AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2013GL059069

Key Points:

- Sustained ASE mass flux increase: 77% since 1973
- Thwaites accelerated by 33% during the last 6 years
- Speed changes are pervasive and rapid: major implications for ice flow modeling

Supporting Information:

- Readme
- Table S1
- Table S2

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Citation:
Mouginot, J., E. Rignot, and B. Scheuchl (2014), Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013, *Geophys. Res. Lett.*, *41*, doi:10.1002/2013GL059069.

Received 19 DEC 2013
Accepted 7 FEB 2014
Accepted article online 12 FEB 2014

Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013

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Abstract We combine measurements of ice velocity from Landsat feature tracking and satellite radar interferometry, and ice thickness from existing compilations to document 41 years of mass flux from the Amundsen Sea Embayment (ASE) of West Antarctica. The total ice discharge has increased by 77% since 1973. Half of the increase occurred between 2003 and 2009. Grounding-line ice speeds of Pine Island Glacier stabilized between 2009 and 2013, following a decade of rapid acceleration, but that acceleration reached far inland and occurred at a rate faster than predicted by advective processes. Flow speeds across Thwaites Glacier increased rapidly after 2006, following a decade of near-stability, leading to a 33% increase in flux between 2006 and 2013. Haynes, Smith, Pope, and Kohler Glaciers all accelerated during the entire study period. The sustained increase in ice discharge is a possible indicator of the development of a marine ice sheet instability in this part of Antarctica.

1. Introduction

Pine Island, Thwaites, Haynes, Smith, Pope, and Kohler Glaciers are among the fastest-flowing glaciers in continental Antarctica [*Rignot et al.*, 2011b]. Combined together, they drain one third of the West Antarctic Ice Sheet into the Amundsen Sea Embayment (ASE), or 393 million square kilometers. Their mass flux into the southern Pacific Ocean (280 ± 9 Gt/yr in 2007) [*Rignot*, 2008] is comparable to that of the entire Greenland Ice Sheet into the Arctic Ocean [*Rignot and Kanagaratnam*, 2006]. Since first revealed with satellite radar interferometry in the 1990s [*Rignot*, 1998], this sector has been significantly out of balance [*Rignot et al.*, 2008; *Chen et al.*, 2009; *Rignot*, 2002] due to glacier speedup [*Rignot*, 2001, 2006, 2008; *Joughin et al.*, 2003]. Concurrent with the acceleration in ice flow, the glaciers have been thinning and their grounding-line positions—where ice goes afloat—have been retreating at a rate of 1 km/yr, one of the fastest retreat rates in the world [*Rignot*, 1998, 2001; *Rignot et al.*, 2013; *MacGregor et al.*, 2012; *Holland et al.*, 2008]. Together, the ASE glaciers are major contributors to sea level rise from Antarctica with about 0.28 ± 0.05 mm/yr between 2005 and 2010 [*Shepherd et al.*, 2012], which itself amounts to about 10% of the global sea level rise (3 mm/yr) [*Church and White*, 2011]. Together, these glaciers and their catchment basins combined contain 1.2 m global sea level rise.

Prior studies have shown that Pine Island Glacier sped up from 2.25 km/yr in 1974 [*Crabtree and Doake*, 1982; *Williams et al.*, 1982; *Lindstrom and Tyler*, 1984] to >4 km/yr by 2008 [*Rignot et al.*, 2002; *Joughin et al.*, 2003; *Rignot*, 1998, 2008]. No change in speed was reported for the time period 2009–2010 [*Joughin et al.*, 2010]. Satellite observations also showed that between 1996 and 2006, Thwaites Glacier [*Rignot et al.*, 2002; *Rignot*, 2008] had been slowly widening, with no major change in speed over its fast-moving, central portion. Substantial changes in speed have been recorded on Smith Glacier, which accelerated 75% between 1996 and 2006 [*Rignot*, 2008]. No significant change in speed was noted between 1973 and 1992 for its neighbor Kohler Glacier [*Lucchitta et al.*, 1994].

Here, the mass flux from all the glaciers in the ASE over the last 41 years is revisited, combining data spanning from Landsat in 1973 to satellite radar interferometry data in 2013. We then estimate the mass flux of the glaciers and present maps of the evolution of ice flow over the entire drainage basin since 2006. We conclude with analysis and discussion of the nearly half-a-century evolution of this major sector of West Antarctica.

