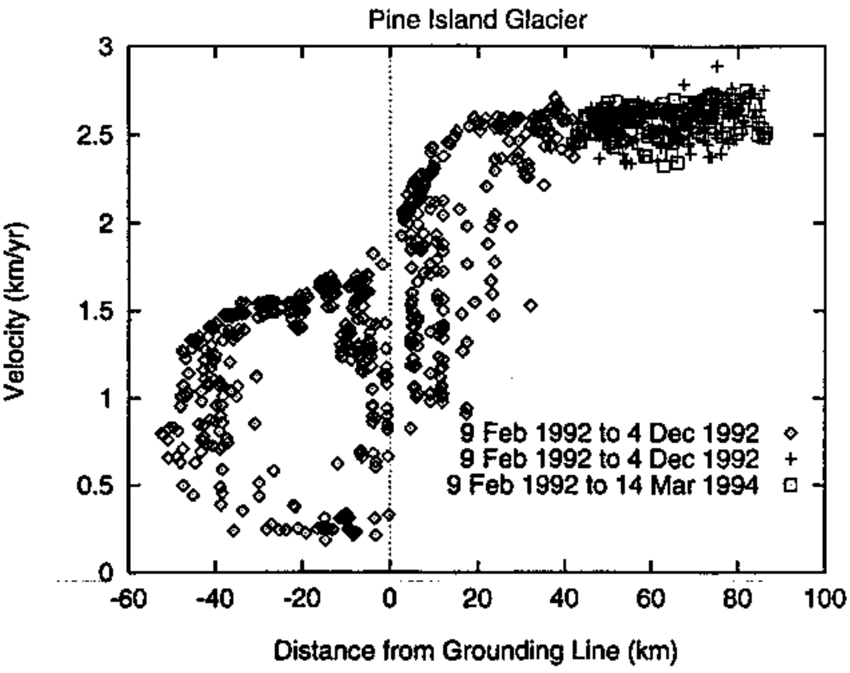

Fig. 3. Pine Island Glacier. Average velocity plotted against distance from grounding line of Crabtree and Doake [Ref. 10]. Negative values in grounded part of glacier,positive values in floating part. Upper part of glacier from Figs. 2 and 3 in Lucchitta et al. [Ref. 7] (diamonds); lower part covering two time intervals (crosses and squares). Scatter reflects velocity differences across width of glacier. Note rapid increase in velocity across grounding line.

Previous investigations [Refs. 10, 11, 12], based on MSS Landsat images of 1973 and 1975, established average velocities for the floating section of 2.1 to 2.4 km/yr, about 0.4 km/yr lower than those of this report. The apparent increase in velocities may reflect speeding up of the glacier within the last 10 to 20 years; however, it may also reflect the improved accuracy of ERS-1 images over Landsat images. ERS-1 images have better resolution, internal geometry, and scale and location accuracy than Landsat MSS images.

The terminus of the Pine Island Glacier was at its most advanced stage in the Landsat image of 1973, before a 15-km-wide iceberg calved. For the last 20 years, the front has fluctuated only a few kilometers around the post-calving front of 1973 [Ref. 13], and was again at this position in March 1994. On the glacier's southwest side, the position of the front is apparently controlled by a small ice-rise spur jutting into the glacier's path. Overall, a retreat of 0.8 km/yr of the Pine Island Glacier front, as observed from 1966 to 1985 by Kellogg and Kellogg [Ref. 14], is not supported by the more recent data.

THWAITES GLACIER

The Thwaites Glacier (Fig. 1) is the fastest moving ice stream in West Antarctica and drains an area of 121,000 km2 [Ref. 15]. The subglacial floor of the drainage area reaches the Byrd Subglacial Basin, more than 2000 m below sea level [Ref. 4]. The glacier lacks a buttressing ice shelf.

ERS-1 images for this area were coregistered by the coordinates provided, as only one outcrop was visible. When matching the images by this outcrop and the rolling, presumably stationary topography of the grounded ice sheet, residual errors were locally as much as 2 pixels of the compressed image, or the equivalent of 50 m on the ground. However, the pixel offsets due to the error were in directions where they had only minor effects on the measurements.

