

# Rapid glacier retreat rates observed in West Antarctica

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## Abstracts

The Pope, Smith, and Kohler glaciers, in the Amundsen Sea Embayment of West Antarctica, have experienced enhanced ocean-induced ice-shelf melt, glacier acceleration, ice thinning, and grounding line retreat in the past thirty years. Here we present observations of the grounding line retreat of these glaciers since 2014 using a constellation of interferometric radar satellites combined with precision surface elevation data. We find that the grounding lines develop spatially-variable, kilometre-scale, tidally-induced migration zones. After correction for tidal effects, we detect a sustained pattern of retreat coincident with high melt rates of un-grounded ice, marked by episodes of more rapid retreat. In 2017, Pope Glacier retreated 3.5 km in 3.6 months, or 11.7 km/yr. In 2016-2018, Smith West retreated at 2 km/yr and Kohler at 1.3 km/yr. While the retreat slowed down in 2018-2020, these retreat rates are faster than anticipated by numerical models on yearly time scales. We hypothesize that the rapid retreat is caused by un-represented, vigorous ice-ocean interactions acting within newly-formed cavities at the ice-ocean boundary.

## Introduction.

The Amundsen Sea Embayment (ASE) sector of West Antarctica, which includes the Pine Island, Thwaites, Haynes, Pope, Smith and Kohler glaciers, dominates the present-day contribution to sea level rise from Antarctica (1-2). Their ice volume above flotation is equivalent to a 1.2-meter global sea level rise. Located on the western flank of the ASE, the Pope, Smith, and Kohler glaciers drain 7% of the ASE into the Crosson and Dotson ice shelves, but contribute 24% of the total loss from ASE, with an average 32 Gt/yr mass loss ( $1 \text{ Gt} = 10^9 \text{ ton} = 10^{12} \text{ kg}$ ) during the time period 1979-2017 (2-3) (Fig. 1). Although their combined ice discharge is 3 times lower than that of the neighboring Pine Island and Thwaites glaciers, their rapid speed up and retreat rate, along mostly retrograde bed slopes (i.e. bed elevation drops in the inland direction), are diagnostic of what an extensive glacier retreat associated with a “marine ice sheet instability” may look like in the broader remainder of West Antarctica in the future (4).

A number of changes were noted in prior studies of these glaciers. At the grounding line - where ice detaches from the bed and becomes afloat - the velocity of Pope Glacier increased from 370 m/yr in 1989 to 775 m/yr in 2016, which doubled its ice discharge from  $5.5 \pm 0.6$  to  $9.5 \pm 0.7$  Gt/yr (5). Near the grounding line, grounded ice thinned at 9 m/yr between 2003 and 2008 while floating ice melted at 40 m/yr (6-8). The grounding line retreated at 0.64 km/yr from 1996 to 2014 (5). On Smith East and West, the velocity increased by 280% (710 m/yr) and 370% (800 m/yr), respectively, in 1992-2015, which tripled their combined ice discharge as the grounding line retreated into thicker ice (5). Between 2002 and 2009, Smith West thinned at 7 m/yr on grounded ice and melted at 70 m/yr on floating ice (9). From 1992 to 2016, the grounding line of Smith West retreated at 2 km/yr, which was the fastest retreat rate in Antarctica (10), while Smith East retreated

at 0.5 km/yr. In contrast, Kohler exhibited no speed up between 1994 and 2016 and its grounding line migrated back and forth between 1996 and 2014 (5).

### **Short-term grounding line variability.**

Here we present a new time series of 1-day repeat synthetic aperture radar interferometry (InSAR) observations from the COSMO-SkyMed (CSK) constellation to survey the Pope, Smith East and West and Kohler glaciers multiple times a year and update on their grounding line position since year 2014. We combine the CSK differential InSAR (DInSAR) data (Fig. S1) with time-tagged TanDEM-X (TDX) digital elevation models (DEM) of the ice surface. The time series of DInSAR data reveals the temporal evolution of the grounding line caused by tidally-induced migrations on top of a long-term grounding line retreat (see Methods) (11-12) (Fig. 1). The TDX DEMs (Fig. S2-3) quantify temporal changes in ice surface elevation caused by changes in ice flow dynamics and surface mass balance on grounded ice, and additionally by bottom ice melt by the ocean waters on floating ice (Fig. S3). In the DInSAR technique, we form the difference between a first 1-day InSAR pair that includes signal associated with the nearly-steady horizontal motion of the glacier and the tidal-dependent vertical tidal motion of the floating ice with a second 1-day InSAR pair, acquired within 1 to 4 of 16-day cycles later, to eliminate the steady, horizontal motion of the glacier and detect the residual pattern of tidal motion. The DInSAR technique combines 4 SAR images from 4 epochs to image a differential pattern of tidal motion. We posit that the vertical motion detected farthest inland in the DInSAR data corresponds to the most positive (upward) tide,  $h_{max}$ , among the 4 epochs because the high tide will lift the glacier farther off the bed and allow seawater to intrude farther inland beneath the glacier, whereas low tide will force the grounding line to re-advance (12). We model the tidal heights at the time of passage of the satellites using the Circum-Antarctic Tidal Simulation (CATS2008) (13) and correct the results

for changes in atmospheric pressure. We examine the relationship between observed grounding line position from each DInSAR element and the modeled maximum tide ( $h_{\max}$ ) at the time of passage of the satellites (Fig. 2).