Table 1. Ice Flux in Gt/yr at the 2011 Grounding Line of Pine Island, Thwaites, Haynes, Smith/Pope, and Kohler Glaciers, in the Amundsen Sea Embayment (ASE) of West Antarctica From 1973 to 2013[a]

Year	Pine Island	Thwaites	Haynes	Smith/Pope	Kohler	Total
1974.0 ± 1.00	78 ± 7	-	-	-	-	189 ± 17[b]
1978.0 ± 5.00	-	72 ± 7	10 ± 2	12 ± 2	-	191 ± 17[b]
1981.0 ± 7.50	-	-	-	-	17 ± 2	193 ± 17[b]
1986.0 ± 2.00	-	83 ± 8	12 ± 2	14 ± 2	-	197 ± 17[b]
1987.0 ± 1.00	87 ± 7	-	-	-	-	197 ± 17[b]
1989.0 ± 1.00	-	91 ± 8	-	16 ± 2	-	220 ± 17[b]
1992.2 ± 0.08	84 ± 2	91 ± 3	-	-	17 ± 1	220 ± 10[b]
1994.3 ± 0.04	87 ± 3	93 ± 3	11 ± 1	17 ± 2	18 ± 2	226 ± 11
1996.1 ± 0.25	89 ± 2	96 ± 4	11 ± 1	20 ± 1	20 ± 1	235 ± 9
2001.0 ± 0.29	97 ± 3	97 ± 4	12 ± 1	20 ± 2	20 ± 1	247 ± 12
2002.0 ± 0.29	98 ± 3	-	-	-	-	249 ± 12[b]
2003.0 ± 0.29	101 ± 3	98 ± 4	11 ± 1	22 ± 2	21 ± 2	253 ± 12
2004.0 ± 0.29	103 ± 3	102 ± 4	12 ± 1	22 ± 2	21 ± 2	260 ± 12
2005.0 ± 0.29	108 ± 3	101 ± 4	12 ± 1	23 ± 1	23 ± 3	268 ± 11
2006.0 ± 0.29	111 ± 9	103 ± 4	12 ± 1	25 ± 2	26 ± 3	278 ± 17
2006.9 ± 0.29	116 ± 3	104 ± 4	12 ± 1	27 ± 1	26 ± 1	285 ± 10
2007.9 ± 0.29	127 ± 3	110 ± 4	13 ± 1	29 ± 1	27 ± 1	306 ± 10
2008.9 ± 0.29	132 ± 4	114 ± 4	13 ± 1	30 ± 1	28 ± 1	317 ± 11
2009.9 ± 0.29	134 ± 4	116 ± 4	13 ± 1	31 ± 1	29 ± 2	323 ± 12
2010.9 ± 0.29	135 ± 4	119 ± 5	13 ± 1	31 ± 1	31 ± 2	328 ± 13
2011.7 ± 0.08	135 ± 4	122 ± 5	14 ± 1	30 ± 1	31 ± 1	332 ± 12
2012.9 ± 0.08	133 ± 4	124 ± 5	15 ± 1	30 ± 3	31 ± 3	333 ± 15
2013.5 ± 0.13	132 ± 4	126 ± 5	14 ± 1	31 ± 1	31 ± 3	334 ± 14

[a]Fluxes are corrected for ice thickness change (see supporting information for details).
[b]Missing glacier fluxes are interpolated.

2. Data and Methods

We derive ice velocity using data from the Landsat Thematic Mapper and MultiSpectral Scanner, the Earth Remote Sensing imaging radar satellite (ERS-1/2), the Advanced Land Observation System (ALOS) Phased-array L-band Synthetic Aperture Radar (PALSAR), the RADARSAT-1/2 radars, and the TANDEM-X mission.

Ice surface velocities prior to 1992 are from Landsat data. Using sequential images, average velocities are calculated from the displacements of recognizable surface features such as crevasses and rifts. Velocities for Pine Island Glacier in 1973–1975 and 1986–1988 and Thwaites Glacier in 1988–1990 are from the National Snow and Ice Center (NSIDC); other velocity data are from this study. To track image features, we coregister the Landsat scenes with the 2004 Landsat Image Mosaic of Antarctica (LIMA) by selecting a set of ground control points with zero velocity and then calculate image offsets between registered images acquired at different times. LIMA registration accuracy is better than 1 pixel (30 m). Our results are in excellent agreement with those obtained prior to the advent of LIMA [*Rosanova et al.*, 1998; *Ferrigno et al.*, 1993; *Lucchitta et al.*, 1994, 1995]. We estimate accuracy of the glacier displacements to be 4 pixels, yielding errors in ice velocity ranging from 16 m/yr to 60 m/yr depending on the time interval between images.

The ERS-1/2 data are 1 day repeat data from the winter of 1995–1996 processed interferometrically using a combination of ascending and descending passes [*Joughin et al.*, 1998]. The remaining radar data are analyzed using a speckle tracking algorithm [*Michel and Rignot*, 1999]. Partial coverage of the glaciers is available in the winters of 1992 and 1994 during a 3 day cycle of ERS-1. The RADARSAT-1/2 data are 24 day repeat data from six winters between 2001 and 2006, fall 2011, and spring 2013. The ALOS PALSAR data are 46 day repeat cycle data acquired during five consecutive winters between 2006 and 2011. The TANDEM-X data are 11 day repeat data, from the winter of 2012 and summer 2013. All data are calibrated and mosaicked together using the procedure described by *Mouginot et al.* [2012]. Errors in InSAR ice velocity (after 1992) are 5 m/yr [*Rignot et al.*, 2011b; *Mouginot et al.*, 2012].

