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# Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data

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[1] The Advanced Land Observation System (ALOS) Phased-Array Synthetic-Aperture Radar (PALSAR) is an L-band frequency (1.27 GHz) radar capable of continental-scale interferometric observations of ice sheet motion. Here, we show that PALSAR data yield excellent measurements of ice motion compared to C-band (5.6 GHz) radar data because of greater temporal coherence over snow and firn. We compare PALSAR velocities from year 2006 in Pine Island Bay, West Antarctica with those spanning years 1974 to 2007. Between 1996 and 2007, Pine Island Glacier sped up 42% and ungrounded over most of its ice plain. Smith Glacier accelerated 83% and ungrounded as well. Their largest speed up are recorded in 2007. Thwaites Glacier is not accelerating but widening with time and its eastern ice shelf doubled its speed. Total ice discharge from these glaciers increased 30% in 12 yr and the net mass loss increased 170% from 39 ± 15 Gt/yr to 105 ± 27 Gt/yr. Longer-term velocity changes suggest only a moderate loss in the 1970s. As the glaciers unground into the deeper, smoother beds inland, the mass loss from this region will grow considerably larger in years to come.

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## 1. Introduction

[2] Synthetic-aperture radar interferometry (InSAR) has proven to be a valuable tool for measuring ice motion and grounding line position [e.g., *Joughin et al.*, 1996; *Rignot*, 1996]. Estimates of ice sheet mass balance have been obtained with this technique for the entire Greenland and Antarctic ice sheets, with few areas left unsurveyed [*Rignot and Kanagaratnam*, 2006; *Rignot et al.*, 2008]. Most InSAR data collected to date have been acquired at the C-band frequency (5.6 GHz or 5.6 cm wavelength). Data collected at the L- and C-band frequencies by the Space Shuttle Experiment SIR-C in 1994, however, indicated that longer radar wavelengths offer superior temporal coherence on snow and ice surfaces because of their penetration into the snow and firn [*Rignot et al.*, 1996, 2001; *Dall et al.*, 2001]. Yet, few satellite L-band InSAR data have been collected on glacier ice, and nearly none on ice sheets.

[3] C-band radars have been successful at measuring ice motion even though they were not designed for this application, but their month-long repeat cycle has made it challenging to get good coherence in certain parts of Antarctica, except for a brief period of time in 1996 when two Earth Remote Sensing (ERS) satellites were put along the same orbit one day apart, and in winter 1992 and 1994 when the ERS-1 satellite was in a 3-day exact repeat mode. The opportunity for short-term mapping of wet, dynamic coastal regions of Antarctica disappeared in March 2000 when ERS-1 ceased operations. Unfortunately, these sectors are the most important for the present-day ice sheet mass balance [*Rignot et al.*, 2008].

[4] Here, we examine data collected by the ALOS PALSAR L-band radar in 2006, six months after launch. We show results from the Amundsen Sea sector of West Antarctica and compare them with those obtained with Radarsat, ERS, and Landsat between 1974 and 2007. Changes in flow speed measured at the grounding lines are converted into changes in mass flux, which in turn are converted into changes in mass balance. We conclude with a discussion of the evolution of glaciers and mass balance in this region and their past and future impact on sea level rise.

## 2. Data and Methodology

[5] The Advanced Land Observation System (ALOS) Phased-array L-band Synthetic-Aperture Radar (PALSAR) was developed by the Japan Aerospace Exploration Agency (JAXA) and the Japanese Resources Observation System Organization (JAROS) and launched in January 2006. The radar operates at 1.27 GHz (24 cm wavelength). The data analyzed herein were acquired in May–September 2006, at horizontal receive and transmit polarization, with a 41.5° look angle off nadir, 7.5 m × 4.1 m resolution, respectively, in slant-range (across-track) and azimuth (along-track), a 70 km swath width, a −34 dB noise equivalent backscatter cross section, a 46-day repeat cycle, and sun-synchronous, ascending (evening) orbits of the satellite. The data were obtained as raw individual frames from JAXA via the Alaska Satellite Facility (ASF). Frames were concatenated and processed into single look complex tracks using the Gamma Remote Sensing processor (http://www.gamma-rs.ch).

