In situ measurements of snow accumulation in the Amundsen Sea Embayment during 2016

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Running header: Snow accumulation in the Amundsen Sea Embayment

Abstract

Measurements of snow accumulation are critical for reliable prediction of future ice mass loss and hence projections of sea level change. However, there are currently very few published in situ measurements of snow accumulation in the Pine Island-Thwaites Glacier catchment of the Amundsen Sea Embayment, and none from low elevation sites west of 100.77º longitude. Here we report measurements of snow accumulation over an 11-month period in 2016 at six sites in the Pine Island-Thwaites Glacier catchment. The average accumulation rates of 0.10 ± 0.01 to 1.26 ± 0.22 m w.e. yr^{-1} are comparable with those derived from airborne radar for the period 1985-2009, suggesting very high rates of snowfall, particularly in the vicinity of the grounding line.

Keywords

Pine Island Glacier, Thwaites Glacier, ice sheet, grounding line, ERA-interim re-analysis

Introduction

The Amundsen Sea sector is currently the dominant contributor to ice mass loss from the Antarctic Ice Sheet. Glaciers draining this sector have thinned and retreated dramatically in recent decades (e.g. Rignot et al., 2014), probably in response to increased delivery of warm Circumpolar Deep Water, that is melting ice shelves from beneath (Jacobs et al., 2011; Thoma et al., 2008). This has resulted in a negative mass balance for this sector of the ice sheet. Our understanding of how the ice sheet will respond to future environmental change is dependent upon reliable model predictions, which require knowledge of current ice mass loss.

An ice sheet shrinks when the loss of ice from flow across the grounding line is greater than the amount of surface accumulation through snowfall. Such mass change is associated with change in sea level because water is lost to the surrounding ocean through outward transport across the grounding line. In the Amundsen Sea Embayment (ASE; Fig. 1), ice discharge from Pine Island and Thwaites Glaciers has been increasing in recent years, and model predictions suggest this rate of mass loss will increase in the coming decades (Joughin et al., 2014; DeConto & Pollard, 2016; Ritz et al., 2015). However, a scarcity of records of snow accumulation in the region is limiting the reliability of future mass loss predictions, and hence projections of sea level change (Medley et al., 2014), because the surface mass balance of the ice sheet cannot be reliably determined whilst uncertainty surrounding the magnitude of surface accumulation remains high. Here we report in situ measurements of accumulation rate for six sites across the ASE during 2016.

Figure 1

Accumulation rates in the Amundsen Sea region

Despite the importance of quantifying ice volume change in the ASE for predicting future sea level change, there are few published in situ measurements of accumulation in the Pine Island-Thwaites Glacier catchment. Dedicated drilling campaigns such as the International Trans-Antarctic Scientific Expedition (ITASE) have increased our understanding of snow accumulation and climate variability over much of West Antarctica (Kaspari et al., 2004), while a series of ice cores drilled along the Ellsworth Land coast captured snow accumulation variability at the outer edges of the Pine Island catchment over the past 300 years (Thomas et al., 2015). However, to date, only three intermediate-depth records, drilled in December 2010–January 2011 (Medley et al., 2014), are available from within the Pine Island-Thwaites catchment.

Ice core records, in conjunction with airborne radar, have been used to confirm that both the re-analysis data (Thomas and Bracegirdle, 2015) and the Regional Atmospheric Climate Model (RACMO; Medley et al., 2014; Thomas et al., 2017; Lenaerts et al., 2017) across West Antarctica are reliably capturing the spatiotemporal variability in snow accumulation. For the Pine Island-Thwaites catchment there is no significant trend in either measured or modelled snow accumulation between 1985 and 2009 (Medley et al., 2014). This is consistent with observations from WAIS Divide (Banta et al., 2008) and the central West Antarctic basin (Wang et al., 2017), but contrasts with both the significant increases in snow accumulation observed on the Ellsworth Land coast (Thomas et al., 2015 and 2017) and the opposing significant decreases in snow accumulation observed in western West Antarctica (Burgener et al., 2013; Wang et al., 2017) for the same period.