Ice fluxes are calculated by combining surface velocity from different years with ice thickness from year 2004 [*Fretwell et al.*, 2013] corrected for temporal changes in ice thickness derived from time series of satellite altimetry data (see Table 1 and supplemental information). For each glacier, we calculate the average flux from five different flux gates, approximately equally spaced, located within a few kilometers upstream of

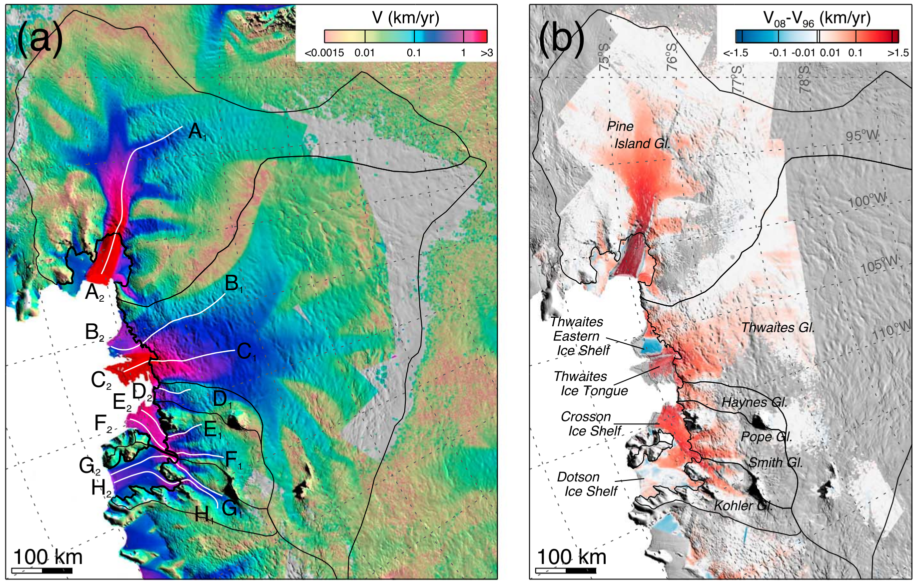

Figure 1. (a) Flow speed of the Amundsen Sea Embayment (ASE) sector of West Antarctica, color coded on a logarithmic scale and obtained combining satellite observations spanning from year 1996 to year 2013 with flux gates at the location of the grounding lines in 2011 (thick black lines) [*Rignot et al.*, 2011a] and topographic divides (thin black lines); and (b) change in flow speed between 2008 and 1996 color coded on a logarithmic scale and overlaid on a MODIS mosaic.

the 2011 grounding-line positions. The flux is corrected to account for surface mass balance and ice thinning between the flux gate and the 2011 grounding line. This process helps quantify errors in flux estimates. When few gaps are present in the velocity record along flux gates (<30%), we employ ice velocity from the closest year with no gap, which we adjust vertically at both ends of the missing segments and linearly interpolate in between. For years with more than 30% gap, we scale the ice flux to that measured in the closest year with no gap.

Following *Wingham et al.* [2009], ice thinning is modeled as a parabolic trend: $h(\tau) = h_{2004} - \dot{h}_{2004}(\tau - 2004) - \frac{1}{2}\ddot{h}_{2004}(\tau - 2004)^2$, where $h(\tau)$ is the ice thickness at a given year τ, h_{2004} is the ice thickness from BedMap-2 [*Fretwell et al.*, 2013] in 2004, $\dot{h}_{2004}$ is the thickening rate (>0 means thickening) deduced from 2003–2008 ICESat data calculated as in *Pritchard et al.* [2012] (see supporting information), and $\ddot{h}_{2004}$ is the acceleration in thickening in 2004. *Wingham et al.* [2009] estimate $\ddot{h}_{2004} = -0.12$ m/yr^2 between 1995 and 2006 for Pine Island Glacier, or about 7% of the 2004 thinning rate. For the other glaciers, we assume an acceleration in ice thinning at the grounding line $\ddot{h}_{04}$ of 7% of $\dot{h}_{04}$. This would mean that ice started thinning around 1988 with a quadratic increase since then. Thus, we neglect the glacier thinning that may have occurred during the period 1973–1988 [*Jenkins et al.*, 2010]. We have no information on thinning rates prior 1992, but they were presumably smaller, because the glacier acceleration was less. Assuming a thinning rate of 1 m/yr, the glaciers may have been 15 m thicker in 1973 than in 1988, which corresponds to an error of about 1% on the ice flux.