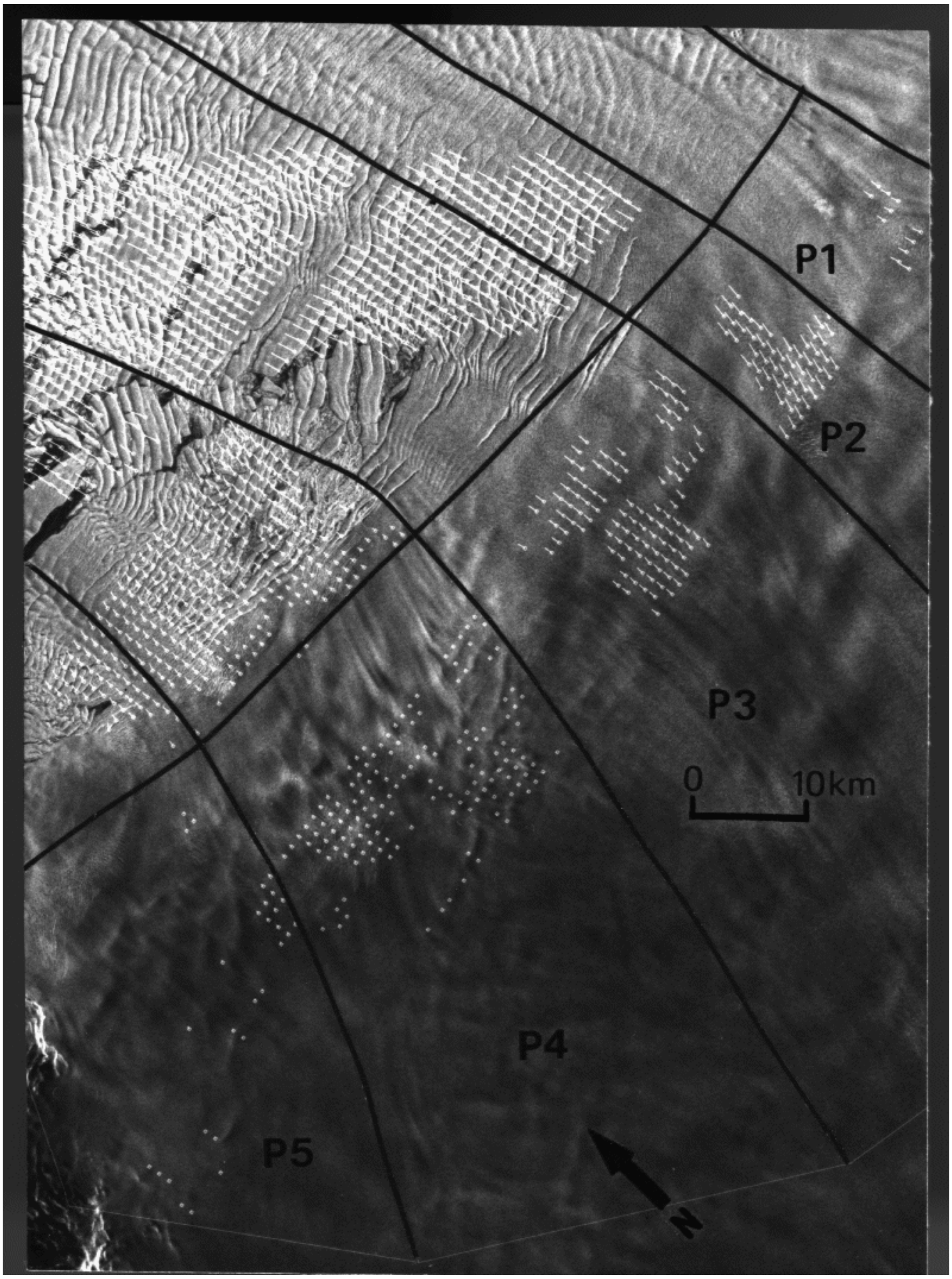

Fig. 4

Displacement vectors for the time interval 1993 to 1994 (Table 1), for the part of the glacier that crosses the grounding line, are shown in Fig. 4. (The grounding line, as shown, separates rolling topography of the ice sheet from the crevassed ice tongue). Vectors for the tongue only (1992 to 1993, Table 1) are shown in Fig. 5. Average velocities for the fastest moving, central parts of the glacier (path 2 in Figs. 4, 5, and 6) ranged from about 2.2 km/yr just above the grounding line to around 3 km/yr in the proximal glacier tongue to 3.4 km/yr at the limit of the measurements of the images. The eastern and western parts of the main glacier (paths 1 and 3 in Figs. 4, 5 and 6) moved at a lower rate of about 1.5 km/yr above the grounding line, but accelerated to the tongue velocity in the floating part. West of the main glacier (paths 4 and 5 in Figs. 4 and 6) the ice moved at an even lower 0.2 to 0.6 km/yr above the grounding line, accelerating more gradually to about 3 km/yr in the ice tongue. In this area the tongue consisted of many large icebergs that were apparently swept along by the central part of the tongue.