The temporal variability in accumulation within the Thwaites-Pine Island catchment is significant at annual scale (Medley et al., 2013, fig. 3), and the spatial variability, as estimated by RACMO, is large (Lenaerts et al., 2017). Average snow accumulation at the outer edges of the catchment ranges from 200–300 mm w.e. yr^{-1} while values in excess of 1000 mm w.e. yr^{-1} are expected at the coast (Medley et al., 2014). However, to date, all the in situ snow accumulation records used to evaluate these climate models have been drilled at elevations greater than 1200 m above sea level. A suite of in situ observations of snow accumulation from low elevation sites (i.e. less than 1200 m above sea level) on Pine Island Glacier and its tributaries was recently published (Morris et al., 2017), but to our knowledge, none have been obtained from further afield, including the areas to the north of Pine Island Glacier (Eights Coast) and west of 100.77º longitude along the Walgreen Coast, which includes Thwaites Glacier (Fig. 1). With increasing scientific interest in the region, particularly at sites near the grounding line, it is imperative that the annual snow accumulation at low elevations across the whole Pine Island-Thwaites Glacier catchment is verified.

Method

We visited six sites across the Amundsen Sea Embayment (Fig. 1) on two occasions, the first in January 2016 and the second in December 2016. The purpose of these visits was to service seismic stations of the UKANET seismic network near Pine Island Glacier (sites prefixed by ‘PIG’; Fig. 1), and to locate and raise equipment depoted in January 2016 at Mt Murphy (site D115; Fig. 1). All the UKANET sites are located within the catchment of Pine Island Glacier, whereas D115 is located on the western margin of the Thwaites-Haynes Glacier catchment.

Figure 2

The seismic stations are powered by solar energy during the summer. At installation, the heights of the solar panels above the snow surface were recorded using a tape measure. At all sites, flags marking the station locations were visible above the ice sheet surface, although sometimes only just (Fig. 2a). Servicing entailed raising the seismometer back toward the surface via vertical shafts dug with shovels (Fig. 2b). By repeating the measurement of the solar panel height above (or below, following complete burial) the snow surface, we were able to determine the total depth of snow that had fallen during the period of approximately 11 months between initial deployment and servicing.

The equipment depoted at D115 in early 2016 was marked by ten 3 m-high bamboo canes topped by black cloth flags. Here the canes and flags became completely buried by snow (Fig. 2c) during the subsequent 11 months, and were relocated using ground-penetrating radar and a metal detector. The green tarpaulin covering the depot (Fig. 2d) was eventually reached by digging a vertical shaft through which the snow depth to the base of the depot was measured. Details of each site, with measurements of snow depth are shown in Table I. The measurement uncertainty is no more than 10 cm. The time period over which the measurements were collected is short, thus uncertainties related to internal ice deformation, glacier flow and drift are likely to be minimal. There was no evidence for significant drift at any of the sites (no undulations in topography above the D115 depot or build-up of snow around flags/solar panels marking the UKANET sites). Furthermore, D115 had moved downstream by 45 m over the 11 month period, which is not far enough to have any significant effect on snow depth measurements.

In order to calculate snow accumulation – the net result of precipitation, sublimation, wind erosion and melt – as metres of water equivalent per year at each site for comparison with other records, e.g. those from airborne radar and ice cores (Table I), the density of the snow must be known. However, due to the opportunistic nature of our measurements, we were unable to measure snow density at our sites. Snow density increases with depth and we have therefore used an average density profile, based on a compilation of six low elevation sites on Pine Island Glacier that are situated near our sites (iSTAR sites 15-19, and 22; Morris et al., 2017) (grey squares in Fig. 3). The average density for the top metre based on this compilation is 419 kg m^{-3}, which is very close to a value of 420 kg m^{-3} used in an earlier study to calculate mean accumulation rate across the wider Pine Island-Thwaites Glacier catchment from airborne radar (Medley et al., 2014).