The error in ice thickness is 40 m [*Fretwell et al.*, 2013]. Estimates of flux error δF integrate errors in velocity δV and thickness δH along flux gates as $\delta F = H\delta V + V\delta H$. When a scaling factor is used to estimate flux, the associated error δF is calculated as $\delta F = \alpha\delta F_0 + F_0\delta\alpha$, where α is the scaling factor and F_0 the scaled flux (see supporting information). $\delta\alpha$ is taken as 0.05.

In 1996 and 2008, a nearly complete mapping of ice velocity over the northernmost reaches of the entire ASE sector was possible. We detect the spatial pattern of change in ice velocity (Figure 1b). Comprehensive mappings of velocity change are also available for 2009, 2010, and 2011. Velocity mapping is only partial prior to 1996 or after 2011 due to a lack of data acquisition by satellites or the termination of satellite missions. In the upper reaches of Thwaites and Pine Island Glaciers, data coverage is incomplete due to sparse data acquisitions, combined with low coherence levels attributed to significant reworking of the ice/snow surface by weathering.

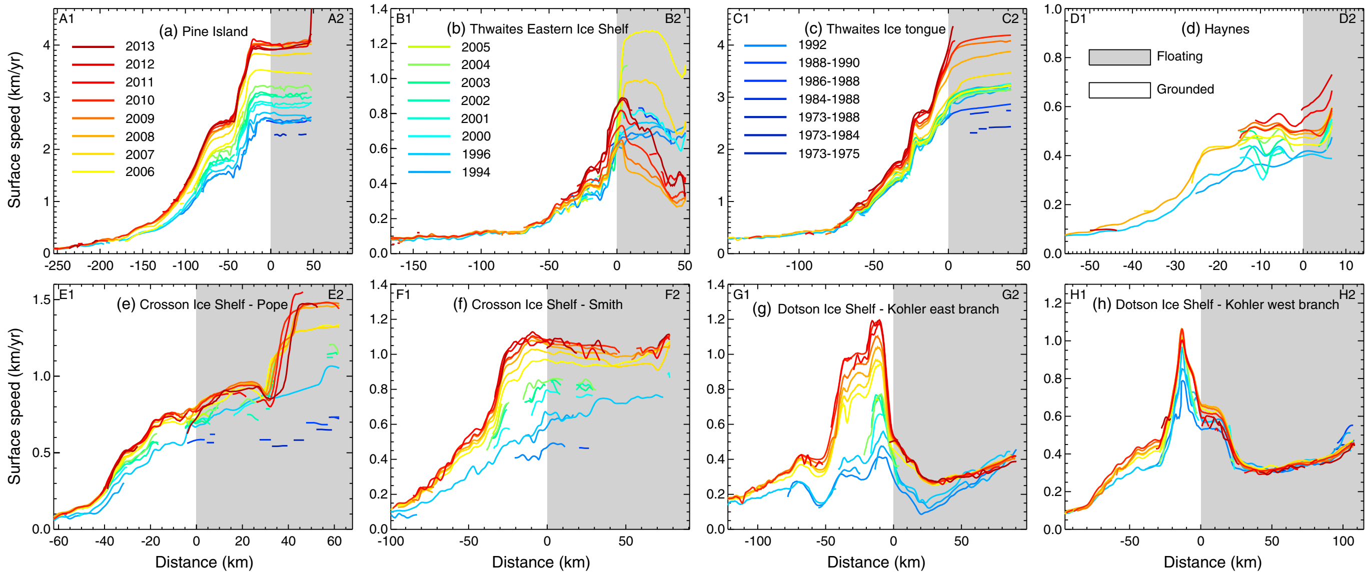

Figure 2. (a–h) Flow speed along the flow lines, A_1/A_2 to H_1/H_2, respectively, shown in Figure 1 spanning from year 1973 (blue) to year 2013 (red). Grey shading is used for the floating part of the glaciers in 1996 [*Rignot et al.*, 2011a].

3. Results

Figure 1 shows the ice flow of the ASE sector and the spatial pattern of speedup between 1996 and 2008. Pine Island Glacier is 30 km wide at the grounding line, fed by nine tributaries, and developing a 55 km long floating section that flowed at 4 km/yr in 2006. Thwaites Glacier is 120 km wide, with a 60 km wide fast-moving section that develops into the Thwaites Glacier Tongue to the west and a 60 km wide slower-moving section that flows into an ice shelf buttressed by ice rumples to the east, herein the Thwaites Eastern Ice Shelf (TEIS), an unofficial name. Farther west is the 46 km wide Haynes Glacier, with no floating section, which calves directly into the ocean at a flow speed of about 0.6 km/yr. Pope is a 14 km wide glacier that flows into Crosson Ice Shelf at 0.8 km/yr. Smith Glacier has two tributaries which flow into Crosson Ice Shelf at 1 km/yr. Kohler Glacier flows into Dotson Ice Shelf via one branch to the east of the Kohler Range flowing at 1.1 km/yr through a set of ice rises and rumples indicative of a shallow water column and a second branch to the west of the Kohler Range flowing at 1 km/yr. Interestingly, no study had previously noted the existence of the two branches for Kohler Glacier and the fact that Kohler only flows into Dotson Ice Shelf. In particular, the eastern branch of Kohler should not be confused with Smith Glacier, which is farther east.