[6] A speckle tracking technique [*Michel and Rignot*, 1999] was applied on image pairs acquired 46 days apart. Averaging boxes for speckle tracking were 128 (range) × 256 (azimuth) samples in size, with a grid spacing of 32 × 64 samples, and a search window of 64 × 64 samples. The offsets were median filtered to remove bad matches. A plane fit was adjusted through non-moving areas such as ice islands, nunataks, and ice caps and removed from the offset fields to obtain absolute displacements. The displacements were then converted into easting and northing velocities assuming surface parallel flow and using a digital elevation model of Antarctica that combines ICESAT and ERS-1

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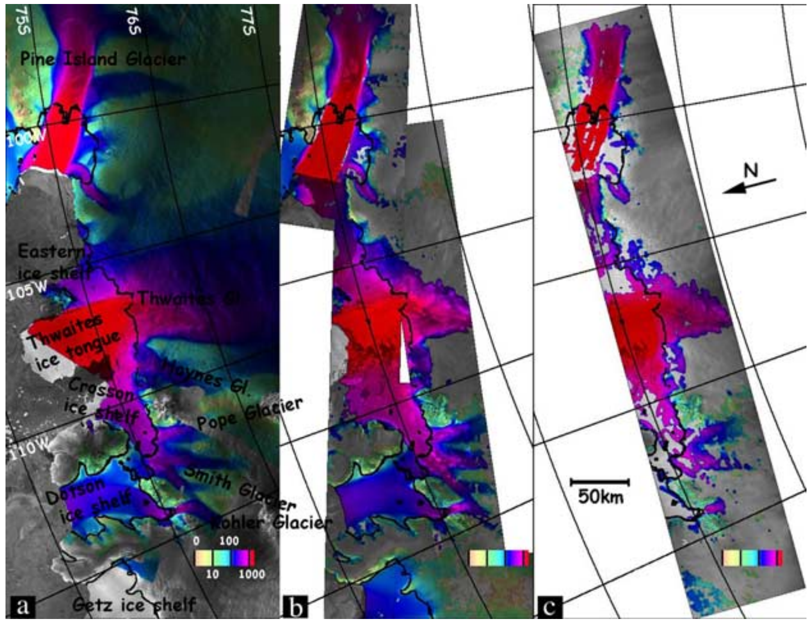

**Figure 1.** Velocity of West Antarctic glaciers draining into the Amundsen Sea using (a) ERS-1/2 January–March 1996, (b) PALSAR May–September 2006; and (c) Radarsat-1 August–September 2006 data overlaid on radar brightness color coded on a logarithmic scale from 10 m/yr (brown), to 50 m/yr (green), 100 m/yr (blue) to 1000 m/yr (pink) and more than 1000 m/yr (red). Grounding line positions for year 1992 and 1996 are black thin lines along the coast.

radar altimetry (J. Bamber, unpublished data, 2006) (Figure 1a). The precision of PALSAR velocities is 2 m/yr, or 3 times better than Radarsat-1.

[7] We compare the PALSAR velocities with those measured using ERS-1/2 ascending/descending tracks in spring 1996 (5 m/yr precision); Radarsat-1 in years 2000 to 2005 (6 m/yr precision); and Landsat imagery [*Lucchitta et al.*, 1994; *Ferrigno et al.*, 1993] (5 to 10% precision). To do the latter, we visually placed the Landsat measurement points in the PALSAR image mosaic as no precise latitude longitude information was available for these data. The error associated with this process is small compared to the inherent precision of the Landsat measurements.

[8] Ice fluxes are calculated by combining surface velocity with ice thickness data from year 2002 [*Thomas et al.*, 2004a]. Ice velocity is mapped with no data gap along the selected thickness profiles in the study area only for years 1996 and 2006. To calculate ice fluxes in other years, we determined the multiplicative factor to apply on the 2006 velocities to match the other year velocities and applied the same factor on the 2006 mass flux. This is justified by the fact that the multiple year velocity profiles are brought into excellent agreement with the scaling technique. We neglect glacier thinning before or after the year of the thickness measurements (2002) because glacier thinning of 2 m/yr at the location of the thickness data [*Thomas et al.*, 2004a] introduces an uncertainty of +12 to −10 m for years 1996 and 2007, respectively, which is 1% of a total thickness of 1.2 km. We have no information on thinning rates prior to 1992, but they were presumably smaller than for 1974–2002 because the glacier speed up was less. Assuming a thinning rate of 1 m/yr, the glaciers may have been 30 m thicker in 1974, i.e. an error in flux of 2.5%.

