



Extending the record of Antarctic ice shelf thickness change, from 1992 to 2017

Anna E. Hogg^{a,*}, Lin Gilbert^b, Andrew Shepherd^a, Alan S. Muir^b, Malcolm McMillan^c

^a Centre for Polar Observation & Modelling, School of Earth and Environment, University of Leeds, LS2 9JT, UK

^b Centre for Polar Observation & Modelling, Department of Earth Sciences, University College London, WC1E 6BT, UK

^c Centre for Polar Observation & Modelling, Centre of Excellence in Environmental Data Science, Lancaster University, Lancaster LA1 4YW, UK

Received 16 July 2019; received in revised form 18 May 2020; accepted 20 May 2020

Available online 3 June 2020

Abstract

Over the past two decades, Antarctic ice shelves have retreated, thinned and suffered catastrophic collapse. In this study we extended the 25-year long record of ice shelf thickness change in Antarctica, from 2010 to 2017. In the Amundsen Sea Sector where widespread ice shelf thinning dominates the signal, a 51% slowdown in the rate of ice loss over the last 7-years can be attributed to a coincident decrease in ocean temperatures in the region since 2010. Overall, ice shelves in Antarctica have thickened by an average of 1.3 m between 2010 and 2017 as ice losses from West Antarctica are compensated by ice gains in East Antarctica and the Antarctic Peninsula, reversing the negative trend of the previous two decades. The detailed spatial pattern of ice shelf thickness change across Antarctica, demonstrates the need for future investment in high spatial resolution observations and techniques.

© 2020 COSPAR. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Keywords: Ice shelf; Altimetry; Thickness change; Antarctica

1. Introduction

Floating ice shelves fringe 74% of Antarctica's coastline, providing a direct link between the ice sheet and the surrounding oceans. Ice shelves are important because (i) they have retreated and thinned in key parts of the continent during a period of environmental change (Shepherd et al., 2003) (Paolo et al., 2015), (ii) their buttressing effect is known to modulate the grounded ice sheet contribution to global sea level rise (Rignot et al., 2004, Reese et al., 2018), (iii) ice melting causes ocean freshening which in turn influences patterns of ocean circulation, and (iv) changes in their mass contribute a modest amount ($49 \pm 8 \mu\text{m}/\text{yr}$) to the rate of sea level rise due to steric effects (Shepherd et al., 2010). Over the past three decades,

satellites have observed the retreat (Scambos et al., 2009) (Cook and Vaughan, 2010), thinning (Paolo et al., 2015) and disintegration (Rott et al., 1996) of Antarctic ice shelves in two key sectors of the continent. On the Antarctic Peninsula, ice shelves have on average retreated by 18% over the last 50 years (Cook and Vaughan, 2010), and large sections of the Larsen-A (Rott et al., 1996), Larsen-B (Rack and Rott, 2004), and the Wilkins (Padman et al., 2012) ice shelves have collapsed catastrophically in 1995, 2002, and 2008, respectively. On the Larsen-C Ice Shelf, a 200 km long iceberg calved in July 2017, reducing the ice shelf area by more than 10%, raising questions about the stability of the remaining ice and the physical mechanism responsible for triggering this event (Hogg and Gudmundsson, 2017). Ice shelf retreat and rapid collapse is thought to be driven by either crevasse propagation by melt water ponding, a process driven by atmospheric warming which causes ice shelf melt water lakes to form

* Corresponding author.

E-mail address: A.E.Hogg@leeds.ac.uk (A.E. Hogg).

in crevasses on the ice shelf surface (Scambos et al., 2000), or by warmer ocean water causing thinning due to increased sub-marine basal melt rates. On a number of ice shelves including George VI and Wilkes it was shown that snow densification caused by warm atmospheric temperatures was not large enough to cause the rate of ice shelf thinning observed (Pritchard et al., 2012) (Padman et al., 2012), indicating that ocean driven basal melt may be the dominant process. In the Amundsen Sea Embayment, ice shelves at the terminus of the Pine Island and Thwaites Glaciers have thinned at rates in excess of 5 m per year for more than two decades (Paolo et al., 2016). This signal has been attributed to long-term change in the amount of warm ocean water reaching and eroding the ice shelf base (Depoorter et al., 2013) (Paolo et al., 2018), and has coincided with an acceleration in the rate of ice lost from the grounded ice sheet (Konrad et al., 2017). On Totten and Cook in East Antarctica where little or no surface melt is thought to occur, ice shelf thinning has also been measured (Rignot et al., 2013) which may indicate that ocean processes are the driving mechanism. In other areas on the Antarctic Peninsula such as the Larsen-C ice shelf there is less certainty about the mechanism driving change as independent studies have identified both atmospheric and oceanographic processes to be dominant (Pritchard et al., 2012) (Shepherd et al., 2003).

While these examples demonstrate that ice shelves can respond to change over short timescales, long data records are required to disentangle natural variability from longer term more permanent change. Multidecadal observations of ice shelf evolution improve our knowledge of the timescale over which changes can occur, increasing our capability to forecast how they will evolve in response to environmental change. Estimates of global ice mass losses are now reliant on satellite Earth Observation data as they provide the spatial and temporal sampling and multi measurement capability necessary to measure, and determine the processes driving imbalance. Satellite altimetry provides a >25-year record of ice elevation change, however, the large radar altimeter footprint size (~10 km) and relatively poor performance of historical sensors such as ERS-1 & -2 and Envisat in regions of steeply sloping terrain, typical of the grounding zone, can lead to under-sampling of the most rapidly changing regions of ice (Shepherd et al., 2001) (Paolo et al., 2015). Higher resolution satellite observations have been used to reveal small scale ice shelf features such as meltwater ponds and streams on the ice shelf surface (Kingslake et al., 2017), and deep sub-shelf meltwater channels that can erode ice locally by up to 200 m (Gourmelen et al., 2017). Concentrated melting along inverted basal channels may potentially lead to heightened crevassing on the ice shelf surface, in turn affecting the future ice-shelf stability. Higher resolution observations of ice thickness change are required to detect the maximum rates of ice shelf thinning, which are thought to occur at the ice sheet grounding line (Jenkins, 2011). In this study we use CryoSat-2 satellite data to measure the

continent wide pattern of ice shelf thickness change on all Antarctic ice shelves, at a relatively fine, 2 km spatial resolution.