Table I

Results

Accumulation rates at our six sites are in the range 0.10 ± 0.01 to 1.26 ± 0.22 m w.e. yr^{-1} (Table I and Fig. 3). These rates equate to snow depths of 0.25–3.8 m depth over a period of approximately 330 days, including the austral winter. The highest accumulation rates were recorded at sites D115 and PIGD, which lie within 30 and 50 km of the modern grounding line, respectively, both along the Walgreen Coast (Fig. 1). D115 is located 14 km to the south of Mt Murphy, a prominent mountain which rises nearly 2000 m above the site (Fig. 2c) and which is therefore likely to cause particularly high snowfall there. Significantly lower accumulation rates were recorded at sites in the eastern Pine Island Glacier catchment (sites PIG1, PIG2 and PIG3) than in the west. This is likely due to their location within a precipitation shadow of mountains along the Eights Coast (Fig. 3), and, for PIG3, wind-scouring due to its low elevation and location on the glacier margin. We did not find a correlation between accumulation rate and altitude. This is probably because the differing effects of orography and aspect at each site make the accumulation gradient more complex; therefore a detailed assessment of the terrain geometry at each site would be needed to evaluate these effects.

Figure 3

Discussion

Comparison of our results with accumulation rate ranges for the Pine Island-Thwaites sector (Medley et al., 2014) shows that accumulation rates in 2016 from 5 out of the 6 sites lie within the average ranges for the period 1985-2009 (0.18–1.37 m w.e. yr^{-1} for the Pine Island Glacier catchment and 0.21–0.84 m w.e. yr^{-1} for the Thwaites Glacier catchment). Rates exceeding 1 m w.e. yr^{-1} – similar to that recorded at D115 in 2016 (1.26 ± 0.22 m w.e. yr^{-1}) – were observed by Medley et al. (2014) along the coast near Pine Island Glacier. Mean annual accumulation rates calculated for sites on Pine Island Glacier and its tributaries range from 0.23-0.80 m w.e. yr^{-1} (Morris et al., 2017). Accumulation rates in 2016 from 4 out of 5 of our sites on Pine Island Glacier (i.e. excluding D115, which is situated more than 280 km west of Pine Island Glacier) lie within this range. iSTAR site 22 is located at PIGD (Fig. 3); Morris et al. (2017) reported an accumulation rate for that site of 0.78 m w.e. yr^{-1} which is identical within error to our value of 0.80 ± 0.13 m w.e. yr^{-1}.

Figure 3 shows our data in comparison with accumulation rates for the area determined by Medley et al. (2014). Only 3 of our sites (PIG3, PIG4 and PIGD) directly overlap with their grid, although the others are located only 10–35 km from it. The accumulation rate calculated for PIGD (0.80 ± 0.13 m w.e. yr^{-1}) concurs with that determined by Medley et al. (2014). For PIG3 and PIG4, our measurements suggest accumulation rates that differ by up to 0.2 m w.e. yr^{-1} (lower for PIG3, and higher for PIG4; Fig. 3). However, the resolution of Medley's grid is 25 km; since PIG3 and PIG4 are located only 15 and 11 km, respectively, from areas with accumulation rates that match those we measured, we conclude that our data are in good agreement with those derived from the airborne radar and ice core glacio-chemical analysis. Although D115 has a higher accumulation rate than any observed for the Thwaites Glacier catchment, none of the accumulation rates calculated from snowpit measurements at our sites are exceptional for this region. This is illustrated by a comparison with precipitation-evaporation (P-E) from ERA-interim re-analysis (Dee et al., 2011), the average of which suggests that 2016 had the fifth highest annual precipitation in this region since 1979 (Fig. 4). We therefore consider our results for snow accumulation to be representative of P-E in an above-average, but not anomalously high, year. The average snow accumulation determined from all snowpit sites in this study (0.63 m w.e.) is in agreement with the average P-E from ERA-interim (0.66 m w.e.) for the same sites over the same time period (i.e. not a complete year). This suggests that the ERA-interim re-analysis is capturing precipitation variability in the region as observed previously for higher elevation sites (Thomas and Bracegirdle, 2015). Furthermore, the 2016 data suggest that there has not been any significant change in accumulation rates in the region since early 2011 when the firn cores DIV2010, PIG2010 and THW2010 (Fig. 3) were collected (Medley et al., 2014).