[9] To convert ice flux into mass balance, we employ snow accumulation calculated from a regional atmospheric climate model [*van den Broeke et al.*, 2006; *van de Berg et al.*, 2006] and averaged for the years 1980–2004. We estimated the absolute precision of the accumulation rates to be 14% in this sector [*Rignot et al.*, 2008].

## 3. Results

[10] PALSAR 46-day speckle tracking (Figure 1b) works well even in areas where signal coherence is lost with Radarsat-1 (Figure 1c), which makes velocity calibration easier and more robust with PALSAR. Signal coherence is the multiplicative product of the decorrelation from the interferometric baseline, volume scattering from snow, thermal noise from the radar system and changes in the reflecting surface [*Hoen and Zebker*, 2000]. Radarsat-1 results on other years/seasons, shorter/longer baselines, are similar to those shown here, so the loss of coherence is not due to the baseline or snow scattering. The radar backscatter of the snowy surface is high above the noise floor, so decorrelation from thermal noise is negligible as well. This leaves surface weathering as the main cause for the loss of coherence after 24 days (Figure 1c) versus 1-day (Figure 1a).

[11] At L-band, signal coherence is high on ice shelves, which are radar-bright because of percolation and refreezing of melted snow. The longer repeat cycle and higher look angle of PALSAR versus Radarsat-1/ERS-1 causes vertical displacements of the ice shelf induced by oceanic tides (1 m) to be much smaller than horizontal ice motion in 46 days (140 to 380 m). Hence, PALSAR-derived ice-shelf velocities have little tidal contamination. At high elevation and on radar-dark islands and ice caps, PALSAR speckle tracking no longer operates as signal coherence drops too low. We find that the signal to noise ratio of these areas is only 2–4 dB, hence speckle tracking is destroyed by thermal noise. PALSAR data acquired at 31° look angle, as done after

