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Key Points:
- Sentinel-1 is a breakthrough mission for systematic, widespread, continued, grounding line mapping in Antarctica
- Pope, Smith, and Kohler Glaciers are undergoing major changes. The Grounding line of Smith Glacier continues to retreat at 2 km/yr
- Crosson and Dotson Ice Shelves lost many pinning points, which significantly threatens their stability in years to come

Supporting Information:
- Supporting Information S1

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Grounding line retreat of Pope, Smith, and Kohler Glaciers, West Antarctica, measured with Sentinel-1a radar interferometry data

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Abstract We employ Sentinel-1a C band satellite radar interferometry data in Terrain Observation with Progressive Scans mode to map the grounding line and ice velocity of Pope, Smith, and Kohler glaciers, in West Antarctica, for the years 2014–2016 and compare the results with those obtained using Earth Remote Sensing Satellites (ERS-1/2) in 1992, 1996, and 2011. We observe an ongoing, rapid grounding line retreat of Smith at 2 km/yr (40 km since 1996), an 11 km retreat of Pope (0.5 km/yr), and a 2 km readvance of Kohler since 2011. The variability in glacier retreat is consistent with the distribution of basal slopes, i.e., fast along retrograde beds and slow along prograde beds. We find that several pinning points holding Dotson and Crosson ice shelves disappeared since 1996 due to ice shelf thinning, which signal the ongoing weakening of these ice shelves. Overall, the results indicate that ice shelf and glacier retreat in this sector remain unabated.

1. Introduction

The Amundsen Sea Embayment (ASE) sector of West Antarctica has been undergoing significant changes over the past few decades and is the largest contributor to sea level rise from Antarctica at present [*McMillan et al.*, 2014; *Mouginot et al.*, 2014; *Rignot et al.*, 2014; *Sutterley et al.*, 2014]. Spaceborne remote sensing is crucial to assess its state of mass balance, detect temporal and spatial changes in mass balance, and provide ice sheet numerical models with suitable observations and boundary conditions to model the evolution of ice in this sector. The position of the grounding line, where ice detaches from the bed and becomes afloat in the ocean, is especially critical to know with precision in order to define where basal friction of glacier ice drops to zero and where ice melts in contact with the ocean or breaks up into icebergs. Prior attempts at mapping grounding lines have been limited because few spaceborne SAR missions offer the short-term repeat pass capability required to map the differential vertical displacement of floating ice at tidal frequencies with sufficient detail to resolve grounding line boundaries in areas of fast ice deformation [*Rignot et al.*, 2011a; *Li et al.*, 2015].

On the eastern part of ASE, the satellite record has indicated that Pine Island and Thwaites glaciers have been thinning, their grounding lines have been retreating at rates of 1–2 km/yr, and their speeds have been increasing with time [*Rignot*, 2008; *Park et al.*, 2013; *Rignot et al.*, 2014; *Mouginot et al.*, 2014]. On the western part of ASE, Pope, Smith, and Kohler glaciers also contribute to ice drainage from the ASE through Crosson and Dotson ice shelves. In the 1980s, when the glaciers were estimated to be close to a state of mass balance, they drained about 15% of the mass flux from the ASE. At present, however, the same glaciers contribute 23% of the mass loss from ASE, i.e., their rate of change has been nearly twice as large as the rate of change of Pine Island and Thwaites glaciers [*Mouginot et al.*, 2014]. While the grounding lines of Kohler and Smith have been observed to retreat between 1996 and 2011 [*Rignot et al.*, 2014], no data has been obtained to quantify the retreat of Pope Glacier since 1996, and no new grounding line mapping has been performed for any of these glaciers since 2011.

Observations from satellite altimeters indicate that Dotson and Crosson ice shelves, which are respectively fed by Kohler and Smith/Pope glaciers, have been thinning between 2003 and 2008 [*Pritchard et al.*, 2012]. A more recent study looking at a longer record suggests that ice thickness decreased by 10% and 18%, respectively, on Dotson and Crosson ice shelves between 1994 and 2012 [*Paolo et al.*, 2015]. A breakup of these ice shelves would reduce butressing of their tributary glaciers and likely trigger a significant increase in glacier speed, e.g., as observed in the wake of the collapse of Larsen B in the Antarctic Peninsula [*Scambos et al.*, 2004; *Rack and Rott*, 2004; *Rignot et al.*, 2004] and thereby increase their contribution to sea level.