We find a larger-than-expected variability in grounding line position as a function of tide. On Smith West, the grounding line migrates at tidal frequencies over a 3-km wide grounding zone – where the grounding line migrates with changes in oceanic tide – in 2016-2017. In 1992-1995, the grounding zone was 1.6 km wide (Fig. 3). The larger tidally-induced grounding zone in 2016-2017 is consistent with a flatter bed topography at that location (14-15) compared to 1992-1995 (Fig. 3). A flatter topography favors intrusion of pressurized seawater at the glacier bed at high tide over a larger area. Conversely, the grounding zone will be narrower along steeper parts of the bed, e.g. along the side margins or at bed peaks (Fig. 1), if tidal migration is controlled by hydrostatic equilibrium (11-12).

We find a positive, linear relationship between observed grounding line position and modeled maximum tide,  $h_{\max}$  (Fig. 2). The slope of the regression varies from glacier to glacier and is time dependent as the grounding line retreats to a different bed position (Table 1). If we assume flotation, the sensitivity of the grounding line position to tidal height,  $\gamma$ , is given by the bed and surface slopes and the density of seawater and ice (See Methods). We find, however, that the observed grounding line migration is amplified by a factor,  $a$ , that varies from 1 to 37 (Table 1), i.e. the migration is one order of magnitude larger than expected from flotation. Within the grounding zones of Pope, Smith and Kohler glaciers, we find that ice deviates from flotation by only  $3.9 \pm 6$  m,  $2.5 \pm 8$  m, and  $2.2 \pm 6$  m, respectively (Fig. S5).

**Long term grounding line migration.**

We employ the empirical relationship between grounding line position and tidal height to derive a mean - or tidal-corrected - position of grounding line at different epochs, and in turn use these results to determine the longer term (months to years) migration independent of the tidal state (Fig. 3). We find that the grounding line of Smith East retreated at 1.4 km/yr in 2011-2016 along a relatively flat bed, or 3 times faster than in 1996-2011 (5). The grounding line remained stable in 2016-2017 at a transition to prograde slopes, followed by a retreat at 2.4 km/yr in 2017-2018, and a slow down to 0.9 km/yr in 2018-2020 along steeper prograde slopes (Fig. 3). The grounding line of Smith West retreated  $3.0 \pm 0.4$  km in 2016-2017,  $1.5 \pm 0.4$  km in 2017-2018, and remained stable in 2018-2020, for an average 0.9 km/year retreat in 2016-2020, or 50% slower than in 1992-2011 (Fig. 3). During 2014-2020, the retreat proceeded on a nearly flat bed whereas in 1996-2011 the grounding line retreated along retrograde slopes (600-m drop in elevation in 30 km). On the western flank of Smith West (Point D in Fig. S3), 11 km<sup>2</sup> of grounded ice disappeared between February 2016 and December 2017, accompanied by a 2.3 km/yr retreat of the grounding line.

To the east, Pope Glacier retreated  $2.7 \pm 0.8$  km in 2014-2016, or 1.3 km/yr, versus 0.6 km/yr in 1994-2014 (5). The grounding zone is only 1 km wide (Fig. 3). In January-May 2017, over a period of only 113 days, the grounding line retreated  $3.5 \pm 0.8$  km (see Methods), or 11.7 km/yr. The grounding line subsequently retreated at 0.8 km/yr in 2017-2018 and remained stable in 2018-2020 as the grounding line transitioned to prograde bed slopes which extend another 20 km inland. During 2016-2020, the grounding line average a retreat rate of 1 km/yr.

To the west, Kohler Glacier exhibits a 2-km wide grounding zone along prograde bed slopes (Fig. 3). The grounding line retreated  $2.3 \pm 0.4$  km in 2016-2018 but did not retreat in 2018-2020, for an average 0.5 km/year retreat in 2016-2020, or 60% higher than in 1995-2016. A prior

study suggested a re-advance of the grounding line in 2011-2014 (5). The grounding line now stands 7 km away from Smith West and 2 km from retrograde slopes. At the current rate, the two glaciers will merge within the next 15 years. This merger will have two implications. First, the connection of ice shelf cavities will change the ocean circulation beneath Dotson (16). Second, the prograde bed slopes of Kohler, which explained its apparent stability in 1992-2014, did not stop the retreat. Similarly, Smith East retreated slowly along prograde slopes in 2017-2020.

Retreat rates of 3 km/yr on Smith West in 2016-2017, 2.4 km/yr on Smith East in 2017-2018, 11.7 km/yr in 3 months on Pope in 2017, and 2.3 km/yr on Kohler in 2016-2018 are large compared to those observed on other glaciers in Antarctica and Greenland. The grounding line of Jakobshavn Isbræ, central west Greenland, retreated at 0.5 km/yr in 2002-2016, with a brief 3.8 km jump in 2011-2012 (17). Zachariae Isstrøm, northeast Greenland, retreated at 0.55 km/yr in 2014-2019 (18-19). Helheim retreated by 4 km between August 2004 and August 2005 (19), but partially re-advanced in subsequent years. In West Antarctica, Thwaites has retreated at 1 km/yr on average since 1992, similar to Pine Island (11-12, 21). The observed high retreat rates of Smith, Pope and Kohler in recent years are however consistent with retreat rates as large as 5 to 10 km/yr inferred recently for former paleo ice streams (23), giving credence to the fact that glaciers can retreat at speeds of several km per year.