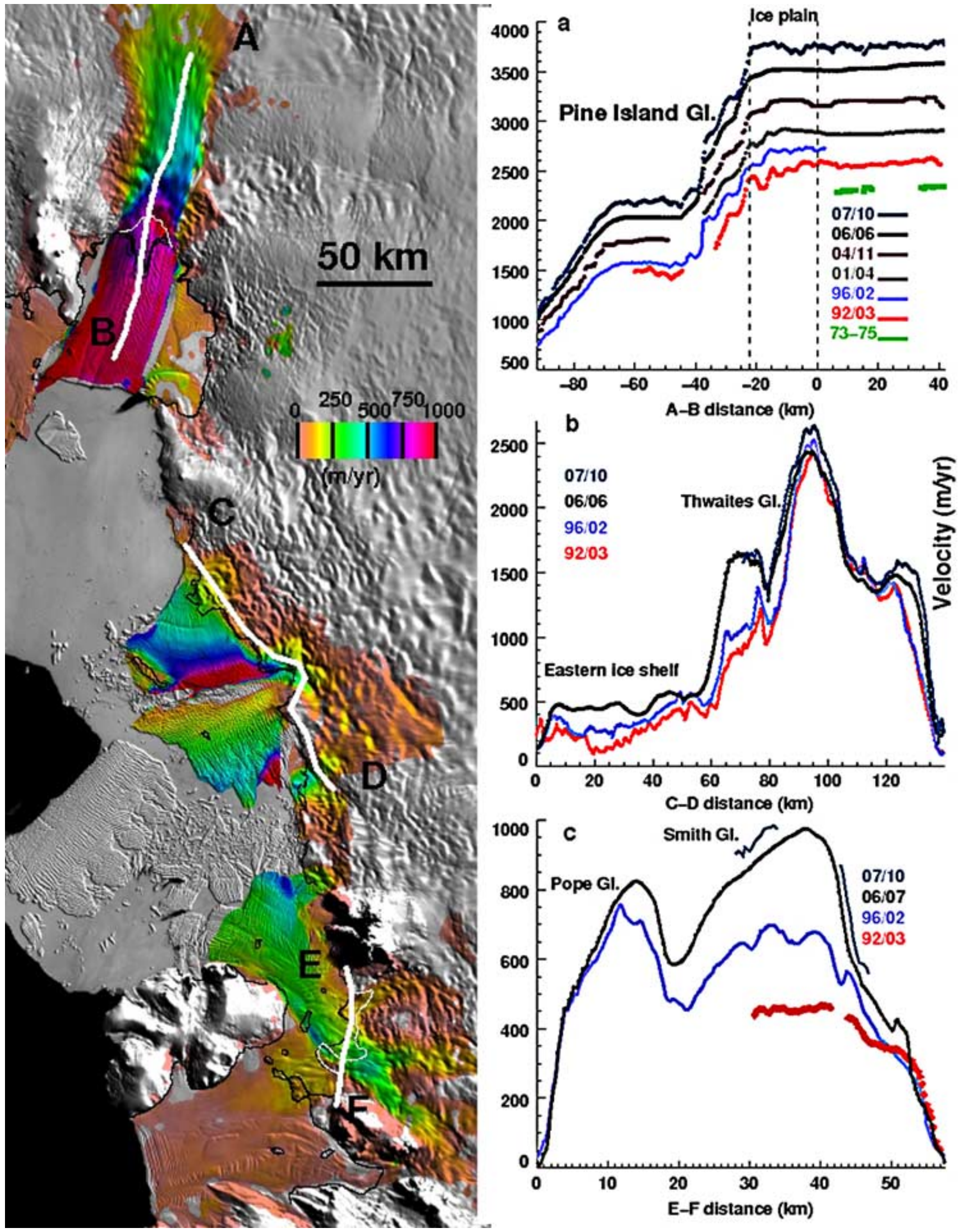


**Figure 2.** (left) Velocity increase between 1996 and 2006 color coded between 0 and 1000 m/yr (linear scale) and overlaid on a MODIS mosaic of Antarctica. Glacier grounding lines from January 1996 are black thin lines; from December 2007 in white. (right) Profiles A-F (indicated by thick lines) for (a) Pine Island, with the location of the ice plain, (b) Thwaites, and (c) Smith glaciers.

2006, will improve the signal to noise ratio, but it may remain difficult to track ice motion in radar-dark interior basins.

[12] In the easternmost sector of Getz Ice Shelf, we detect no change in velocity since 1996 (Figure 1). A comparison with Landsat data suggests no change in ice-shelf velocity since 1974. Similarly, a comparison of PALSAR and Landsat velocities on Dotson Ice Shelf suggests no change in speed, which is consistent with the stability observed between 1973 to 1990 by *Lucchitta et al.* [1994]. We detect no speed up on Kohler Glacier, upstream of Dotson Ice Shelf. Its ice flux has not changed in the last few decades.

[13] In Pine Island Bay, PALSAR and Radarsat-1 velocities from mid 2006 are in excellent agreement. This verifies that the velocity mapping is sensor independent and that PALSAR data can be used interchangeably with ERS-1 and Radarsat-1. When comparing data from different years, however, we detect large changes in speed (Figure 2). Pine Island Glacier sped up 34% between 1996 and 2006, or 3%/yr. The acceleration was 0.8%/yr in 1974–1987 and 2.4%/yr in 1996–2000 [*Rignot*, 2006]. In year 1974, the glacier speed at the flux gate was 65% of the 2006 value. We used this factor to estimate the 1974 flux (Table 1). Speed up propagates beyond the limit of the PALSAR data. In the last 16 months, the glacier sped up another 8%, which confirms an escalating increase in speed, for a total increase of 42% since 1996 and 73% since 1974.