All glaciers and ice shelves in ASE experience some level of flow acceleration during 1996–2008, except for the slow-moving TEIS and Dotson Ice Shelf (Figures 1–3). Where we detect acceleration, the change in speed is also proportional to the speed, i.e., larger changes are detected over faster-moving portions of the glaciers. The changes in speed are not localized at the grounding line, i.e., they extend far inland, along all tributaries and on all glaciers. On Pine Island Glacier, a change in speed is detected almost over the entire drainage system, up to 250 km from the grounding line. Changes in speed extend nearly to the flanks of the topographic divides and are only limited by the detectability of the signal (± 10 m/yr). Note that this is the first time that the full extent of the speedup is presented, since the second full mapping of ice velocity of Pine Island Glacier (first one is 1996) took place only in 2006.

On Thwaites Glacier, changes in speed affect the entire portion of the system where InSAR velocities are available. The acceleration extends along the two main tributaries several hundreds of kilometers inland, to the limit of the 2008 mapping. On Haynes, Pope, Smith, and Kohler, the changes in speed affect the entire sector mapped with InSAR as well. In contrast, we detect no change in speed on Dotson Ice Shelf during that time period, consistent with results obtained in prior studies [*Lucchitta et al.*, 1994].

On Pine Island Glacier, the ice shelf flow speed (Figure 2a) increased by 1.7 km/yr, or 75%, between 1973 and 2010. After 2010, the ice shelf experienced no further acceleration and even slowed down by 0.1 km/yr between 2009 and 2013. Ice velocity, however, kept increasing farther inland between 2009 and 2013 (Figures 2a and 3). The calving of a large tabular iceberg in 2011 [*Howat et al.*, 2012] appeared as a sector of

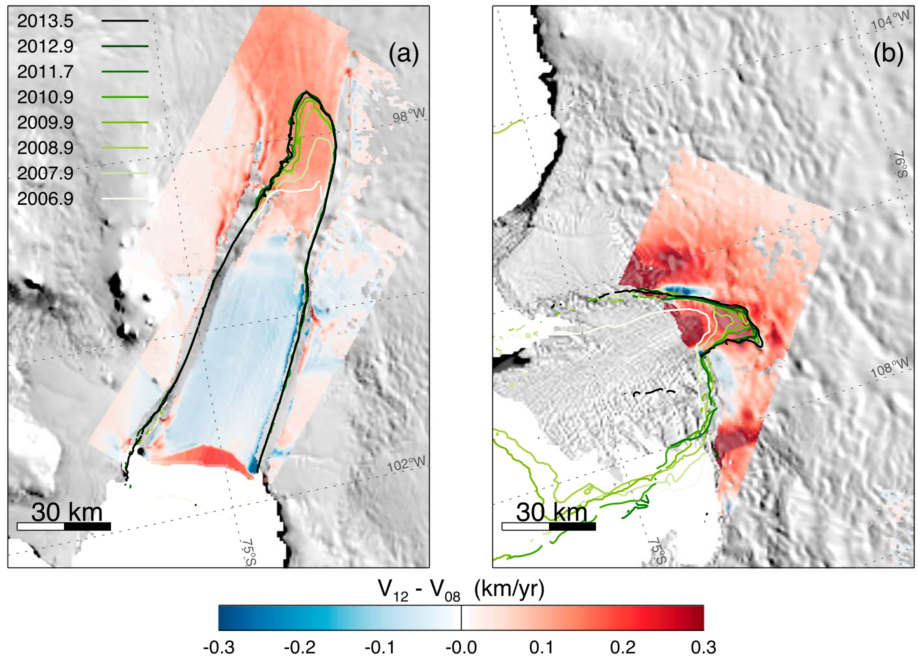

Figure 3. Change in flow speed from year 2008 to year 2012 on (a) Pine Island and (b) Thwaites Glaciers. Green-colored lines indicate the position of the contour of flow speed at 2.3 km/yr (Pine Island Glacier) and 2.5 km/yr (Thwaites Glacier) for the years 2006 to 2013.

200 m/yr speedup at the ice shelf front, with no impact on the rest of the flow (Figure 3a). In total, the ice flux of Pine Island increased from 78 ± 7 Gt/yr in 1973 to a maximum of 135 ± 4 Gt/yr in 2010 (Figure 4) and remained at its 2010 level with 132 ± 4 Gt/yr in the summer of 2013. Total ice discharge increased by 69% in 41 years.