#### **Ice-ocean interactions in the grounding zones.**

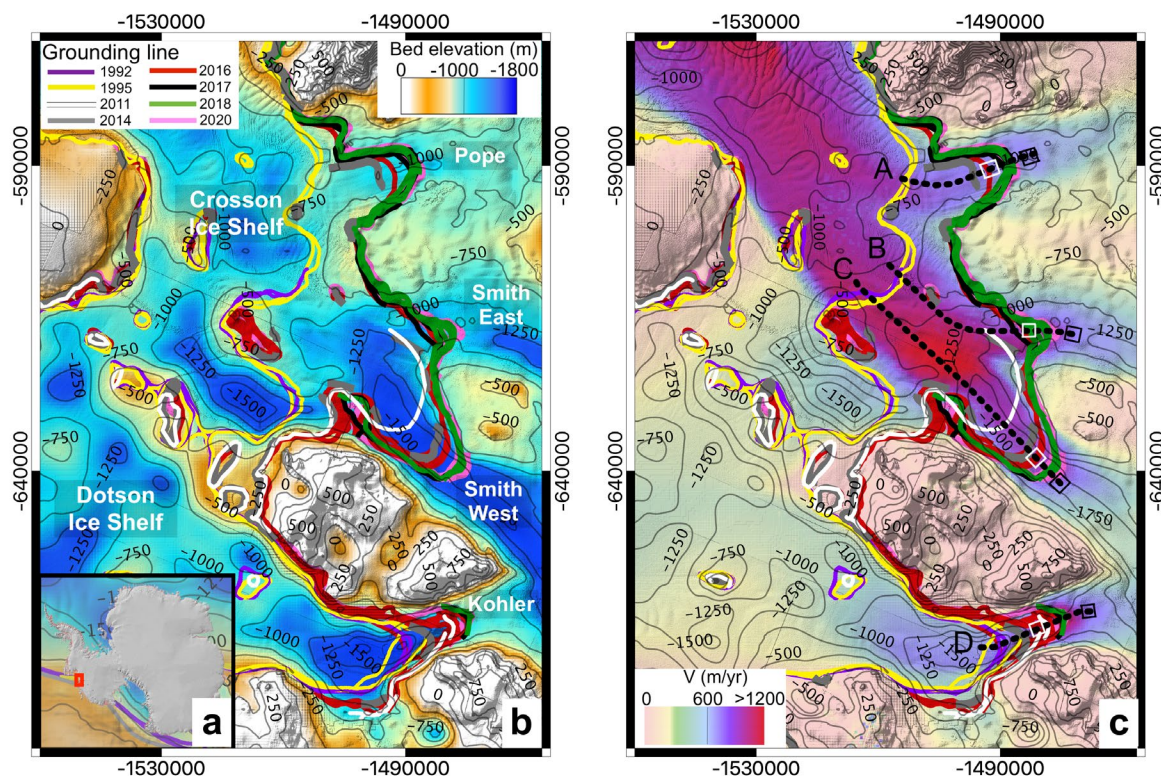
The time series of DEMs document the rate of ice thinning accompanying the retreat. The highest thinning rates are observed in areas of freshly un-grounded ice (6-7) and are caused by a combination of dynamic thinning and bottom melt by the ocean waters (surface mass balance is less than 0.5 m/yr in this region (25), hence is not a factor). On land, dynamic thinning equals the rate of ice thinning, which we calculate over grounded ice adjacent to the freshly un-grounded ice

(Fig. 1). We assume that the same rate of dynamic thinning applies on un-grounded ice, subtract this rate from the observed rate of ice thinning, assume hydrostatic equilibrium, and deduce the resulting bottom melt rate (See Methods). Ice only deviates from flotation by a few meters due to bending stresses (11, 24) in these regions. Above the 2020 grounding lines, we detect ice thinning at 4 to 7 m/yr on Pope, Smith and Kohler glaciers (Fig. 4) and peak values of 9 m/yr on Smith West in 2011-2014 (Fig. S3). For ice that ungrounded on Pope in 2014-2017, we calculate a bottom melt rate of  $86 \pm 9$  m/yr (Fig. 4a, Fig. S5, Fig. S6). On Smith East, dynamic thinning of 5 m/yr in 2011-2019 on grounded ice translates into a melt rate of  $22 \pm 6$  m/yr on freshly un-grounded ice (Fig. 4b). For Smith West, grounded ice thinning at  $6 \pm 0.4$  m/yr yields a  $65 \pm 6$  m/yr melt rate of un-grounded ice. For Kohler, grounded ice thinning at 3-4 m/yr yields  $19 \pm 7$  m/yr melting of un-grounded ice. At select locations D-E (Fig. S3) on Smith West, inferred bottom melt rates exceed 100 m/yr, e.g. 140 m/yr in 2016–2017 at D. On Kohler, the melt rate is  $100 \pm 9$  m/yr in 2016-2019 at Point F (Fig. S3). These melt rates are high compared to melt rates observed on the ice shelf proper (26) and in the upper range of values employed in numerical ice sheet models (9, 27-29).