All glaciers in the ASE sector drain from submarine basins, i.e., areas where the bed elevation is well below sea level [*Fretwell et al.*, 2013] . Several of the glaciers are currently retreating on a retrograde bed, i.e., where the bed elevation decreases farther inland, which makes them prone to marine instability [*Weertman*, 1974; *Meier and Post*, 1987] because the grounding line ice flux increases with the cubic power of ice thickness [*Schoof*, 2007]. It has been suggested that most of the ASE sector is undergoing an irreversible retreat at present because most of the glaciers are retreating along a retrograde bed and no major bumps exist farther upstream that could slow down their retreat [*Joughin et al.*, 2014; *Rignot et al.*, 2014; *Goldberg et al.*, 2015].

Sentinel-1a, launched on April 3, 2014, is the first of two Synthetic Aperture Radar (SAR) satellites developed by the European Space Agency as part of the European Union Copernicus Program [*Potin et al.*, 2015]. Sentinel-1b was successfully launched on April 25, 2016. These satellites and their recently approved successors are dedicated to Earth observations with near global coverage until at least 2030. Sentinel-1a has a 12 day repeat orbit and features a C band (5.4 GHz frequency) SAR with a phased-array antenna capable of acquiring data in a variety of modes [*Schubert et al.*, 2015]. Following the calibration/validation of the second satellite, the repeat orbit of the constellation will be shortened to 6 days. The main acquisitions over the Earth's land masses are made in Interferometric Wide Swath (IW) mode, a Terrain Observation with Progressive Scans SAR (TOPS) mode, which poses challenges for interferometric phase analysis in the presence of ground motion.

In this study, we employ a novel procedure for processing Sentinel-1a TOPS mode data over icy terrain that preserves the phase information sufficiently well to map the glacier grounding lines with precision for the first time since ERS-2 in 2011. Ice velocity is also a product of this data analysis. We analyze both products and their quality in the ASE sector of West Antarctica. We compare the results with earlier mappings to assess changes of grounding line position and ice velocity. We compare the pattern of retreat with high-resolution bed topography data, assess the changes in ice flux and mass balance of the glaciers, and conclude on their evolution since year 2011.

2. Data and Methods

TOPS data are acquired for enhanced radiometric performance over traditional ScanSAR data, which are affected by scalloping (repeating weak azimuth stripes at both edges of the focused burst image) [*Shimada*, 2009]. A TOPS IW swath is 250 km wide. It is formed by combining three subswaths acquired in parallel by electronically steering the antenna [*Meta et al.*, 2010]. The subswaths overlap in the cross-track direction by about 2 km. The incidence angle varies from 29° to 46° across the entire swath. We analyze scenes in single-look complex format that are about 170 km in length. The data have a pixel spacing of 13.9 m in azimuth (along track direction) and 2.4 m in slant range (across track direction), which correspond to a ground resolution of 20 m in azimuth and about 5 m in ground range.

Within each subswath, the data are acquired in a series of bursts, each about 20 km in length, overlapping by about 2 km in the along track direction. The bursts are synchronized from pass to pass to ensure proper alignment of interferometric pairs. Within each burst, the antenna operates a backward-to-forward azimuth electronic steering scan, resulting in an azimuth-varying Doppler history. In the areas of overlap, the surface is therefore imaged repeatedly with different satellite positions and Doppler histories.

The first step of standard TOPS data processing is to mosaic the burst images together. This step is followed by precise coregistration of the data based on precision orbit data. Phase jumps at burst boundaries can usually be avoided by precise coregistration of TOPS data to 1/1000th of a pixel which is challenging to meet from orbits alone [*González et al.*, 2015]. Exploiting the burst-to-burst overlapping regions to remove these residuals is possible but not if there is rapid motion on the ground.