2. Data and methods

We used 7 years of Level 2 synthetic aperture radar interferometric (SARIn) mode CryoSat-2 radar altimetry data acquired between 2010 and 2017, to measure ice shelf elevation change. Data flagged as unreliable by the ground segment processing were culled and then each elevation data point was corrected for dry and wet atmosphere, ionosphere, inverse barometric effects, solid earth tide, ocean loading and ocean tide, using the Circum-Antarctic Tidal Simulation (CATS2008) model (Padman et al., 2002). Once filtered and corrected, the data are binned into regularly spaced 2 by 2 km grid cells on a polar stereographic projection, before elevation change was computed using an iterative Levenberg-Marquardt least squares fitting method, using measurements of time, slope-corrected geographic location, elevation, backscattered power and orbit heading (McMillan et al., 2014), (Eq. (1)).

$$z(x, y, t, h) = z_m + a_0x + a_1y + a_2x^2 + a_3y^2 + a_4xy + a_5h + a_6t. \quad (1)$$

where z is height, x is the easting component of location, y is the northing component of location, h is satellite heading, t is time, z_m is constant height at $t = 0$, and a_{0-6} are the coefficients of the fit. The track heading component corrects for anisotropy in the ascending and descending tracks caused by the response of the snowpack to stable wind patterns in the interior of the Antarctic Ice Sheet (Armitage et al., 2014), however this correction is less significant in coastal ice shelf areas as wind patterns are more variable. Grid cells where the plane fit model was well constrained were retained based on elevation change rate (<10 m/yr), root mean squared error of the fit (<20 m/yr), slope (<3°), number of data points per grid cell (>15 points) and the time period covered (>2-years). We adjusted the ice shelf surface elevation change measurement to remove the rate of global sea level rise (3.2 mm/yr (Dieng et al., 2017)), which is an external sources of long-term ice shelf height change. A mask of the ice shelf area was produced by manually delineating the calving front in a mosaic of Sentinel-1 synthetic aperture radar images acquired in 2015, and the updated grounding line position was measured using differential interferometry (Rignot et al., 2011). We masked the gridded altimetry data to retain the ice shelf area only, before converting ice shelf surface elevation change to thickness change based on the theory of hydrostatic equilibrium (Eq. (2)) (Fig. 1).

$$z = \frac{(h_{asl} - \delta)\rho_w}{\rho_w - \rho_i} + \delta \quad (2)$$

where z is ice shelf (hydrostatic) thickness, h_{asl} is ice free-board (ice surface elevation above mean sea level) or ice