When similar high melt rates are used to force models, the model results can match the observed retreat, except for Kohler where the modeled grounding line remains stable (9). As noted in prior studies (9,30), elevated ice melt near the grounding line is an additional constraint on the speed of retreat. Wider grounding zones are explainable by the presence of a deformable bed (31) or the propagation of elastic cracks forced by pressurized seawater (32, 33). Intrusion of pressurized seawater in the sub-glacial cavities will melt grounded ice and reduce basal resistance (34). Numerical models indicate that the inclusion of ice melt within a grounding zone significantly increases the speed of retreat (30). Other modeling studies even emphasize that it is not possible to match the observed retreat if ice melt processes are not included in the grounding zone (9, 28).

The Pope, Smith East and West, and Kohler glaciers control a drainage area with an ice volume above flotation equivalent of 6-cm global sea level rise, which is small, so the risks of rapid sea level rise from this sector of West Antarctica are low. Yet the physical processes driving their retreat are the same that operate on neighboring Thwaites and Pine Island, which hold a 1.2 m global sea level rise and may de-stabilize the rest of West Antarctica. Understanding the physical processes driving the fast retreat of Pope, Smith and Kohler, especially the magnitude of ice melt in the grounding zones, is therefore critical to explain and reproduce the observed rates of retreat. The results will in turn help reduce uncertainties in the upper bounds of maximum contribution to sea level rise from West Antarctica in decades to come.





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176 **Figure 1. Pope, Smith East and West, and Kohler glaciers, West Antarctica.** (a) Location map

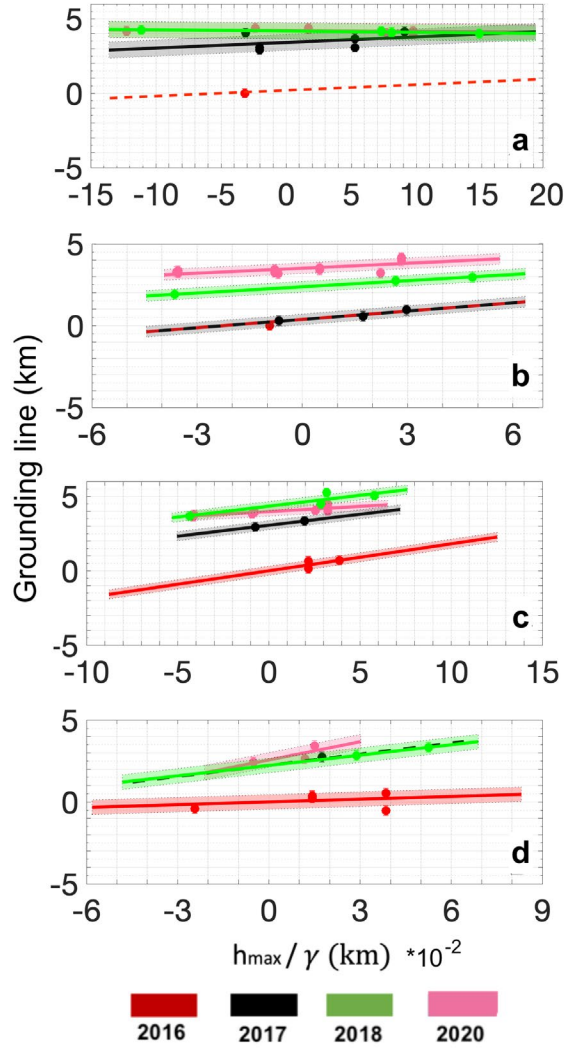
177 in West Antarctica (red box). (b) Shaded-relief bed elevation color-coded from -1800 m (blue) to

178 0 m (brown) with 500-m contour levels (grey) (14-15), and grounding zones color coded from