Fig. 5. Part of Thwaites Glacier tongue. Black lines trending north-south separate paths, black line trending east-west indicates approximate position of grounding line. Small white lines are displacement vectors for time interval 2 March 1992 to 8 September 1993. ERS-1 image 3289-5193, 2 March 1992.

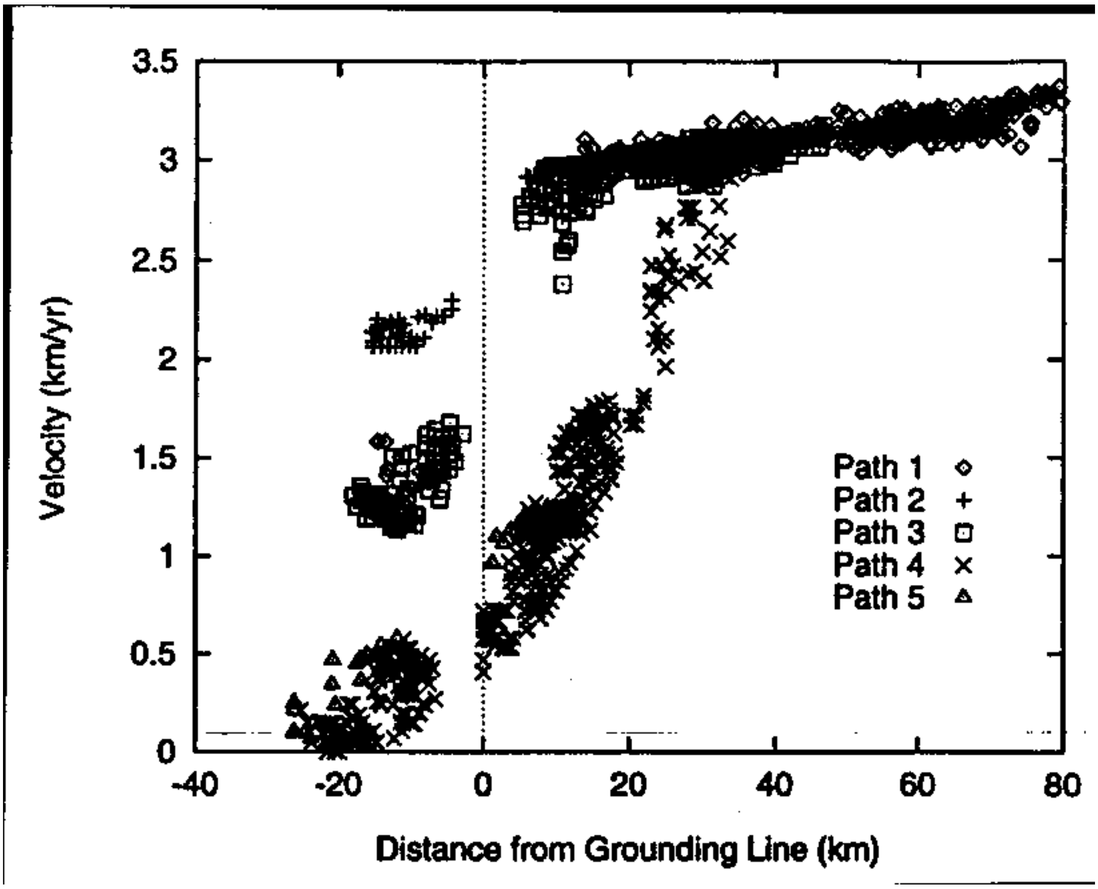

Fig. 6. Thwaites Glacier. Average velocity per paths plotted against distance from grounding line. Negative values in grounded part of glacier, positive values in floating part. Compilation of velocities from September 1993 to March 1994 (Table 1). Note rapid increase in velocity across grounding line.

Fig. 7 shows a compilation of velocities measured on the tongue only. The velocities from March 1992 to September 1993 overlap those from September 1993 to March 1994. For these intervals, no obvious change in velocities could be detected, but the greater spread in values for the earlier and longer interval could indicate that velocities locally varied in space and time, resulting in less clustered averages.

On the Thwaites Glacier, velocities increase about 1 km/yr across the grounding line, similar to the Pine Island Glacier. Here, also, few matching points were recognized by the automated cross-correlation program near the grounding line, suggesting that small crevasses do not retain their shapes in this region, perhaps reflecting a grounding zone.