We implement a different TOPS processing method for imaging the Earth over moving ice as described in Figure S1. First, we subtract the Doppler history of each burst based on the information provided with the single look complex (SLC) data header. This results in a first-order deramping of the SLC data for both the reference and slave image. We perform a classic speckle tracking on the resulting burst SLC data to obtain pixel offsets [*Michel and Rignot*, 1999; *Rignot et al.*, 2011b]. The pixel offsets can be converted into ice velocity [*Nagler et al.*, 2015]. We use an open source speckle tracker that handles residual phase ramps internally [*Mouginot et al.*, 2012]. Using the pixel offsets, the slave SLC is coregistered with the reference SLC; i.e., slave pixels are migrated based on the pixel offsets to match the reference pixels. This process helps recover phase coherence of the radar signals in areas of rapid motion, essentially tracking the scattering phase centers with time. The same registration is also performed on the Doppler history of the slave data. A residual Doppler history between the two scenes is then formed by differencing the resampled slave Doppler history with the Doppler history of the reference SLC. An interferogram is then formed by combining the registered slave SLC and the reference SLC, and the residual phase is subtracted thereby greatly reducing phase jumps at the burst boundaries.

Using this workflow, we processed all Sentinel-1a 12 day repeat data available for our region of interest between 18 October 2014 and 17 January 2016. The resulting velocity products for Pope, Smith, and Kohler glaciers are shown in Figure S2. The final step is to form double difference interferograms that reveal tidal motion of floating ice. We assume that the mostly horizontal motion of ice is constant in between passes, so the differencing reveals short-term variations in ice motion associated with the flexing of ice with changes in oceanic tides. Either three consecutive scenes are combined together into two interferograms spanning 12 (+12) days, or two independent interferograms spanning 12 days are combined to form a double difference interferogram. The assumption of steady horizontal flow of the ice may be violated for various reasons during the differencing, e.g., because of a variability in glacier speed at tidal or longer frequencies.

We selected image pairs closest in time to minimize the effect of long-term changes in speed and with the highest coherence levels. To map the 2014/2015 grounding line over the area of interest, we generated three double difference interferograms (Figure S3). We detect the grounding line at the upstream end of the dense fringe pattern that results from the tidal lift of floating ice forced by changes in oceanic tides. Residual subfringe phase jumps at path boundaries are negligible and have no effect on the quality grounding line mapping. The geolocation accuracy of Sentinel-1A data is about < 2 m [*Schubert et al.*, 2015]. Accordingly, the quality of the grounding line mapping is comparable or even superior to that offered by ERS-1/-2 or RADARSAT-2 described in *Rignot et al.* [2011a, 2014] (i.e., a standard error of $\pm$ 100 m). The dominant factor limiting the performance of Sentinel-1a mapping remains the 12 day repeat orbit, which results in temporal decorrelation of the phase signal, especially in areas of fast ice deformation.

The Sentinel-1a-derived ice velocities are combined with results from Landsat-8 and with an existing time series of ice surface velocity assembled from a suite of other SAR and optical satellites [*Mouginot et al.*, 2014]. Ice fluxes are calculated at the 2011 glacier grounding line using bed elevation and ice thickness from mass conservation [*Morlighem et al.*, 2011]. For years with sparse data coverage, we use a scaling method described in *Mouginot et al.* [2015] to estimate the change in ice flux with respect to a reference year of 2008. Changes in ice thickness measured from ICESat [*Pritchard et al.*, 2012] during 2003–2009 and NASA Operation IceBridge data beyond 2009 are employed to correct the ice fluxes for temporal changes in ice thickness [*Mouginot et al.*, 2015]. A discussion of the errors of the method is provided in supporting information.

3. Results

Figure 1a shows the complete grounding line mapping spanning from 1992 to 2014, along with a complete velocity mapping of the region of interest using all available data from 1996 to 2015. The Sentinel-1a velocity time series from October 2014 to January 2016 is shown in Figure S2. As prior time series of C band repeat pass data have shown [*Rignot et al.*, 2011b], it is common to obtain low coherence levels over repeat cycles of 12 days and longer in this region, and the Sentinel-1a data are no exception. We note that coherence levels tend to be slightly higher during the early Austral summer, i.e., November–December, and lower in Austral winter. Despite these caveats, the Sentinel-1a data extend and complement the time series of ice velocity assembled from prior data [*Mouginot et al.*, 2014] as shown in Figure 2. The ice velocity data generated from these independent sensors have varying error levels depending on the repeat cycle of the data and the radar wavelength, but the results are very consistent from one sensor to the next and of sufficient precision to detect ongoing changes in glacier fluxes into the ocean.