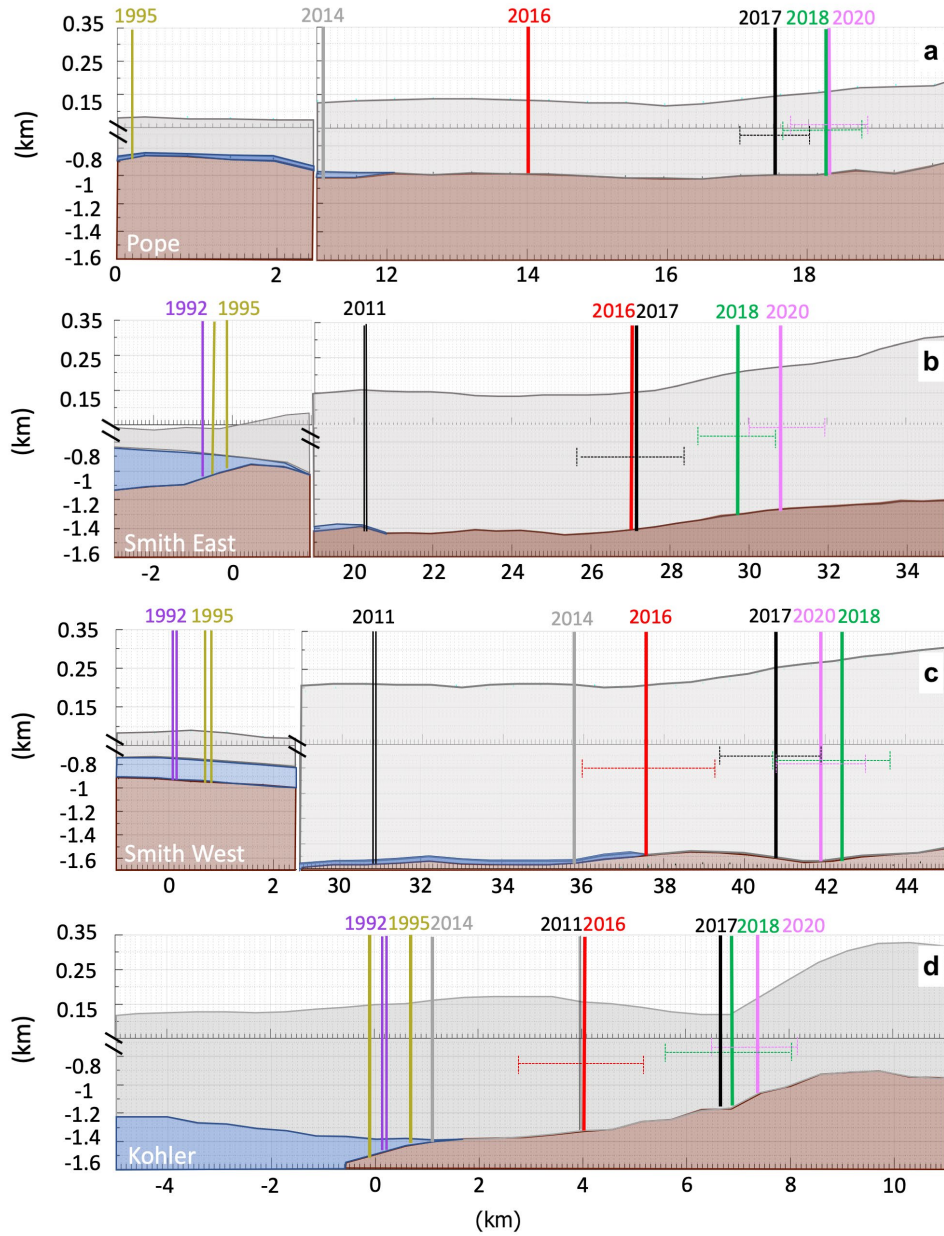
179 1992 to 2020. Retreat rates are shown in Fig. 2-3 along profiles A-D. (c) Ice surface speed in 2016-

180 2017, color coded from brown to red. Black and white boxes near the 2016 grounding lines are

181 used to calculate dynamic thinning and bottom ice melt in Fig. 4.