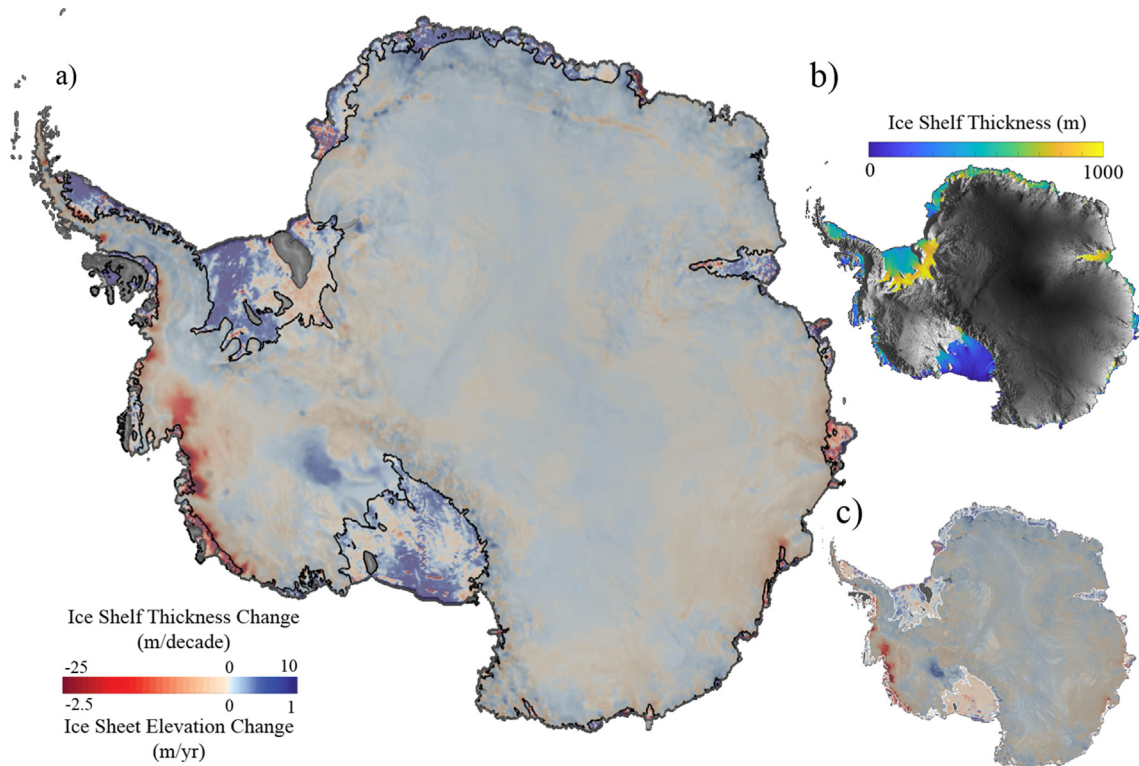


Fig. 1. (a) Map of Antarctic Ice Shelf thickness change measured by the CryoSat-2 radar altimeter satellite between 2010 and 2017. The inland limit of the ice shelves, otherwise known as the grounding line, is annotated (black line), and a map of elevation change measured by CryoSat-2 over the same period is plotted on the Antarctic Ice Sheet. Sub plots show a map of the thickness of Antarctic Ice Shelves (b), and (c) the 25-year rate of ice shelf thickness change measured by ERS-1, ERS-2, and Envisat, and CryoSat-2 satellite radar altimeters combined.

elevation change, ρ_w is density of ocean water (1028 kg/m^3), ρ_i is density of solid ice (917 kg/m^3), and δ is air content of the firn layer which was assumed to be zero.

Gaps in the gridded elevation change data are caused by filtering out poorly constrained grid cells, or due to unsurveyed regions, such as beyond the latitudinal limit of the satellite which is 88°S for CryoSat-2 and 82°S for ERS-1/2 and Envisat. Omission areas were filled using an inverse distance filling algorithm with a maximum 25 km radius. The remaining grid cells with no data were filled with the mean thickness change from each individual ice shelf drainage catchment. We evaluated the density and spatial coverage of CryoSat-2 elevation measurements in comparison to earlier satellite missions, and found that on average observations were returned from 81.9% of the ice shelf area, in comparison with 31.0%, 32.7% and 29.2% from ERS-1, ERS-2 and Envisat respectively (Fig. 2). This improvement in spatial coverage despite using the same grid resolution is attributed to CryoSat-2's long, 369-day precessing orbit, the SARIn operational mode, and the high 88° latitudinal limit which makes this the only altimeter system to currently acquire observations over the whole Antarctic Ice Shelf region. We used the same model fit method to calculate ice shelf thickness change from earlier satellite missions including ERS-1/2

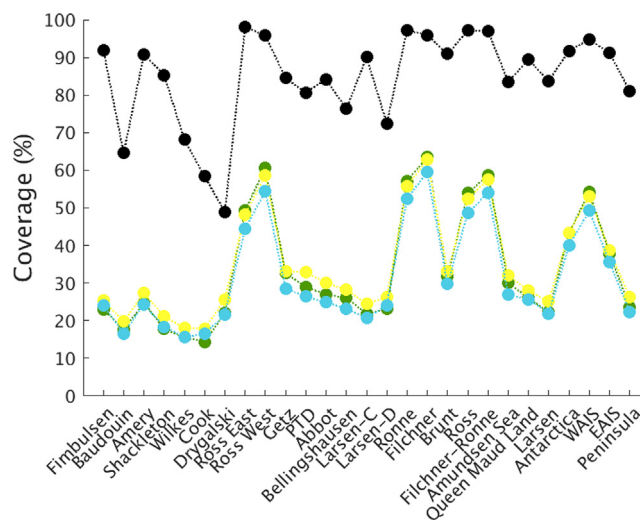


Fig. 2. Percentage coverage of individual Antarctic Ice Shelves by the CryoSat-2 (black) ERS-1 (green), ERS-2 (yellow) and Envisat (blue) satellite radar altimeters. The large difference in coverage between CryoSat-2 and the historical satellites is due to a combination of the drifting orbit which reduces the size of sampling gaps between the fixed orbit ground tracks, and the higher latitudinal limit which removes the pole hole over the most southerly ice shelves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Envisat, with Level 2 elevation measurements used as input data and the same geophysical corrections and post fit filtering applied to all missions. We combined the time series from all four missions by applying a cross-calibration technique (Shepherd et al., 2019), which generates a continuous 25-year record of ice shelf thickness change. At each epoch, we estimate the overall error of our elevation change time series as the standard deviation of the model fit plus errors associated to the calibration between the different satellite missions. The inter-satellite bias error is computed as the standard deviation between modelled elevations during a 2-year period centred on each mission overlap, and finally, we cumulatively sum these errors in quadrature over the full 25-year study period.

3. Results and discussion

We measured the change in ice thickness of ice shelves across Antarctica from 2010 to 2017 (Fig. 1a). Our results show that over the 7-year study period the average ice thickness of 8 ice shelves increased, on the Ross (+1.5 m), Cook (+9.8 m), Amery (+0.8 m), Brunt (+3.9 m), Filchner-Ronne (+2.3 m), Larsen-C (+1.9 m), Larsen-D (+1.3 m), and the Queen Maud Land (+3.3 m) ice shelves (Table 1). In contrast, a decrease in ice thickness

was observed on 9 ice shelves, including Wilkies (−8.1 m), Abbot (−0.5 m), Pine Island, Thwaites & Dotson (−16.2 m), and Getz (−12.0 m) ice shelves in West Antarctica, and the Baudouin (−3.4 m), Shackleton (−3.4 m), Drygalski (−4.8 m) ice shelves in East Antarctica (Table 1). Overall, there is widespread spatial variability in the pattern of thickness change with most ice shelves undergoing a mix of both thinning and thickening. An exception to this is the Amundsen Sea Sector and Getz Ice Shelves which have experienced systematic thinning across the ice shelf, throughout the study period. This signal coincides spatially with the pattern of ice thinning measured on the grounded ice sheet (Fig. 1a), and has been associated with the incursion of warmer Circumpolar Deep Water (CDW) onto the continental shelf driving ice melt (Dutrieux et al., 2014) (Paolo et al., 2018) (Jenkins et al., 2018).