**Table 1.** Mass balance of West Antarctic Glaciers Draining Into the Amundsen Sea Between 1974 and 2007[a]

| Glacier 2007 | Area, $\times$ 10$^6$ km$^2$ | Input, Gt/yr | Outflow, Gt/yr 1974 | 1996 | 2000 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|
| Pine Island | 164 | 61 ± 9 | 65 ± 4 | 77 ± 2 | 85 ± 2 | 100 ± 5 | 107 ± 5 |
| Thwaites | 182 | 75 ± 11 | 80 ± 6 | 93 ± 2 | 97 ± 2 | 101 ± 5 | 109 ± 5 |
| Interstream | 11 | 9 ± 1 | 8 ± 1 | 8 ± 1 | 8 ± 1 | 10 ± 1 | 10 ± 1 |
| Haynes, Smith, Kohler | 37 | 31 ± 5 | 31 ± 4 | 37 ± 4 | 47 ± 4 | 50 ± 5 | 54 ± 6 |
| Total Outflow | 393 | 177 ± 25 | 184 ± 8 | 215 ± 7 | 237 ± 7 | 261 ± 9 | 280 ± 9 |
| Mass Balance | | −7 ± 26 | | −39 ± 26 | −60 ± 26 | −85 ± 26 | −105 ± 27 |

[a]Mass balance is given in gigatons (10$^{12}$ kg) per year. Glacier, glacier name. Area, area of drainage in million square km. Input, average accumulation in Gt/yr ± $\sigma$ for the years 1980–2004. Outflow, ice discharge in Gt/yr ± $\sigma$ for years 1974, 1996 (January), 2000 (October), 2006 (August) 2007 (October). Mass Balance (last row) is calculated as Input minus Outflow, ± $\sigma$. Ice thickness is assumed to be within 1–2% of the 2004 values during the time period of observation.

[14] In 1996–2006, Haynes Glacier accelerated 27% and Smith Glacier 75%. Smith Glacier accelerated 8% in 2006–2007 alone. The velocity of Crosson Ice Shelf in sector P2 [*Lucchitta et al.*, 1994] increased from 0.61 km/yr in 1973–1988 to 0.70 km/yr in 1988–1990 and is 1.11 km/yr in 2006. The 1973–1988 ice shelf velocity was therefore 55% of the 2006 velocity (Table 1).

[15] Flow changes observed on Thwaites Glacier are different and confirm measurements from year 2000 [*Rignot et al.*, 2002]: there is little to no acceleration at the center but a widening of the core of fast flow, accompanied by a doubling of the eastern ice-shelf velocity in 10 yr. The latter was not detected with Radarsat-1 due to a lack of coherence over the ice shelf. The eastern ice shelf is only buttressed by an ice rumple [*Rignot*, 2001] and is undercut by wide rifts at its grounding line which appeared in 2002 and have been widening with time [*Rignot*, 2006]. In October 2007, new cracks severed large sectors of the ice shelf. Farther west, the fast, unconfined floating ice tongue of Thwaites Glacier sped up from 2.68 km/yr in 1972–1984 [*Ferrigno et al.*, 1993] to 2.95 km/yr in 2006, but this has had no effect on grounded ice flow as the floating tongue exerts nearly no buttressing. To estimate the 1974 flux, we assumed that the annual rate of ice flux increase measured between 1992 and 2006 applies to at least half of the period 1974–1996 (9% increase), and we increased the ice flux uncertainty accordingly (±9%).

[16] The results (Table 1) show that the total flux from this entire sector increased from 184 ± 8 Gt/yr in 1974 to 215 ± 7 Gt/yr in 1996, 237 ± 7 Gt/yr in 2000 and 280 ± 9 Gt/yr in late 2007. The mass flux increased more in the last decade than in the prior two decades. The comparison of ice fluxes with snow accumulation indicates that losses increased from 7 ± 26 Gt/yr in 1974, to 39 ± 27 Gt/yr in 1996, and 105 ± 27 Gt/yr in 2007. Changes in snow accumulation between 1980 and 2004 were less than 5% in the study area and are already included in our average accumulation values. The glaciers were therefore nearly balance in the 1970s, except perhaps for Thwaites Glacier. The mass loss increased after that, first slowly, then increasingly rapidly. The last 16 months saw the largest increase in velocity and mass loss.