Previous velocity measurements were made on the tongue only. In 1977, Allen (in Ferrigno et al. [Ref. 16]), estimated an average velocity of 2.0 to 2.9 km/yr based on aerial photographs and Landsat images. Lindstrom and Tyler [Ref . 12] measured an average velocity of 3.6 km/yr from 1972 to 1983 on Landsat images coregistered by icebergs trapped in fast ice, a method that makes their numbers questionable. Ferrigno et al. [Ref. 16] measured average velocities of 2.6 km/yr on Landsat images from 1972 to 1984, and 2.7 to 2.8 km/yr on Landsat images of 1984 to 1990. The average velocities of the Thwaites Glacier tongue of more than 3 km/yr, derived from ERS-1 SAR images, represent an increase of more than 0.4 km/yr over velocities given in the earlier papers (Fig. 8). Are these increases real? One observation suggests that the velocity increases are indeed correct: in one area to the west of the main tongue, identical velocities were obtained from Landsat as well as ERS images.

The main ice tongue has advanced since 1967, after the large Thwaites Iceberg Tongue calved off (Ferrigno et al. [Ref 16]). Since then, the ice front advanced 10 km between 1972 and 1988, and 2 km between 1988 and 1989 [Ref. 17]. The ERS-1 images do not show the front of the main tongue, but a subsidiary tongue on the east side of the main tongue lost six small icebergs, totalling about 10 km in the flow direction between 1992 (Fig. 5) and 1993.

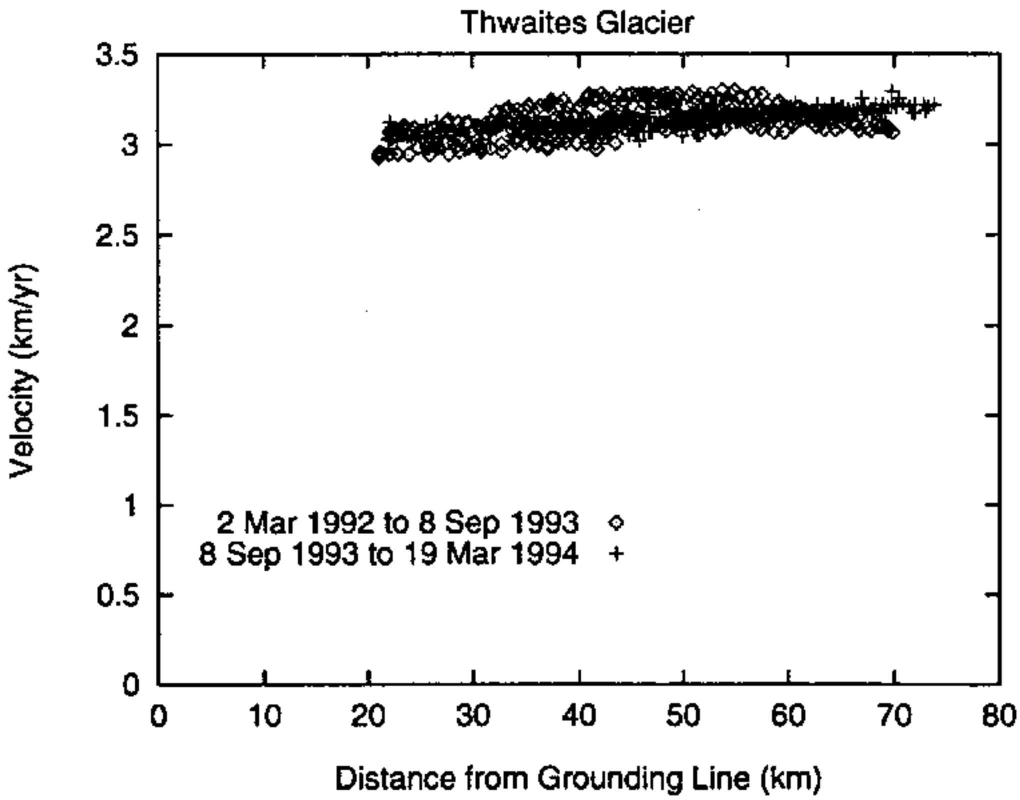

Fig. 7. Tongue of Thwaites Glacier. Average velocity plotted against distance from grounding line. Compilation of velocities for two time intervals for tongue only (frames 5193, Table 1). Note similar velocities for both time intervals.