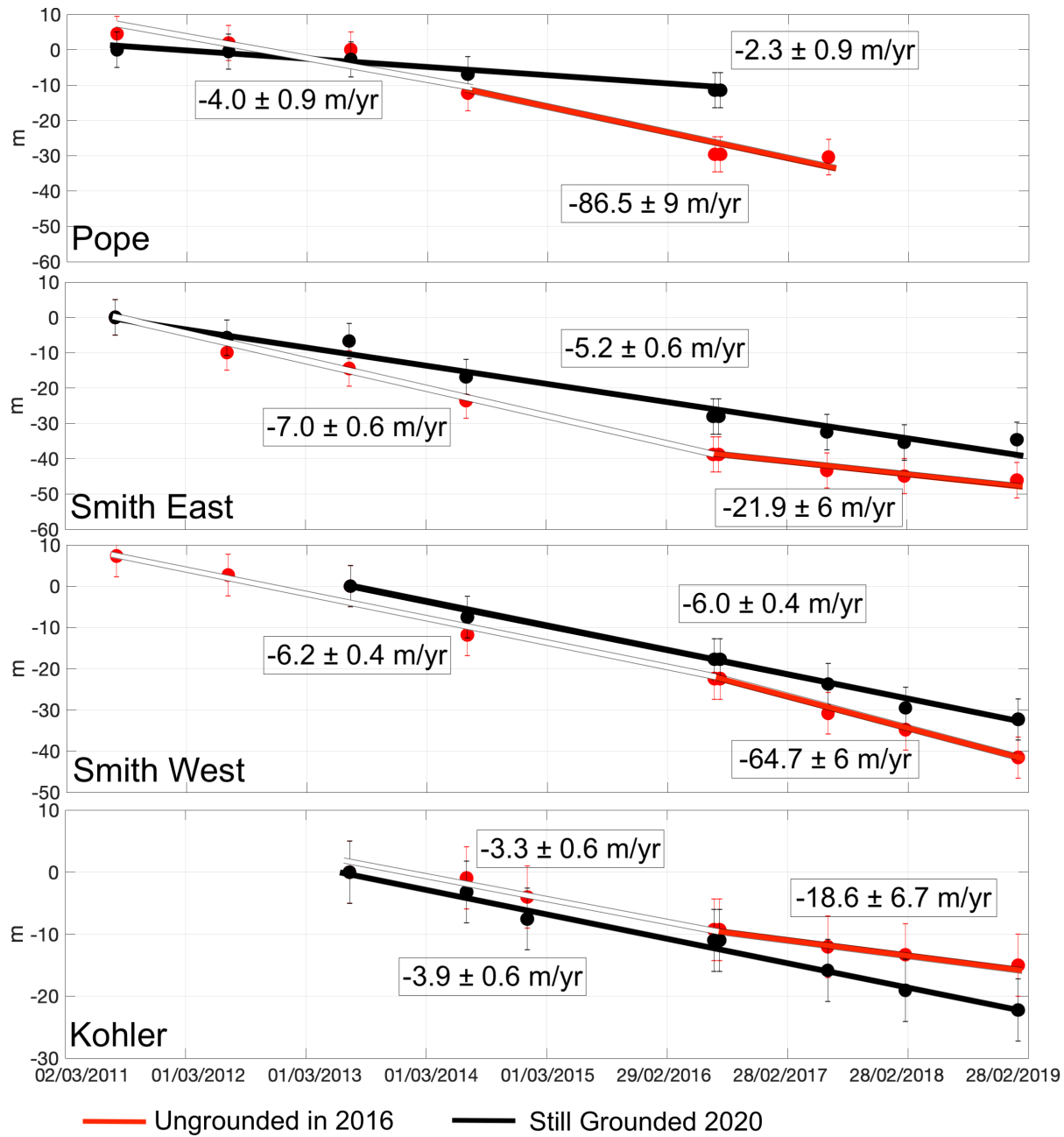


**Figure 2. Tidally-induced grounding line migration (GL) and secular retreat rates at (a) Pope, (b) Smith East, (c) Smith West and (d) Kohler glaciers as a function of maximum tide,  $h_{max}$ , among the 4 epochs of the DInSAR data divided by the  $\gamma$  values deduced from local, time-dependent, surface and bed slopes (Table 1). GL migration is measured along profiles aligned with the flow direction and referenced to the 2016 mean-sea-level GL position. Colored lines are linear regressions of GL versus  $h_{max}/\gamma$ . Shaded areas correspond to a  $1\sigma$  uncertainty. When only one GL measurement is available for a given year (e.g. Pope and Smith East in 2016/Kohler in 2017), a dashed red/black line is used assuming the same regression slope as for the nearest available year (2017 or 2018).**



**Figure 3** Surface and bed profiles of Pope, Smith East, Smith West and Kohler glaciers for year 2011 from BedMachine (14) centered at the grounding zone (GZ) of each glacier (Fig. 1). Solid colored lines mark the GZ at zero tide and error bars the width of the GZ deduced from Fig. 2. GZ in 1995, 2011, 2014 from (5) are not corrected for tide due to a limited set of repeat

observations. The reference position is the grounding line from the 1990s (Fig. 1). Distance is from north (left) to south (right) in km.



**Figure 4. Rate of ice thickness change,  $\frac{dh}{dt_{pre}}$ , and melt rate,  $m_b$ , of West Antarctic glaciers** deduced from a time series of TDX digital elevation data corrected for firm depth (Fig. S3). Black lines correspond to black boxes in Fig. 1 on grounded ice. White lines correspond to white boxes in Fig.1 where ice transitioned from grounded to floating during the time period (marked by a color change from white to red). Other examples are shown in Fig. S3 with the same approach.

**Table 1.** Sensitivity,  $a$ , of the grounding line position, GL (km), to tidal forcing,  $h_{max}$  (m), for Pope, Smith East, Smith West and Kohler glaciers at different times, as a function of surface slope,  $\alpha$ , and bed slope,  $\beta$ , and flotation factor,  $\gamma$ , relative to the 1996 grounding line position (km), and grounding zone (GZ) width (km). For ice in hydrostatic equilibrium on a hard bed, we expect the sensitivity  $a = GL/(h_{max}/\gamma) = 1$ .

| <i>Glacier</i>    | <i>Time<br/>(year)</i> | <i>a</i>        | <i>GL retreat<br/>(km)</i> | <i><math>\alpha</math> %</i> | <i><math>\beta</math> %</i> | <i><math>\gamma</math></i> | <i>GZ width<br/>(km)</i> |
|-------------------|------------------------|-----------------|----------------------------|------------------------------|-----------------------------|----------------------------|--------------------------|
| <b>Pope</b>       | 2017                   | $4.5 \pm 2.1$   | $3.5 \pm 0.4$              | 3                            | 2.7                         | 0.005                      | $1.5 \pm 0.5$            |
| Lon: -111.59      | 2018                   | $1.1 \pm 0.7$   | $4.28 \pm 0.4$             | 3                            | 3                           | 0.005                      | $1.2 \pm 0.5$            |
| Lat: -75.27       | 2020                   | $1.0 \pm 0.7$   | $4.25 \pm 0.4$             | 3                            | 3.5                         | 0.005                      | $1.4 \pm 0.5$            |
| <b>Smith East</b> | 2017                   | $16.0 \pm 2.1$  | $0 \pm 0.4$                | 1.4                          | 3                           | 0.015                      | $2.4 \pm 0.5$            |
| Lon: -112.40      | 2018                   | $12.5 \pm 2.5$  | $2.35 \pm 0.4$             | 1.4                          | 3                           | 0.015                      | $1.9 \pm 0.5$            |
| Lat: -75.18       | 2020                   | $10.10 \pm 2.1$ | $3.25 \pm 0.4$             | 1.7                          | 2.4                         | 0.018                      | $1.7 \pm 0.5$            |
| <b>Smith West</b> | 2016                   | $20.1 \pm 10$   | $0 \pm 0.3$                | 0.5                          | 0.4                         | 0.0053                     | $2.7 \pm 0.5$            |
| Lon: -112.78      | 2017                   | $9.8 \pm 6$     | $3.0 \pm 0.4$              | 1.4                          | 1.1                         | 0.014                      | $2.4 \pm 0.5$            |
| Lat: -75.15       | 2018                   | $14.7 \pm 6$    | $4.5 \pm 0.4$              | 1.4                          | 0.8                         | 0.013                      | $2.4 \pm 0.5$            |
|                   | 2020                   | $6.1 \pm 6$     | $4.0 \pm 0.4$              | 1.5                          | 0.2                         | 0.013                      | $2.5 \pm 0.5$            |
| <b>Kohler</b>     | 2016                   | $5.6 \pm 4$     | $0 \pm 0.5$                | 0.5                          | 3.3                         | 0.033                      | $1.9 \pm 0.5$            |