Between 1973 and 1996, Thwaites Glacier Tongue accelerated by 0.8 km/yr, or 33%. The speed remained stable in 1996–2006 and accelerated again in 2006–2013 by 33%. The flow speed was 4 km/yr at the grounding line in the winter of 2012–2013 (Figure 2c). In contrast, the TEIS (Figure 2b) doubled its speed between 1996 and 2006 then slowed down between 2006 and 2008 from 1.3 to 0.4 km/yr. Starting in 2008, the grounded sector inland of the TEIS sector accelerated, in places by more than 25% by 2013, with ice flow changes propagating more than 30 km upstream of the 2011 grounding line. Over the last 41 years, the total flux of Thwaites Glacier increased from 72 ± 7 Gt/yr in 1973–1984 to 126 ± 5 Gt/yr in summer 2013, or +75%.

Haynes Glacier flow speed at the grounding line changed from 0.4 km/yr in 1992 to 0.6 km/yr in 2013. This increase in ice velocity coincides with the progressive loss of its floating ice shelf that started to calve in 1988 and disappeared completely in 2003 [*MacGregor et al.*, 2012]. Its ice flux increased from 10 ± 2 Gt/yr in 1978 to 14 ± 1 Gt/yr in 2013.

Farther to the west is the Crosson Ice Shelf, fed by Pope and Smith Glaciers, which exhibits small changes in speed between 1973–1974 and 1984–1988, when the ice shelf velocity was 0.6–0.7 km/yr, but which accelerated in the early 1990s to exceed 0.9 km/yr, i.e., a 50% speedup. Starting in 2006, the eastern side of Crosson (Figure 2d) fed by Pope Glacier experienced a large velocity increase of > 60% in the last 25 km, which coincides with a major calving event, whereas the remainder of the ice shelf only sped up by 25%. The velocity upstream of the grounding line increased up to 2011, but the ice shelf sector about 30 km downstream of the grounding line did not change much after 2007. The western side of Crosson (Figure 2e), fed by Smith Glacier, shows a different pattern. Starting in 1996, the ice velocity of the grounded and floating parts of Smith increased continuously. Smith Glacier increased its speed by 64% from 0.7 km/yr in 1996 to more than 1.15 km/yr in 2012 at the grounding line. Overall, the flux of Crosson Ice Shelf increased by 170% in 40 years, from 12 ± 2 Gt/yr in the late 1970s to more than 31 ± 1 Gt/yr in 2013.

The ice front velocity of Dotson Ice Shelf from 1996 to 2010 is 0.4 km/yr, similar to the speed observed in 1973–1986 by *Lucchitta et al.* [1994] (Figures 2d and 2h). Thus, the ice front flux was constant at 5–6 Gt/yr

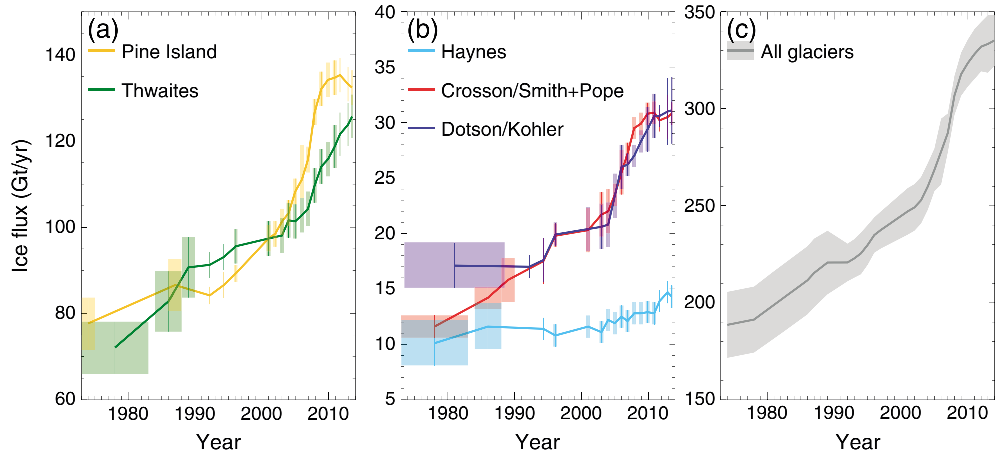

Figure 4. Evolution of ice discharge at the grounding line of (a) Pine Island and Thwaites Glaciers, (b) Haynes, Smith, Pope, and Kohler Glaciers, and (c) all glaciers combined together with the 1σ confidence interval in light gray. For Figures 4a and 4b, the horizontal and vertical extent of the boxes represents the time interval and error associated with the ice flux, respectively.

[*Rignot et al.*, 2013], while the total ice flux into Dotson Ice Shelf increased from 17 ± 2 Gt/yr in 1981 to 31 ± 3 Gt/yr in 2013. The speed of grounded ice eastern branch (Figure 2h) increased from 0.35 km/yr in 1996 to $>$ 1.2 km/yr in 2012. The speed at the grounding line of the western branch of Kohler Glacier increased from 0.8 in 1992 to 1.1 km/yr in 2012.