Ancillary information in Figure 1 includes the glacier bed elevation on grounded ice from a mass conservation approach [*Morlighem et al.*, 2011]. Bathymetry in front of the glaciers is excluded because of the high uncertainty of the BEDMAP-2 data in this region. Recent modeling efforts show that slope alone, particularly if evaluated along a single flow line or a flight line only, may not be sufficient to evaluate the potential stability of the grounding line for that region [*Gudmundsson et al.*, 2012; *Jamieson et al.*, 2012]. We therefore provide the along-flow bed slopes calculated at a sample spacing of 900 m only where ice flows faster than 50 m/yr

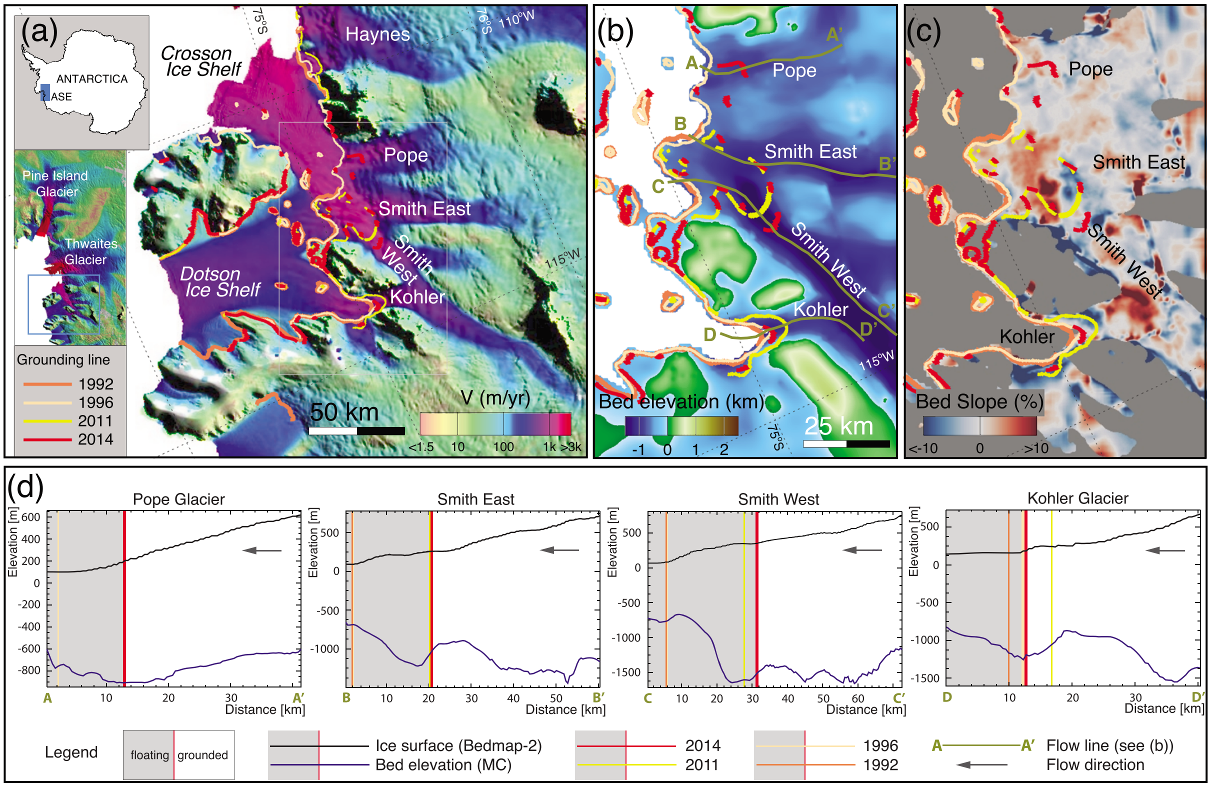

Figure 1. (a) Ice velocity combining various data sets overlaid on a Moderate Resolution Imaging Spectroradiometer (MODIS) mosaic of Antarctica [*Scambos et al.*, 2007]; (b) bed topography from a mass conservation approach [*Morlighem et al.*, 2011] combined with BEDMAP-2 data [*Fretwell et al.*, 2013]; (c) bed slope calculated in the along-flow direction color coded from blue (prograde bed) to red (retrograde bed); (d) along-flow profiles (see Figure 1b for locations) with 2014 grounded and floating portions indicated in white and grey, respectively. Interferometric synthetic aperture radar (InSAR) based grounding line positions are color coded. Grounding lines from 1992 to 2011 are from [*Rignot et al.*, 2011a], The 2014 grounding line is a result of this study and based on Sentinel-1 data.

for better two-dimensional assessment (Figure 1c). Glacier beds along flow lines are shown in Figure 1d. The results highlight areas of retrograde bed, which are more vulnerable to rapid retreat, versus areas of prograde bed, which are conducive to slower retreat of the glaciers [*Thomas*, 1979].