We generated a continuous timeseries of Antarctic Ice Shelf thickness change from 1992 to 2017 from the long satellite radar altimetry record (Fig. 3). The trend in ice shelf thickness change was estimated by fitting a low order polynomial ($n = 3$) over the 25-year period where longer term cycles are present, and by calculating the linear rate over the shorter 7-year present day epoch (Fig. 3). Since 2010, we observed significant variability in the rate of ice shelf thickness change in Antarctica, with the largest

Table 1

Thickness change for all ice shelves in Antarctica, from 2010 to 2017. The linear rate of thickness change is shown for the 7-year and 25-year study periods, and the percentage difference from this longer-term rate is also noted. Errors are shown as the mean variability of the fit. Larger ice shelf regions formed by grouping several smaller shelves, are indicated by italics in the table.

Ice Shelf Name	2010–2017 total ice thickness change (m)	2010–2017 rate of ice thickness change (m/yr)	25-year rate of ice thickness change (m/yr)	Difference from 25-year rate (%)
Fimbulen	3.3 ± 0.13	0.6 ± 0.03	0.3 ± 0.15	73
Baudouin	-3.4 ± 2.93	-0.2 ± 0.01	1.3 ± 0.60	−116
Amery	0.8 ± 0.25	0.2 ± 0.01	0.2 ± 0.11	−5
Shackleton	-3.4 ± 0.02	-0.2 ± 0.01	0.3 ± 0.12	−195
Wilkies	-8.1 ± 0.01	-0.5 ± 0.03	-0.2 ± 0.08	201
Cook	9.8 ± 0.88	0.7 ± 0.04	0.3 ± 0.12	161
Drygalski	-4.8 ± 0.56	-0.3 ± 0.01	-0.1 ± 0.05	112
Ross East	1.7 ± 0.22	0.2 ± 0.01	-0.1 ± 0.04	−348
Ross West	1.1 ± 0.05	0.2 ± 0.01	-0.2 ± 0.08	−214
Getz	-12.0 ± 0.62	-1.8 ± 0.09	-2.1 ± 0.93	−15
PIG, THW & Dotson	-16.2 ± 0.16	-2.4 ± 0.12	-4.9 ± 2.21	−51
Abbot	-0.5 ± 0.56	-0.2 ± 0.01	-0.2 ± 0.08	7
Bellingshausen	-0.2 ± 0.10	0.3 ± 0.02	-0.7 ± 0.30	−151
Larsen-C	1.9 ± 1.31	0.6 ± 0.03	-0.3 ± 0.14	−302
Larsen-D	1.3 ± 0.09	0.5 ± 0.02	0.5 ± 0.21	1
Ronne	2.4 ± 0.01	0.4 ± 0.02	0.1 ± 0.04	348
Filchner	1.8 ± 0.03	0.2 ± 0.01	0.2 ± 0.11	−30
Brunt	3.9 ± 0.10	0.4 ± 0.02	0.4 ± 0.20	−1
Ross	1.5 ± 0.11	0.2 ± 0.01	-0.1 ± 0.06	−268
Filchner-Ronne	2.3 ± 0.01	0.3 ± 0.02	0.1 ± 0.05	168
Amundsen Sea	-9.4 ± 0.51	-1.4 ± 0.07	-2.0 ± 0.90	−28
Queen Maud Land	3.3 ± 0.27	0.5 ± 0.02	0.4 ± 0.20	8
Larsen	1.8 ± 0.79	0.6 ± 0.03	-0.0 ± 0.00	−155349
Antarctica	1.3 ± 0.09	0.2 ± 0.01	-0.1 ± 0.03	−376
WAIS	0.9 ± 0.03	0.1 ± 0.01	-0.2 ± 0.10	−156
EAIS	1.6 ± 0.18	0.2 ± 0.01	0.1 ± 0.04	167
AP	1.0 ± 0.49	0.5 ± 0.02	-0.3 ± 0.13	−259