Figure 3 illustrates the changes in flow speed of Pine Island (left) and Thwaites Glaciers (right) from 2008 to 2012. On Pine Island Glacier, the data reveal a deceleration of the ice shelf flow, but an acceleration of ice flow upstream of the 2011 grounding line concentrated along the western flank of the glacier. On Thwaites Glacier, the TEIS accelerated from 2008–2013. The ice flow accelerated inland of the grounding line in 2008–2012, similar to Pine Island, especially at the glacier center. The change in speed is, however, less uniform than for Pine Island Glacier.

The total ASE ice flux (Figure 4) increased from 189 ± 17 Gt/yr in the 1970s to 334 ± 14 Gt/yr in 2013, or +77%. During the first 30 years, ice discharge increased at a rate of 2.2 Gt/yr^2. Between 2003 and 2010, the rate is 9.5 Gt/yr^2, mainly due to the acceleration of Pine Island Glacier. The record flux year is 2007 with a total ASE ice discharge increasing by 20 Gt/yr in 1 year. After 2010, the total ice flux increases at 2.3 Gt/yr^2, similar to the rate prior to 1996 (Figure 4).

4. Discussion

The large acceleration in ice velocity and ice discharge of Pine Island Glacier between 2002 and 2008 coincides with a period of rapid retreat of its grounding line across an ice plain, a region grounded only a few tens of meters above hydrostatic equilibrium as identified in prior studies [*Corr et al.*, 2001; *Schmeltz et al.*, 2002; *Thomas et al.*, 2004b]. The grounding line is now localized at the inland end of the ice plain [*Park et al.*, 2013]. Both grounding line and flow speed of the glacier have been stable since 2009. This evolution of ice flow until 2009 is remarkably consistent with the modeling developed by *Thomas et al.* [2004a], which was based on a fast retreat of the grounding line across the ice plain.

The changes in speed in the drainage basin of Pine Island Glacier are pervasive and more rapid than anticipated. In 1996, we observed ice velocity changes propagating more than 100 km over a 1 month period, i.e., in a mode that is not compatible with purely advective processes [*Payne et al.*, 2004] but which indicates a rapid transmission of longitudinal stress gradients as predicted by [*Thomas et al.*, 2004a]. Observed velocity changes always propagate in less than a year across the entire basin. These observations are consistent with the modeling of [*Williams et al.*, 2012] suggesting that membrane stresses can be transmitted rapidly over the entire basin. Pure advective processes, in contrast, proceed on time scales of several decades [*Payne et al.*, 2004].

A second major observation of recent changes in ice dynamics is the acceleration of Thwaites Glacier since 2006. Prior observations suggested that the glacier did not experience significant change in flow speed between 1992 and 2005. During a transition period between 2006 and 2008, as the main part of the glacier accelerated, the TEIS switched from accelerating to decelerating. Between 1996 and 2000, the TEIS was reported to be cracking up and rifting at its grounding line [*Rignot*, 2006], which indicated excessive longitudinal straining of the ice shelf, i.e., the ice shelf was pulled away from the continent. This can only be explained from the entrainment of the TEIS by lateral shearing from the fast-moving main ice tongue. The region in between the two floating sections is a complex mixture of rifts, cracks, and icebergs trapped in a zone of intense shear: 4 km/yr to 0.6 km/yr in less than 1 to 9 km. We hypothesize that prior to 2006 the two ice shelves were strongly coupled, which explains the faster flow rate of TEIS. After 2006, the coupling must have decreased, with the result that TEIS decelerates. The physical processes responsible for the change in coupling are unknown at this time. They could be due to oceanic changes [*Jacobs et al.*, 2011, 2012], to the calving of the main ice tongue in 2010 [*MacGregor et al.*, 2012], or to mechanical failure of the ice mélange. For instance, warmer waters beneath the ice shelf would melt the ice tongue faster, reduce back stress from the main glacier, and entrain speedup, which would significantly affect the mechanical rigidity of the mélange between the TEIS and the main ice tongue. After 2008, the TEIS accelerated again, but a restoration of the coupling between the two ice shelves seems unlikely as the main ice tongue calved in 2010. The recent acceleration might be better explained by a reduced buttressing of the pinning point at its terminus [*Tinto and Bell*, 2011; *MacGregor et al.*, 2012] and/or the retreat of its grounding line due to enhanced thinning caused by warmer ocean water. This behavior requires further investigation using numerical modeling. It illustrates the important role of the TEIS in the overall evolution of Thwaites Glacier. The observations also indicate that changes in ice dynamics of Thwaites Glacier are just as significant as those of Pine Island Glacier. Thwaites Glacier is, however, 120 km wide and not confined in a valley [*Fretwell et al.*, 2013], hence with the potential for a much larger increase in ice flux if the flow acceleration continues at the same pace.