## 4. Discussion

[17] Model studies showed that the acceleration of Pine Island Glacier is controlled by its ice-shelf buttressing and the position of its grounding line within the ice plain region [*Corr et al.*, 2001], which is an area grounded only 40–50 m above hydrostatic floatation upstream of the 1996 glacier grounding line [*Schmeltz et al.*, 2002; *Thomas et al.*, 2004b; *Payne et al.*, 2004]. Progressive un-grounding of the ice plain caused by dynamic thinning of the glacier (anywhere from 1–2 m/yr to 5 m/yr) reduces back-stress resistance to flow, increases the longitudinal strain rate of ice, so ice accelerates and thins vertically, which in turn enhances grounding line retreat. The 4-km grounding line retreat of 1996–2000 was sufficient to explain the 10% acceleration of the glacier [*Thomas et al.*, 2004b]. Using the same model, *Thomas et al.* [2004b] predicted that the glacier velocity will reach 3.6 km/yr in the 11 years it will take to thin the ice sufficiently for complete floatation of the ice plain assuming a thinning rate of 2 m/yr. Results presented here show velocities increasing to 3.75 ± 0.1 km/yr and probably ungrounding of most of the ice plain by late 2007, consistent with the more rapid thinning observed since 2002.

[18] We have no InSAR data to confirm the new grounding line position, but an examination of the mottled appearance of the glacier surface in 2002–2007 MODIS data (see the auxiliary material[1]) suggests a grounding line retreat of 15 ± 6 km between January 1996 and December 2007 at the glacier center, nearly the entire ice plain region. Surface bumps visible in 2002 are no longer visible in 2007, which is indicative of a transition to floatation.

[19] If confirmed, near-floatation of the ice plain has major implications for the glacier evolution because the grounding line would be at the edge of a smoother sea bed, well below sea level, and extending more than 250 km inland. If the grounding line retreats in that sector, *Thomas et al.*'s [2004b] model predicts a further doubling of the glacier speed, with the glacier now becoming afloat over seabed 1200 m below sea level, following breakup of the ice shelf to seaward of the ice plain (R. Thomas, personal communication, 2008). This would cause a sea-level rise by up to 1 mm/yr from this one glacier alone. Even though breakup is probably not imminent, continued ice-shelf thinning by about 4 m/yr [*Shepherd et al.*, 2004] would increase its likelihood.

[20] A similar evolution is taking place on the broad ice plain of Smith Glacier [*Rignot et al.*, 2002] (see the auxiliary material). Beyond the ice plain, the glacier follows a deep trench, with no apparent bedrock knolls that could temporarily slow its retreat [*Holt et al.*, 2006]. The contri-

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033365.

bution of Smith Glacier to the total loss from this region will therefore continue to grow rapidly.

[21] It has been suggested that the origin of the flow acceleration, grounding line retreat and thinning of these glaciers is oceanic [*Rignot*, 1998; *Payne et al.*, 2004; *Shepherd et al.*, 2004; *Jacobs*, 2006]. The inferred near balance of the 1970s suggests that the ocean changes responsible for that evolution originated for the most part around that time. This coincides with a period of increasingly more positive southern annular mode (SAM) [*Marshall et al.*, 2004], which has increased westerly wind flow, leading to northward-drift of surface water and sea ice, and bringing warmer Antarctic circumpolar water (ACC) against the coastline. Some of these warm waters may have been able to overflow onto the continental shelf via troughs carved by ice streams from past ice ages, follow the downward slope towards the coastline, and reach the glacier grounding lines [*Jacobs*, 2006]. The ACC water may also be getting warmer [*Gille*, 2002]. As this forcing is likely to continue, it will fuel the retreat and acceleration of ice into deeper parts of West Antarctica.

## 5. Conclusions

[22] ALOS PALSAR is providing useful and timely measurements of ice-shelf and glacier motion in the most challenging and important parts of West Antarctica. As multiple repeat passes are collected in the future, it may be possible to observe differential changes in glacier grounding lines; which are now critical to confirm ungrounding of the ice plains and enable more quantitative analyzes of changes and future trends.

[23] In the mean time, InSAR observations reveal a doubling of the mass loss in ten years from this region of Antarctica, with no slow down, but a steady and increasing uprise in mass flux and mass loss instead. The record changes observed in the last 16 months, on both Pine Island and Smith glaciers, and the breakup of the floating section of Thwaites Glacier, call for increased attention on this sector of accelerated ice flow from West Antarctica. Over the long term, the potential for runaway ungrounding and collapse of this sector of West Antarctica is an open possibility.

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