The velocity time series (Figure 2 and Table S1) indicates that the speed of Pope Glacier peaked in late 2010 and then slightly decreased. In late 2015, the glacier was 2% slower than in 2008. Its ice flux in 2015 was back to its level in 2007 and 1 Gt/yr lower than the peak value of 10.6 $\pm$ 0.6 Gt/yr in late 2010. The ice discharge nearly doubled since the late 1980s. In contrast, Kohler Glacier is one of the most stable glaciers in the region. Its speed only varied by +16% between 1994 and 2008, with a peak in 2008, 2 years earlier than for Pope. The ice flux of Kohler has been relatively steady around 6.1 $\pm$ 0.6 Gt/yr. More significant changes are observed on Smith Glacier. Both tributaries more than doubled their speed since the early 1990s. Smith Glacier discharges about 30 $\pm$ 1.6 Gt/yr into the ASE. We note here that confusion reigns in the literature about the naming convention for Smith. The U.S. Geological Survey (USGS) only labeled its west tributary as Smith Glacier, which has also been identified as a branch of Kohler Glacier in the past. We are not aware of a naming convention for the eastern tributary. To uniquely identify the two tributaries, we distinguish Smith West and Smith East. Smith East has accelerated over the entire observation period and has doubled its speed since the 1990s. The glacier continues to accelerate albeit at a smaller rate than in 2008 (Table S1). Smith West accelerated at twice the rate of Smith East and overall tripled its speed compared to the 1990s. Its ice flux increased at a similar rate to 17.2 $\pm$ 1.2 Gt/yr, but between 2013 and 2015 the rate of increase slowed (Figures 2c and 2d and Table S1).

Figure 3 shows the highest-quality double difference Sentinel-1a interferogram of this region along with grounding line positions in earlier years. Two additional double difference interferograms generated to cover the 15 month observation period display lower correlation levels and provide only partial information for grounding line positions and none over the glaciers of interest (Figure S3). On Pope Glacier, we detect an 11.4 km retreat of the grounding line at the center line between 1996 and late 2014 (Figure 3b). The signal