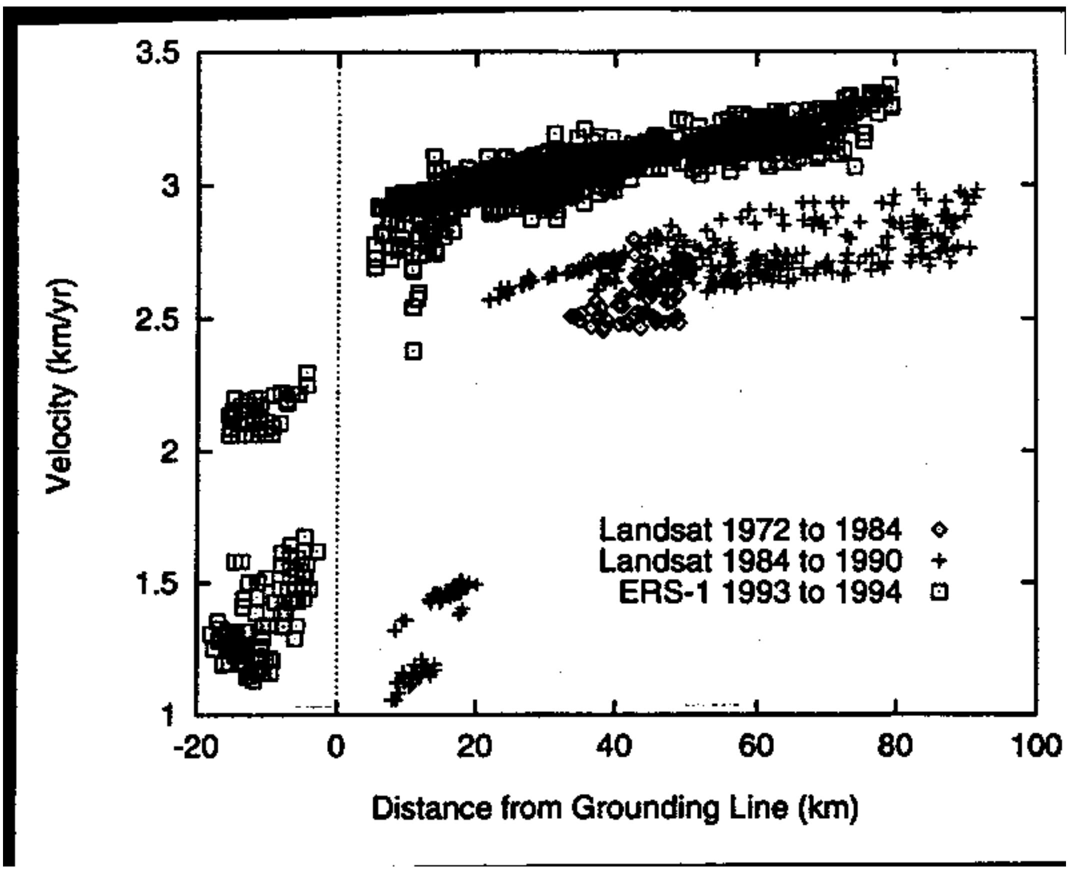

Fig. 8. Thwaites Glacier. Comparison of average velocities from Landsat [Ref. 16] and ERS-1 images (paths 1, 2, and 3 of Figs. 4 and 6). Note apparent increases in velocity with time.

SUMMARY AND CONCLUSIONS

The Pine Island Glacier (maximum velocity measured 2.8 km/yr) and Thwaites Glacier (3.4 km/yr) are faster than most Antarctic ice streams, which generally have velocities less than 1.5 km/yr [Ref. 18]). The Pine Island Glacier is buttressed only by its own floating terminus, wedged between ice walls; the Thwaites Glacier is not buttressed by an ice shelf at all. The lack of shelves may be partly responsible for the high velocities. Another likely cause is the high precipitation rate, around 300 to 400 mm/yr along the coastal areas of the West Antarctic Ice Sheet [Refs. 19 and 20].

Increases in velocity on the order of 0.4 km/yr were observed on both the Pine Island and Thwaites Glaciers, when comparing older Landsat-based with more recent ERS-based measurements. The apparent increases may be due to errors introduced by different imaging systems. However, some velocities remained the same despite the different systems used, suggesting that the velocity increases are correct. The increases could portend surging of the glaciers. Further monitoring is needed.

An increase in velocity of about 1 km/yr occurs where the Pine Island and Thwaites Glaciers flow across their grounding lines. This rapid change may be unique to fast moving glaciers lacking shelves. The observation points to the need to accurately correlate bottom-profile locations and velocities when calculating discharges across the grounding line. Also, only few displacement vectors were recorded by the automated cross-correlation program near the grounding lines. Perhaps this lack of trackable features delineates a grounding zone.

The Pine Island Glacier front has been relatively stable for the last 20 years, fluctuating only a few kilometers around the position of a small ice rise jutting into the glacier's path on its southwest side. A subsidiary tongue on the east side of the Thwaites glacier lost a number of tabular icebergs totalling about 10 km in width between 1992 and 1993; since then its position has been stable.

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