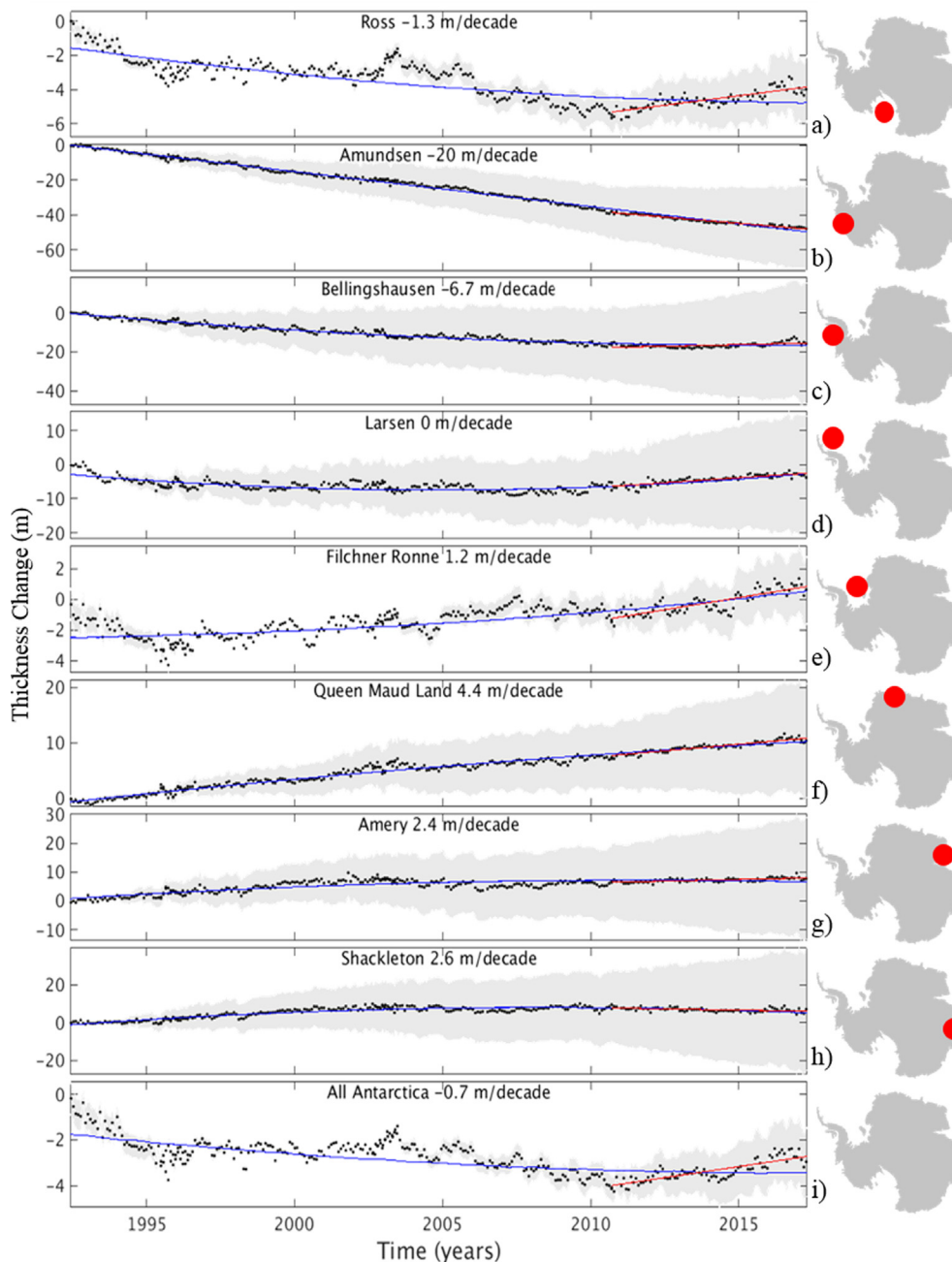


Fig. 3. Timeseries of ice shelf thickness change for 8 major ice shelves in Antarctica, measured by radar altimeter satellites between 1992 and 2017 (grey dots). The linear fit to the timeseries is shown for the period from 2010 to 2017 (red line), and the third order polynomial fit for the full 25-year epoch is also shown (blue line). The cumulative error is also shown for each time series (grey shaded area). The total thickness change per decade, calculated from the full 25-year epoch is annotated. The location of the Ross (a), Amundsen Coast (b), Bellingshausen (c), Larsen (d), Filchner-Ronne (e), Queen Maud Land (f), Amery (g) and Shackleton (h) ice shelves in Antarctica are indicated by the map thumbnails, along with a timeseries for the total change in thickness of all Antarctic Ice Shelves (i). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increase in ice thickness measured on the Cook Ice Shelf at a rate of $+0.69$ m per year, and the fastest thinning observed on the Pine Island, Thwaites, & Dotson ice shelf group, at a rate of -2.4 m per year (Table 1). Despite the fact that the largest thinning took place on the Pine Island, Thwaites, & Dotson ice shelf group in both the most recent and long-term records, the rate of change has reduced by 51% in the past 7-years (Table 1). We compared the record

of ice shelf thickness change measured between 2010 and 2017 with the historical record from 1992 to 2010 (Fig. 1c) (Paolo et al., 2015). This shows that there is variability in the spatial pattern of these signals through time, demonstrating the value of both long-term and contemporary records. The variability is reflected in the difference between the 7 and 25-year rate of thickness change, where ice thickening increased by 268%, 302% and 168% on the

Ross, Larsen-C and Filchner-Ronne ice shelves respectively (Table 1). Overall, between 2010 and 2017 ice shelves in Antarctica thickened by 1.3 m as ice losses from West Antarctica were compensated by ice gains in East Antarctica and the Antarctic Peninsula (Table 1), reversing the negative trend from the previous two decades (Paolo et al., 2015).

Freshwater produced through ice shelf-ocean interactions has been shown to impact on the rate of deep-water formation and ocean circulation (Depoorter et al., 2013), melt water refreezing affects the net ice loss (Joughin et al., 2003), and ice shelf thinning or removal substantially reduces the buttressing effect which protects the grounded ice sheet from unstable retreat (Rignot et al., 2004). In order to assess the response of ice shelves to change in ocean temperatures, we aggregated observations of thickness change into 5-year long epochs spanning the full 25-year record (Table 2). Our results show that there is temporal variability in the pattern of ice shelf thickness change, and that large fluctuations, including a reversal of the thinning trend, can occur over short, sub-decadal time periods. Since 1992, the Getz, and the Pine Island, Thwaites & Dotson Ice Shelves have lost 49.8 m and 119.4 m of ice respectively, however, the biggest losses were observed prior to 2010, rather than the most recent 7-years (Table 2). Measurements of ocean temperature change in the Amundsen Sea show that while the trend for ocean warming has been