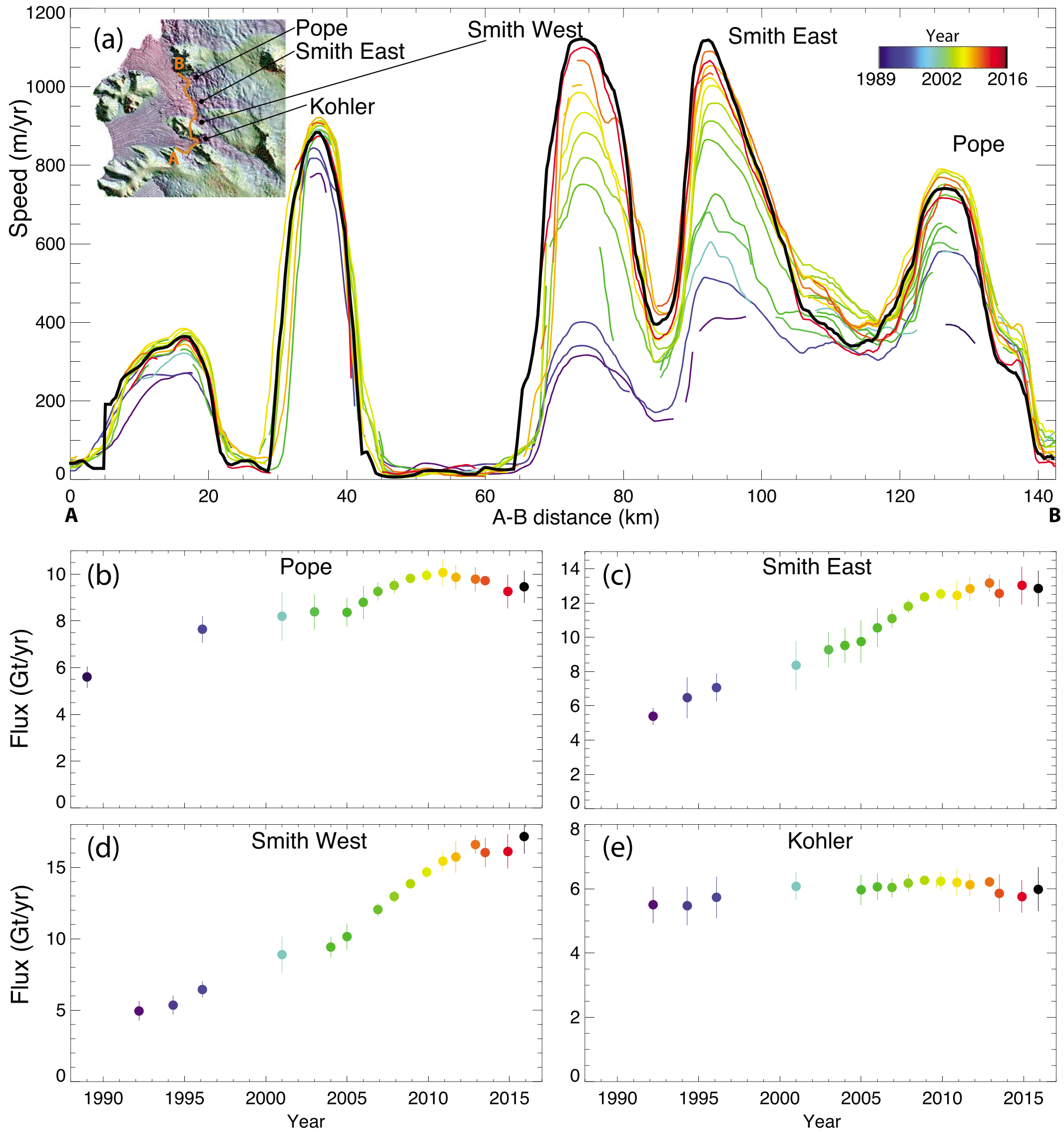

Figure 2. (a) Glacier speed along the A-B flux gate (see inset) color coded from blue to red for years 1989 to 2016 in the Amundsen Sea Embayment of West Antarctica based on [*Mouginot et al.*, 2014] and the results of this study (2014–2016); (b–e) ice flux in Gt/yr (10^{12} kg/yr) for Pope, Smith East, Smith West, and Kohler glaciers for years 1989 to 2016 along the A–B flux gate, with error bars. Ice flux for 2014–2016 is based on Sentinel-1a results combined with Landsat-8 results, fluxes for earlier years are calculated for this gate based on published velocities [*Mouginot et al.*, 2014].

degrades in quality along the ice margins, but grounding line migration is observed along the thickest part of the glacier, which is of most significance since it controls the vast majority of the glacier ice flux. The grounding line of Smith East is only mapped partially along its western flank with Sentinel-1a, but this is sufficient to reveal a significant grounding line retreat since 1996. On Smith West, we measure a 6 km retreat since 2011, i.e., a retreat rate of 2 km/yr since 2011, similar to that measured between 1996 and 2011 (Figure 3c). On Kohler Glacier, we find a readvance of the grounding line since 2011, following a retreat between 1992, 1996, and 2011 (Figure 3d).

Crosson and Dotson ice shelves are anchored by several pinning points or ice rises and rumples labeled here: C1-C5 and D1-D8, respectively (Figure 3). We trace the evolution of these ice rises since 1996. Several of these pinning points have disappeared in the 2014 interferogram: C1, C3, D1, D3, and D6. Analysis of the tide levels for C3 and D6 shows that ephemeral grounding in 2014 cannot be ruled out (Figure S4) [*Padman et al.*, 2008]. Other pinning points have reduced several fold in area extent: C2 and D4. New pinning points formed in areas