Between 1996 and 2008, the grounding line of Smith Glacier retreated across a 20 km long ice plain grounded only a few tens of meters above hydrostatic equilibrium [*Rignot*, 2006]. Ice thinning of several meters per year, recorded by altimeters, must have been sufficient to bring the ice plain to floatation, reduce buttressing at the grounding line, and entrain further speedup, thinning, and glacier retreat [*Thomas et al.*, 2004a]. The Crosson Ice Shelf doubled its grounding-line ice flux in the last 41 years. The flow changes on Crosson Ice Shelf are proportionally larger than those on Pine Island and Thwaites Glaciers. Future studies should examine the apparent great sensitivity of Smith Glacier to thermal forcing from the ocean.

In complete contrast, Dotson Ice Shelf maintained a steady flow during the entire observation period. With an area-average thinning rate of 2.9 ± 0.3 m/yr [*Rignot et al.*, 2013], its ice front flux has remained steady or decreased slightly at about 5–6 Gt/yr [*Rignot et al.*, 2013], while its grounding-line flux continuously increased between 1981 and 2013 from 17 Gt/yr to 31 Gt/yr. The surface mass balance of the 5803 km^2 ice shelf did not change detectably during that period, but the ice shelf volume decreased significantly [*Pritchard et al.*, 2012]. We attribute this evolution to an increase in ice shelf melting, caused by enhanced advection of oceanic heat beneath the ice shelf. The Dotson Ice Shelf has a shallow sub-ice shelf cavity inferred from the presence of numerous ice rises on its northern flank as well as in its center. With a surface mass balance of 16 ± 1 Gt/yr [*Shepherd et al.*, 2012], Kohler Glacier changed from near equilibrium in 1981 to well out of balance in 2013. Assuming Dotson Ice Shelf was also at equilibrium in 1981 and applying the principles of mass conservation between the ice front and the grounding line, we calculate that the area-average melt rate of Dotson Ice Shelf increases by 2.6 ± 0.4 m/yr in 32 years. If we assume a sensitivity of 10 m/yr/°C, this enhanced melt rate (2.6 m/yr) combined with the thinning (2.9 m/yr) reported by *Rignot et al.* [2013] would imply that the average ocean thermal forcing beneath the ice shelf increased by about 0.55°C in 32 years.

Despite steady flow at the grounding line of Pine Island Glacier since 2008 (Figure 3), the ice discharge and mass loss of the ASE sector is increasing during the entire observational period, including in 2010–2013. On Pine Island Glacier, the speedup is propagating inland, which is inconsistent with the modeling claims of stagnation for the next 500 years [*Joughin et al.*, 2010] but consistent with recent studies that indicate a strong coupling between glacier retreat and ice shelf melting [*Favier et al.*, 2014]. The recent acceleration of Thwaites Glacier indicates that all the glaciers in the ASE sector are losing an increasing amount of ice into the ocean every year. These observations are a possible sign of the progressive collapse of this sector in response to the high melting of its buttressing ice shelves by the ocean.

5. Conclusions

Observations of the ASE of West Antarctica since 1973 indicate speedup of all the glaciers and a steady increase in ice discharge into the ocean from the collective ensemble of these large, major glaciers. During retreat across their respective ice plains, Pine Island and Smith Glaciers underwent a rapid increase in ice discharge. However, since 2009, the ice discharge of Pine Island has remained steady. Thwaites Glacier, which had experienced a steady flow since 1992, started to speed up in 2006 and has increased its ice discharge considerably since. The acceleration of Thwaites Glacier more than compensated for the recent stoppage of the acceleration of Pine Island Glacier. These satellite measurements and subsequent results are of importance to revise our understanding and projection of the evolution of this major part of West Antarctica. The velocity data analyzed in this study will be available at NSIDC as part of the MEaSUREs project. Until numerical ice sheet models coupled with realistic oceanic forcing are able to replicate these observations, projections of the evolution of this sector of West Antarctica should be interpreted with caution.

Acknowledgments
This work was performed at the University of California, Irvine, and at the Jet Propulsion Laboratory, California Institute of Technology, under a grant from the National Aeronautics and Space Administration's Cryospheric Science Program and MEaSUREs program. The authors gratefully acknowledge the European Space Agency, the Canadian Space Agency, the Japan Aerospace Exploration Agency, and the Deutsches Zentrum für Luft- und Raumfahrt for the use of ERS-1&-2, RADARSAT-1&-2, ALOS PALSAR, and TanDEM-X data, respectively. Data acquisition was coordinated by the Space Task Group (2006–2009) and the Polar Space Task Group (post 2009).

The Editor thanks Robert Thomas and an anonymous reviewer for their assistance in evaluating this paper.

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