|             |      |                |               |     |     |       |               |
|-------------|------|----------------|---------------|-----|-----|-------|---------------|
| Lon:-114.17 | 2018 | $21.1 \pm 7.5$ | $2.3 \pm 0.4$ | 1.3 | 3.7 | 0.015 | $1.8 \pm 0.5$ |
| Lat: -75.10 | 2020 | $37.2 \pm 7.6$ | $2.5 \pm 0.4$ | 3.2 | 4.2 | 0.033 | $1.7 \pm 0.5$ |

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## Methods

**COSMO-SkyMed (CSK) grounding line analysis:** We survey the Pope, Smith and Kohler glaciers grounding lines using the COSMO-SkyMed (CSK) constellation. The acquisition campaign includes two phases: at the time of phase one (2016-2018), CSK included 4 low-orbit satellites carrying an X band SAR (3.1 cm wavelength) at HH polarization (horizontal transmit and receive). Each satellite has a 16-day repeat cycle. Shorter temporal baselines are achieved using the constellation. We use interferometric acquisitions spanning 1-day time interval with the satellites CSK2 and CSK3 (Fig. S4). In 2019 no data could be acquired due to a change in satellites configuration and the addition of 4 more satellites, including 2 X-band COSMO-SkyMed second generation (CSG) and 2 SAOCOM satellites at L-Band. Phase two started in 2020 and acquisition spanning 1-day intervals restarted using the CSK2 and CSK4 satellites (Fig. S4). Here, we analyze scenes in single-look complex (SLC) mode covering a  $40 \times 40$  km swath from 3 different tracks, at 3 m spacing in the azimuth (along-track) and range (cross-track) directions. CSK SAR interferograms are assembled by concatenating  $4 \times$  CSK STRIPMAP consecutive frames. The incidence angle averages  $21^\circ$  across the swath. We apply 8 looks (number of elements averaged together to reduce noise) in both the range and azimuth directions to improve phase coherence. We use orbit information and pixel offsets to maximize coherence between image pairs. Given the large interferometric baseline characterizing CSK2/3 interferometric pairs, we remove the topographic component of the interferometric phase using time-tagged TDX DEMs acquired closest in time with the CSK data (11). The interferometric baseline is much reduced in phase 2 of this project (less than 100 m), in which case we used the same TDX DEM from 2019 with all data. A grounding line measurement is formed by the differencing two 1-day interferograms. We use 216 stripmap data (an average of 54 SLC per year) divided in 3 tracks (18 images composed by 4

frames per image) acquired between February 2016 and November 2020 to produce 26 differential interferograms (DInSAR) which reveal vertical tidal displacements and other transient motion of the ice, e.g. subsidence/rise of the ice surface with lake drainage/filling (Fig. S1). The precision of detection of the grounding line is greater when the differential tidal signal is larger and typically of the order of 100-200 meters (11-12). We select 22 DInSAR pairs (85% of the total number of pairs) (Fig. S1) that display sufficient tidal signal (i.e. differential tidal signal larger than 4.5 cm corresponding to 3 interferometric fringes in the LOS at X band), acquired no more than 2 months apart to avoid contaminating the vertical signal with seasonal velocity changes. The grounding line is manually picked near the most inland interferometric fringe associated with tidal motion. We verify that in each DInSAR frame we count the same number of fringes across the flexure zone, i.e. the zone of concentrated fringes where ice adjusts to hydrostatic equilibrium across the grounding line. Using multiple grounding line measurements, we identify a grounding zone, i.e. where the grounding line migrates back and forth with changes in oceanic tide (Fig. S1). One grounding line measurement combines data acquired at 4 different times. We expect the grounding line to migrate inland at high tide and seaward at low tide. We posit that the most retreated position of the grounding line corresponds to the most positive (upwards) tidal displacement among the 4 epochs,  $h_{max}$ . We calculate the tidal amplitude using tide predictions from the CATS2008 model with a precision of 5 cm (13)(Table S1). Inverse barometer effect is also taken into consideration following the same approach described in (36) using ERA-INTERIM data (37)(Table S2). Across the grounding zone, we calculate an average surface slope,  $\alpha$ , from the TDX DEM, and a bed slope,  $\beta$ , from BedMachine Antarctica (13-14) along the flow direction (Fig. S3) with a length scale of 3 km and calculate a sensitivity parameter  $\gamma$  as:

$$(38) \quad \gamma = \left(1 - \frac{\rho_i}{\rho_w}\right)\beta + \frac{\rho_i}{\rho_w}\alpha \text{ (Eq. 1)}$$