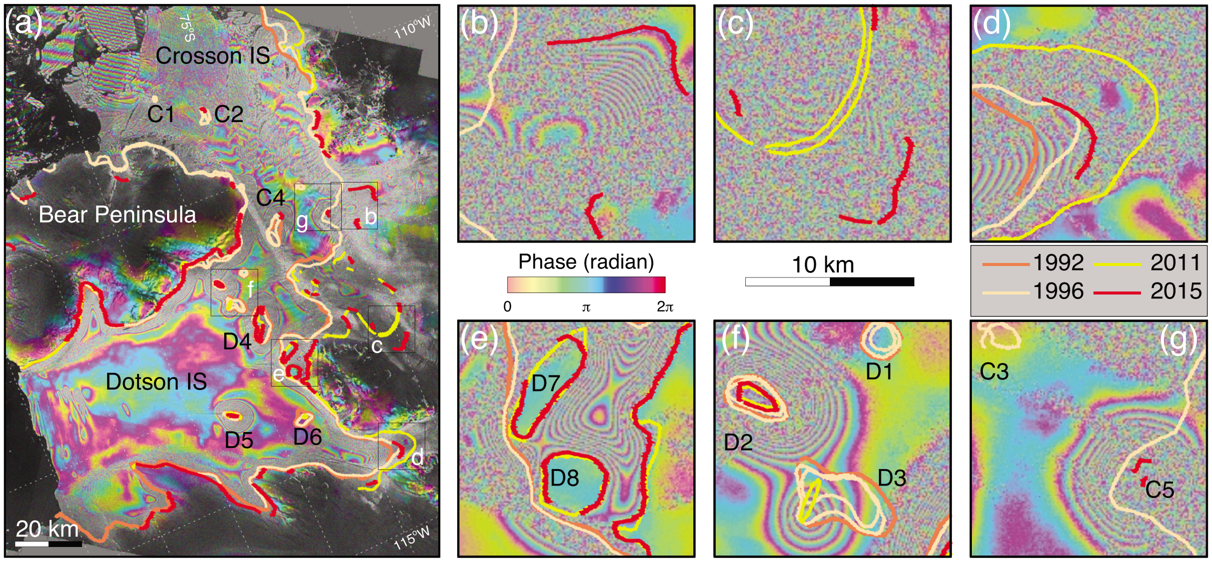

Figure 3. Double difference SAR interferogram combining data from Nov 27, Dec 5, Dec 17, 2014 with (a) an overview plot where (Figures 3b–3g) insets are outlined (starting with Figure 3b in the top left and sorted clockwise). Insets are (b) Pope, (c) Smith West, and (d) Kohler glaciers. (e–g) Insets show details on the evolution of pinning points C1-C5 for Crosson Ice Shelf and D1-D8 for Dotson Ice Shelf in sectors outlined by black boxes (Figure 3a). InSAR grounding lines from 1992 to 2011 are from [*Rignot et al.*, 2011a]. The 2014 grounding line (green) is from this study.

of grounded ice retreat on the flanks of Smith Glacier: D7 and D8. Similarly, a pinning point remains at C5 in 2014 at the center of Smith West following the retreat of grounded ice.

4. Discussion

Measuring ice velocity and grounding line position using SAR data is challenging in the ASE due to significant decorrelation of the signal over long periods due to weathering and high accumulation, combined with the high deformation rate of the glaciers and impact on interferometric phase aliasing [*Arthern et al.*, 2006; *Mouginot et al.*, 2014]. To date, only short-term repeat pass cycle missions have proven useful for measuring grounding lines in this part of Antarctica [*Rignot et al.*, 2014]. Here we find that sufficiently high signal correlation is achieved only on a few occasions on the fast moving portions of the glaciers to yield reliable mappings of grounding lines. A repeat cycle of 6 days (Sentinel-1 constellation) instead of 12 days (Sentinel-1a alone) will improve the mapping capability.

Between 1996 and 2014, Pope Glacier has been retreating along a retrograde bed, with an elevation that dropped from 600 m below sea level (bsl) to 900 m in about 10 km (Figures 1c and 1d). The grounding line now stands on a flatter part of the bed for another 4.5 km before hitting a prograde bed that rises about 250 m in 18 km. Cryosat-2 data indicate continued surface elevation decreases between 2011 and 2014 in this region but at a slower pace on Pope Glacier compared to 2003–2009 [*Helm et al.*, 2014]. While this suggests a potential for additional grounding line retreat in the coming years, the decrease in speed and flux of Pope Glacier suggest that the retreat rate is likely to become slower. We posit that the 2014 grounding line may not reveal the point of farthest retreat between 1996 and 2014, which might have occurred closer to the velocity peak.

Between 1992 and 2014, the grounding line of Kohler has been migrating back and forth across the 7 km long depression in bed elevation (Figures 1c and 1d). The grounding line in 2014 is nearly identical to the 1996 grounding line and is located at the deepest part of the bed. We conclude that this glacier will display the slowest rates of change in the region due to retreat progressing on a steep prograde bed.