present since measurements were first collected in the early 1990's, the spread of temperature values is wider in some years, suggesting the presence of both warm and cold water. In 2000, ocean temperature measurements collected in the Amundsen Sea ranged from approximately +1.1 to -0.25 °C, a spread of ~ 1.35 °C, but in 2006 the range was 66% smaller (~ 0.45 °C) with warmer temperatures between approximately + 1.2 and +0.75 °C recorded (Schmidtko et al., 2014). More recently, cooler ocean temperatures have been recorded since 2010, with atmospheric forcing from a strong la Niña event driving cooler temperatures in 2012 (Dutrieux et al., 2014). Vertical temperature profiles acquired in front of the Dotson Ice Shelf, also showed the presence of relatively cool water in 2000, and again between 2012 and 2016 (Jenkins et al., 2018), providing further evidence to support the presence of cooler periods despite the long-term warming trend. While the poor spatial coverage of ocean temperature data limits the extent to which we can establish if the relatively warmer or cooler ocean water came into direct contact with ice shelves in the region throughout the last 25-years, our observations do show that thinning of the Pine Island, Thwaites & Dotson group was lowest (-14.0 m) between 2012 and 2017 when the relatively cooler ocean water was observed. In the neighboring Bellingshausen Sea, observations show that ocean warming since the late 1970's has also coincided with long-term ice shelf thinning since 1992 (Fig. 3). However, a

Table 2

Ice shelf thickness change in Antarctica measured over defined 5-year epochs starting in 1992, and total thickness change measured over the full 25-year record.

Ice Shelf Name	Total observed thickness change (m)					
	1992–1997	1997–2002	2002–2007	2007–2012	2012–2017	1992–2017
Fimbulsen	2.2	1.8	-0.2	3.4	2.9	9.7
Baudouin	9.4	4.4	8.8	12.0	-5.6	26.0
Amery	4.5	5.2	-2.9	1.9	2.2	7.9
Shackleton	3.1	4.1	-2.6	-0.6	-1.9	5.9
Wilkies	3.7	-0.7	-4.7	-3.6	-5.6	-6.1
Cook	1.9	0.1	0.2	2.4	4.9	8.6
Drygalski	-5.8	0.0	-0.2	-2.6	-1.4	-5.6
Ross East	-2.9	-0.3	-0.9	-0.4	1.2	-2.8
Ross West	-2.8	-2.0	-0.6	-0.6	1.4	-4.3
Getz	-7.2	-9.8	-10.1	-10.9	-8.8	-49.8
PIG, THW & Dotson	-27.1	-24.6	-24.3	-24.6	-14.0	-119.4
Abbot	-0.9	-2.8	-1.6	-1.0	-1.7	-4.5
Bellingshausen	-3.9	-4.6	-4.8	-3.9	1.3	-15.8
Larsen-C	-8.5	-1.8	-5.0	1.0	0.2	-13.1
Larsen-D	2.0	0.4	1.6	3.4	0.7	9.5
Ronne	-2.3	0.4	0.3	-0.9	1.6	-0.3
Filchner	-0.7	2.0	1.0	-0.1	0.9	4.1
Brunt	1.2	3.2	2.0	0.7	1.6	9.5
Ross	-2.9	-1.0	-0.8	-0.6	1.3	-3.5
Filchner Ronne	-1.9	0.8	0.4	-0.8	1.4	0.7
Amundsen Sea	-8.6	-10.4	-10.0	-10.2	-7.8	-48.2
Queen Maud Land	2.0	2.7	1.3	2.2	1.7	10.4
Larsen	-4.6	-0.9	-2.5	1.3	0.4	-4.1
Antarctica	-2.1	-0.4	-0.8	-0.8	0.8	-2.8
WAIS	-3.1	-1.6	-0.9	-1.8	0.6	-6.5
EAIS	-1.0	1.1	-0.4	0.2	1.0	1.5
AP	-3.9	-2.5	-3.6	-0.7	0.7	-9.0

reduction in the rate of ice shelf thinning on the Bellingshausen Ice Shelves since 2010, as also observed by other regional studies (Adusumilli et al., 2018), may be explained by a temporally coincident modest deepening of the warm CDW in the water column to 300 m depth (Schmidtke et al., 2014), reducing melt rates in this region. In the Getz region, an influx of CDW has been attributed to driving grounding line retreat inland since 2003, with slower rates reported during a moderately colder period from 2010 to 2015 (Christie et al., 2018). The coincidence of relatively cool ocean temperatures and a possible deepening of the CDW, with a reduction in the 5-year rate of ice shelf thinning in the Amundsen and Bellingshausen Sea Sectors, provides evidence to suggest that these ice shelves are directly susceptible to short term fluctuations in ocean heat content. In other regions of Antarctica other potential drivers, such as atmospheric forcing, may play a larger role than ocean temperature change. In Queen Maud Land, the persistent ice shelf thickening (Fig. 1) observed throughout the 25-year record (Table 1, Fig. 3), can in part be attributed to anomalously large snowfall events that occurred in 2009 and 2011 (Lenaerts et al., 2013). In the future, acquisition of more spatially and temporally extensive ocean temperature and snowfall data should be prioritized, especially at repeat measurement locations, in order to disentangle short term fluctuations in ice shelf forcing from long term persistent change.

In both Greenland and Antarctica, convection-driven buoyant meltwater plumes formed through discharge of subglacial meltwater, are thought to force higher melt rates at the grounding line on ocean terminating glaciers and ice shelves (Jenkins, 2011) (Slater et al., 2016). In Antarctica, while seasonal meltwater production is not as widespread as in Greenland, the presence of active sub-glacial lakes near the grounding line may have important implications for ice melt when drainage events occur (Smith et al., 2017). On large ice shelves such as the Filchner-Ronne, and Ross Ice Shelves, ice thinning has also been observed at the calving front as turbulent tidal mixing advects warm surface water to the ice front (Arzeno et al., 2014). However, previously observations of small spatial scale, high melt rates have been limited by the relatively coarse 30 km spatial resolution of historical ice shelf thickness change observations (Shepherd et al., 2003) (Paolo et al., 2015). In the future, studies should exploit the improved spatial coverage of CryoSat-2 (Fig. 2), advanced techniques such as ‘swath mode’ altimetry, and new satellites such as ICESat-2 to further increase the spatial resolution of observational datasets which will allow the detailed spatial pattern of Antarctic ice-shelf thinning to be resolved in ever more detail.