where  $\rho_i = 917 \text{ kg m}^{-3}$  and  $\rho_w = 1027 \text{ kg m}^{-3}$  are, respectively, the density of ice and seawater. At flotation, when the tide changes by  $dh^+$ , the grounding line should migrate inland by  $dGL = dh^+/\gamma$  on a rigid bed based on hydrostatic equilibrium (i.e. with  $dh^+ = 1 \text{ m}$  and  $\gamma=0.01$  we expect  $dGL$  to be 100 m). The most inland position of the grounding line verifies,  $dGL_{max} = h_{max} / \gamma$ . In reality, however, because of visco-elastic bed deformation and tidal pressure (30-31), the migration is amplified by a factor  $a$ :  $dGL_{max} = a h_{max} / \gamma$  (Fig. 2). The inferred values of the amplification factor,  $a$ , are listed in Table 1.

**TanDEM-X DEM (TDX) Bed topography and height above flotation in Antarctica:** We generate a time series of 241 time-tagged DEMs using the global TDX product (35) for geocoding and calibration for the time period 2011-2019. The SAR processing chain comprises 6 steps: 1) spaceborne monostatic TerraSAR-X processing, 2) bistatic TDX processing, 3) interferometric combination of images, 4) phase unwrapping, 5) phase-to-height conversion and 6) geocoding to a latitude/longitude grid. Using Airborne Topographic Mapper (ATM) data over grounded ice, we estimate a relative height accuracy of 2.1 m (Fig. S2). For calculating the height above flotation,  $h_f$ , we use surface elevation above mean sea level,  $h_{dem}$ , and ice-equivalent thickness,  $H_i$ , from BedMachine Antarctica (14-15) that combines ice thickness derived from airborne radar depth sounders with InSAR-derived ice velocity and RACMO2.3 surface mass balance data (25). On floating ice, the surface elevation of BedMachine Antarctica,  $h_{dem}$ , is corrected with a firn densification,  $d$ , that is calibrated with all available ice shelf thickness data. The height above flotation,  $h_f$ , is:

$$h_f = h_{dem} - H_i \left(1 - \frac{\rho_i}{\rho_w}\right) - d \quad (\text{Eq. 2})$$

The error in  $h_f$  is 6 m based on an uncertainty of 2 m for  $h_{dem}$ , 50 m in  $H_i$  and 2 m for the firm depth,  $d$ , which is optimized so  $h_f \sim$  zero on the ice shelf proper.

**Ice Shelf melt rate:** Time series of surface elevation and grounding line position allow us to calculate the ice shelf melt rates,  $m_b$ . From the time series of height above floatation, we identify the time when  $h_f$  crosses 0 m and calculate the slope of change in elevation when ice is grounded,  $dh/dt_{gd}$ , and after ice becomes afloat,  $dh/dt_{fl}$ . A comparison of  $h_f$  with the grounding line position helps gain confidence in the detection of the transition to floatation.  $dh/dt_{gd}$  is the thinning rate of grounded ice due to ice dynamics.  $dh/dt_{fl}$  is the thinning rate of floating ice or recently un-grounded ice, which includes dynamic thinning and ice shelf melt. The ice shelf melt,  $m_b$ , is deduced from the difference between these quantities:

$$(39) \quad \frac{dh}{dt_{gd}} = \nabla(\mathbf{u} \cdot \mathbf{h}) + m_s \quad (\text{Eq. 3})$$

$$\frac{dh}{dt_{fl}} = [\nabla(\mathbf{u} \cdot \mathbf{h}) + m_s + m_b] / f \quad (\text{Eq. 4})$$

$$m_b = f \frac{dh}{dt_{fl}} - \frac{dh}{dt_{gd}} \quad (\text{Eq. 5})$$

where  $h$  is the surface elevation,  $m_s$  is the surface mass balance,  $\mathbf{u}$  is the depth-averaged velocity, and  $f = \rho_w / (\rho_w - \rho_i) \sim 9.33$  is a flotation factor deduced from the densities of ice and seawater. We assume that dynamic thinning does not change rapidly in space as ice un-grounds over length scales of a few ice thickness. We confirm this by verifying that the grounded ice thinning rate in a box adjacent to the 2020 grounding line is similar to that calculated in a nearby box on ice that becomes un-grounded during the observation period (Fig. 1, 4). This Eulerian framework, based on the change in elevation at a fixed point in space, reveals how rapidly ice melts as the grounding line retreats and ice is exposed to warm ocean waters.

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**Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or Supplementary Material. We thank the Italian Space Agency (ASI) for providing CSK data [original COSMO-SkyMed product ASI, Agenzia Spaziale Italiana (2007–2020) and the German Space Agency (DLR) for providing TDX data (original TanDEM-X product DLR (2007–2019)]. CSK data are publicly available through data grants from ASI. TanDEM-X CoSSC products were through scientific proposal OTHER0103 and are publically available. Velocity (<https://nsidc.org/data/NSIDC-0484/versions/2>) and bed machine (<https://nsidc.org/data/NSIDC-0756/versions/2>) data products are available as MEaSURES products at the National Snow and Ice Data Center, Boulder CO (NSIDC). Geocoded interferograms, grounding line positions, reference surface elevation, reference ice thickness, reference height above flotation, and reference ice velocity are available at <https://doi.org/10.7280/D1B114>.