Smith Glacier is responsible for the largest change in this part of ASE. The glacier is still accelerating in 2014–2015, but the rate of acceleration has dropped compared to 1996–2011 and the glacier flux has essentially leveled off since 2012. Both tributaries are retreating along deep troughs. In 2014, the grounding line of Smith East is located along a prograde bed that becomes retrograde again in only about 2–3 km, about 100 m higher in elevation, after which the bed drops by 400 m and remains retrograde for another 30 km.

On Smith West, following a fast retreat that brought the bed elevation to 1500 m bsl, the grounding line is retreating along a short prograde section, before remaining essentially at the same depth for another 30 km. We project that grounding line retreat will likely proceed unabated in this sector for years to come despite the recent steadiness of ice flux and glacier speed. It is rather remarkable that the grounding line of Smith West continues to retreat at the same 2 km/yr rate since 2011 despite the presence of a less favorable geometry. This suggests that some reinforcing phenomena help fuel the retreat. One clear positive feedback is that the melt rate of ice in contact with ocean waters increases linearly with depth due to the pressure dependence of the freezing point of seawater, which added another 0.75°C to the ocean thermal forcing as a result of the retreat since 1996. Another feedback may be that since 1996, the grounding line has retreated from the relatively shallow sill to deeper waters, where warmer waters have been able to access the sub-ice shelf cavity and generate higher melt rates typical of the ice shelf.

The combined flux from all glaciers has steadily increased in recent years but the increase has slowed since 2012 to reach a level that remains about twice as high as in 1996. This apparent stabilization of the ice flux should not be interpreted as a temporary stabilization of the glaciers since the grounding line of Smith is still retreating at a record pace of 2 km/yr. For comparison, the grounding line of Pine Island and Thwaites glaciers retreat at rates closer to 1 km/yr and Jakobshavn Isbræ in Greenland retreats at rates closer to 0.6 km/yr. We attribute the pause in ice flux to the presence of a flatter bed upstream of the current grounding line positions, combined with a relative cooling of the ocean waters in Pine Island Bay since about 2009, which may have produced a pause in the magnitude of ice shelf melt rates [*Dutrieux et al.*, 2014].

The loss of pinning points on Dotson and Crosson ice shelves is consistent with the reported thinning of these ice shelves [*Paolo et al.*, 2015]. These changes are likely to reduce ice shelf buttressing and signal that glacier speed up may increase in the future as more pinning points are removed. At the current rate of thinning, pinning points C2, C4, D6, and D5 are likely to disappear in the coming years. Enhanced rifting of Crosson Ice Shelf has been reported since year 2000 [*MacGregor et al.*, 2012]. The ice shelf displays more variability in ice flow than Dotson as manifest by the presence of residual fringes on the ice shelf even after double differencing of the data (Figure 3a). This variability did not exist in radar interferograms collected in 1996 [*Rignot et al.*, 2014]. This suggests that the ice shelf is no longer homogeneous, the large blocks that compose it are slightly dissociated from one another and moving in a nonuniform, time-varying fashion. In contrast, no significant rifting is observed on Dotson Ice Shelf, which flows more slowly than Crosson Ice Shelf and is thinning at a slower rate [*Paolo et al.*, 2015]. Spaceborne double difference SAR interferometry provides the only tool to precisely assess and monitor pinning points. Ongoing data acquisitions are therefore crucial to evaluate how ice shelf buttressing will change with time.

5. Conclusions

Following the first year of Sentinel-1a operations, we present an updated time series of ice velocity, flux, and grounding line positions for the western sector of ASE. We find that the ice velocity of Pope and Kohler glaciers peaked between 2008 and 2010 and is now slightly decreasing. The grounding line of Kohler Glacier readvanced since 2011 along a prograde bed. We also found an 11 km grounding line retreat along Pope Glacier, which pushed it back at the edge of a slightly prograde bed, less favorable for rapid retreat. In contrast, Smith West's grounding line is still retreating at 2 km/yr along a deep trough despite a pause in its acceleration in ice flow, and Crosson Ice Shelf has lost a number of pinning points that have held it together, indicating that it is slowly falling apart. These changes indicate overall that ice shelf and glacier retreat continue unabated in this sector of Antarctica. We expect the Sentinel-1 mission, especially with two satellites, to provide valuable and timely mapping of the evolution of grounding lines and glacier speed in this region and in other sectors of Antarctica.

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