4. Conclusions

Ice shelves are an important part of the glaciological system because they provide a direct link between oceans and the grounded ice sheet. In this study we used CryoSat-2

radar altimetry data to extend 25-year record of ice shelf thickness change across Antarctica, through to 2017. Our results showed that a slowdown in the rate of ice-shelf thinning in the Amundsen and Bellingshausen Sea regions since 2010, may be linked to a reduction in the relatively warm Circumpolar Deep Water which has previously driven submarine melting in the ice shelf cavity. By measuring ice shelf thickness change at relatively high spatial resolution, we found that the spatial pattern of thinning is highly variable across Antarctica, and on individual ice shelves, and that this should be further investigated in the future in order to avoid underestimating the maximum rates of ice loss. Despite 25-years of observations of ice shelf collapse and thickness change, we do not yet fully understand the detailed interaction between ice shelves and the physical mechanisms that drive both longer-term permanent, and short-term temporary change. This means a direct link between ice shelves and global climate change cannot be conclusively established, and it makes it difficult to predict the magnitude of changes that are required to destabilize an ice shelf, triggering collapse. Observations of ice shelf thinning and disintegration can serve as test cases, to help improve our ability to predict the period over which such changes may occur, and to ultimately determine the timescale of natural ice shelf variability. In the future, observations and models must be combined to improve our understanding of how the projected warming of ocean waters will likely affect the ice shelves in Antarctica, and the role they play in buttressing the grounded ice sheet against unstable retreat.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was led by the NERC Centre for Polar Observation and Modelling, supported by the Natural Environment Research Council (cpom300001). AEH was funded by a European Space Agency Living Planet independent research fellowship (No. 4000112797/15/I-SBo) jointly funded by the European Space Agency, the University of Leeds, and the British Antarctic Survey, along with a NERC Fellowship (NE/R012407/1). Special thanks goes to Stephen Plummer who provided valuable guidance as the ESA Technical Officer on this project. The authors gratefully acknowledge the ESA for the use of CryoSat-2 data.

References

- Adusumilli, S., Fricker, H.A., Siegfried, M.R., Padman, L., Paolo, F.S., Ligtenberg, S.R.M., 2018. variable basal melt rates of Antarctic Peninsula ice shelves, 1994–2016. *Geophys. Res. Lett.* 45, 4086–4095.

- Armitage, T.W.K., Wingham, D.J., Ridout, A.L., 2014. Meteorological origin of the static crossover pattern present in low-resolution-mode CryoSat-2 data over central Antarctica. *IEEE Geosci. Remote Sens. Lett.* 11, 1295–1299.
- Arzeno, I.B., Beardley, R.C., Limeburner, R., Owens, B., Padman, L., Springer, S.R., Stewart, C.L., Williams, M.J.M., 2014. Ocean variability contributing to basal melt rate near the ice front of Ross Ice Shelf, Antarctica. *J. Geophys. Res. Oceans* 119, 4214–4233.
- Christie, F.D.W., Bingham, R.G., Gourmelen, N., Steig, E.J., Bisset, R. R., Pritchard, H.D., Snow, K., Tett, S.F.B., 2018. Glacier change along West Antarctica's Marie Byrd Land Sector and links to inter-decadal atmosphere–ocean variability. *The Cryosphere* 12, 2461–2479.
- Cook, A.J., Vaughan, D.G., 2010. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. *The Cryosphere* 4, 77–98.
- Depoorter, M.A., Bamber, J.L., Griggs, J.A., Lenaerts, J.T.M., Ligtenberg, S.R.M., van den Broeke, M.R., Moholdt, G., 2013. Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature* 502, 89–92.
- Dieng, H.B., Cazenave, A., Meyssignac, B., Ablain, M., 2017. New estimate of the current rate of sea level rise from a sea level budget approach. *Geophys. Res. Lett.* 44, 3744–3751.
- Dutrieux, P., de Rydt, J., Jenkins, A., Holland, P.R., Ha, H.K., Lee, S.H., Steig, E.J., Ding, Q., Abrahamsen, E.P., Schröder, M., 2014. Strong sensitivity of pine island ice-shelf melting to climatic variability. *Science* 343, 174–178.
- Gourmelen, N., Goldberg, D.N., Snow, K., Henley, S.F., Bingham, R.G., Kimura, S., Hogg, A.E., Shepherd, A., Mouginot, J., Lenaerts, J.T.M., Ligtenberg, S.R.M., van de Berg, W.J., 2017. Channelized melting drives thinning under a rapidly melting antarctic ice shelf. *Geophys. Res. Lett.* 44, 9796–9804.
- Hogg, A.E., Gudmundsson, G.H., 2017. Impacts of the Larsen-C Ice Shelf calving event. *Nat. Clim. Change* 7, 540–542.
- Jenkins, A., 2011. Convection-driven melting near the grounding lines of ice shelves and tidewater glaciers. *J. Phys. Oceanogr.* 41, 2279–2294.
- Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T.W., Lee, S. H., Ha, H.K., Stammerjohn, S., 2018. West Antarctic ice sheet retreat in the Amundsen sea driven by decadal oceanic variability. *Nat. Geosci.* 11, 733–738.
- Joughin, I., Rignot, E., Rosanova, C.E., Lucchitta, B.K., Bohlander, J., 2003. Timing of recent accelerations of Pine Island Glacier, Antarctica. *Geophys. Res. Lett.* 30 (13), 1706.
- Kingslake, J., Ely, J.C., Das, I., Bell, R.E., 2017. Widespread movement of meltwater onto and across Antarctic ice shelves. *Nature* 544, 349–352.
- Konrad, H., Gilbert, L., Cornford, S.L., Payne, A., Hogg, A., Muir, A., Shepherd, A., 2017. Uneven onset and pace of ice-dynamical imbalance in the Amundsen Sea Embayment, West Antarctica. *Geophys. Res. Lett.* 44, 910–918.
- Lenaerts, J.T.M., van Meijgaard, E., van den Broeke, M.R., Ligtenberg, S.R.M., Horwath, M., Isaksson, E., 2013. Recent snowfall anomalies in Dronning Maud Land, East Antarctica, in a historical and future climate perspective. *Geophys. Res. Lett.* 40, 2684–2688.
- McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., Wingham, D., 2014. Increased ice losses from Antarctica detected by CryoSat-2. *Geophys. Res. Lett.* 41, 3899–3905.
- Padman, L., Costa, D.P., Dinniman, M.S., Fricker, H.A., Goebel, M.E., Huckstadt, L.A., Humbert, A., Joughin, I., Lenaerts, J.T.M., Ligtenberg, S.R.M., Scambos, T., van den Broeke, M.R., 2012. Oceanic controls on the mass balance of Wilkins Ice Shelf Antarctica. *J. Geophys. Res.: Oceans* 117, C01010.
- Padman, Laurie, Fricker, A, Helen, Coleman, Richard, Howard, Susan, Erofeeva, Lana, 2002. A new tide model for the Antarctic ice shelves and seas. *Annals of Glaciology* 34, 247–254. <https://doi.org/10.3189/172756402781817752>.
- Paolo, F.S., Fricker, H.A., Padman, L., 2015. Volume loss from Antarctic ice shelves is accelerating. *Science* 348, 327–331.
- Paolo, F.S., Fricker, H.A., Padman, L., 2016. Constructing improved decadal records of Antarctic ice shelf height change from multiple satellite radar altimeters. *Remote Sens. Environ.* 177, 192–205.
- Paolo, F.S., Padman, L., Fricker, H.A., Adusumilli, S., Howard, S., Siegfried, M.R., 2018. Response of Pacific-sector Antarctic ice shelves to the El Niño/Southern Oscillation. *Nat. Geosci.* 11, 121–126.
- Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H.A., Vaughan, D.G., van den Broeke, M.R., Padman, L., 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484, 502–505.
- Rack, W., Rott, H., 2004. Pattern of retreat and disintegration of the Larsen B ice shelf, Antarctic Peninsula. *Ann. Glaciol.* 39, 505–510.
- Reese, R., Gudmundsson, G.H., Levermann, A., Winkelmann, R., 2018. The far reach of ice-shelf thinning in Antarctica. *Nat. Clim. Change* 8, 53–57.
- Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A., Thomas, R., 2004. Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophys. Res. Lett.* 31, L18401.
- Rignot, E., Jacobs, S., Mouginot, J., Scheuchl, B., 2013. Ice-shelf melting around antarctica. *Science* 341, 266–270.
- Rignot, E., Mouginot, J., Scheuchl, B., 2011. Ice flow of the antarctic ice sheet. *Science* 333, 1427–1430.
- Rott, H., Skvarca, P., Nagler, T., 1996. Rapid collapse of northern larsen ice shelf, antarctica. *Science* 271, 788–792.
- Scambos, T., Fricker, H.A., Liu, C.-C., Bohlander, J., Fastook, J., Sargent, A., Massom, R., Wu, A.-M., 2009. Ice shelf disintegration by plate bending and hydro-fracture: satellite observations and model results of the 2008 Wilkins ice shelf break-ups. *Earth Planet. Sci. Lett.* 280, 51–60.
- Scambos, T.A., Hulbe, C., Fahnestock, M., Bohlander, J., 2000. The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *J. Glaciol.* 46, 516–530.
- Schmidtke, S., Heywood, K.J., Thompson, A.F., Aoki, S., 2014. Multidecadal warming of Antarctic waters. *Science* 346 (1227), 207–221.
- Shepherd, A., Wingham, D., Payne, T., Skvarca, P., 2003. Larsen ice shelf has progressively thinned. *Science* 302, 856–859.
- Shepherd, A., Wingham, D., Wallis, D., Giles, K., Laxon, S., Sundal, A. V., 2010. Recent loss of floating ice and the consequent sea level contribution. *Geophys. Res. Lett.* 37, L135503.
- Shepherd, Andrew, Gilbert, Lin, Muir, Alan S., Konrad, Hannes, McMillan, Malcolm, Slater, Thomas, Briggs, Kate H., Sundal, Aud V., Hogg, Anna E., Engdahl, Marcus E., 2019. Trends in Antarctic Ice Sheet Elevation and Mass. *Geophysical Research Letters* 46, 8174–8183. <https://doi.org/10.1029/2019GL082182>.
- Shepherd, A., Wingham, D.J., Mansley, J.A.D., Corr, H.F.J., 2001. Inland thinning of pine island glacier, West Antarctica. *Science* 291, 862–864.
- Slater, D.A., Goldberg, D.N., Nienow, P.W., Cowton, T.R., 2016. Scalings for submarine melting at tidewater glaciers from buoyant plume theory. *J. Phys. Oceanogr.* 46, 1839–1855.
- Smith, B.E., Gourmelen, N., Huth, A., Joughin, I., 2017. Connected subglacial lake drainage beneath Thwaites Glacier, West Antarctica. *The Cryosphere* 11, 451–467.