Figure 4

During the 11-month period over the austral winter of 2016, our sites experienced 2-4 m of snowfall. Large amounts of snowfall such as this have severe implications for logistics, especially when equipment and fuel is to be stored at a site for periods of several months or years. The results of this study suggest that depots on snow or ice in the Pine Island-Thwaites Glacier catchment would be best located on as flat an area as possible, and on berms of at least 4 m height for large amounts of equipment/fuel. Marking smaller caches with flagpoles of at least 6 m length and raising depots of any size annually would mitigate against loss by complete burial. These suggestions are especially important for work in the vicinity of the grounding line where accumulation rate is presently particularly high. Even though the Medley et al. (2014) data only describe the period up to 2009, the consistency of our 2016 data with theirs suggests that their accumulation rate grid (their Fig. 7b) can be used as a reliable guide for assessing suitability of work sites in the ASE region.

Conclusions

In situ measurements of accumulation rates across the ASE in 2016 are within average ranges derived from airborne radar data for the period 1985–2009 by Medley et al. (2014) and neutron probe measurements made on Pine Island Glacier in 2014 by Morris et al. (2017), with the exception of a site near Mt Murphy where accumulation rate exceeded 1 m w.e. yr^{-1}. When compared with existing published data for the earlier time period and the average P-E predicted for 2016 by ERA-interim re-analysis, this value is high but within the expected range of variability. Results from our study imply that the highest accumulation rates in the ASE occur near the grounding line of the Walgreen Coast on the western side of Pine Island Glacier; in 2016, rates in this region corresponded with up to 4 m of snowfall within an 11-month period. Although based on data from 1985-2009, the accumulation map (Medley et al., 2014, fig. 7b) can be used as a guide for choosing suitable locations for depoting equipment and fuel. Our results suggest that 4 m-high berms or 6 m-high marker poles, as well as annual raises, should be routinely considered for depots to be left over winter in the Pine Island-Thwaites region, especially near the grounding line.

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Author Contributions

JSJ conceived the study. JSJ and JPO’D undertook the fieldwork and all authors contributed to writing the manuscript.

Details of Data Deposit

The data in Table I are freely available within the Discovery Metadata System of the UK Polar Data Centre, found at https://data.bas.ac.uk.

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Figure Captions

Figure 1: Map of Amundsen Sea Embayment, showing location of our field sites (green). Coloured background is ice velocity (Rignot et al., 2011a and 2011b), which highlights the major ice streams in the region and overlies imagery from the Landsat Image Mosaic of Antarctica. The dark blue line is the 2011 grounding line (Rignot et al, 2011c).

Figure 2: Photographs of field sites. (a) Seismic station (marked by flags) and fuel depot (marked by fuel drum near the aircraft) at PIGD, as viewed on arrival at the site. The flags mark the top of 4 m-high poles, which are only just visible above the snow surface. (b) The seismic station and solar panel at site PIG4, buried by 2.1 m of snow. (c) Location of completely buried equipment and fuel depot at D115 (with Mt Murphy in the background). The roughness of the snow surface in the foreground is the result of extensive digging in an attempt to locate the buried depot. (d) The D115 equipment depot on the surface in January 2016, prior to burial. Black flags mark the top of 3 m-high bamboo canes.

Figure 3: Map showing comparison between accumulation rate at our sites (black circles) and average accumulation rates in the Pine Island-Thwaites Glacier catchments from 1985–2009 (Medley et al., 2014). The location of three firn cores, the latter with associated average accumulation rates from 1985–

2009 (Medley et al., 2014), are shown as red stars. Also shown are the locations of the ITASE firn/ice cores (Kaspari et al., 2004) and firn cores from the iSTAR traverse (Morris et al., 2017). The square grey symbols represent the six iSTAR core sites whose average density we used to calculate accumulation rates (see text) Glacier catchments from the Antarctic Digital Database (www.add.antarctic.ac.uk) are outlined in white.

Figure 4: Annual average precipitation-evaporation (P-E) from ERA-interim re-analysis (1979-2016; black line). The average snow accumulation determined from measurements of all snowpits in this study is represented by the red circle, and is in agreement with the average P-E from ERA-interim for the same sites (blue triangle) over the same 11-month period.

Figures

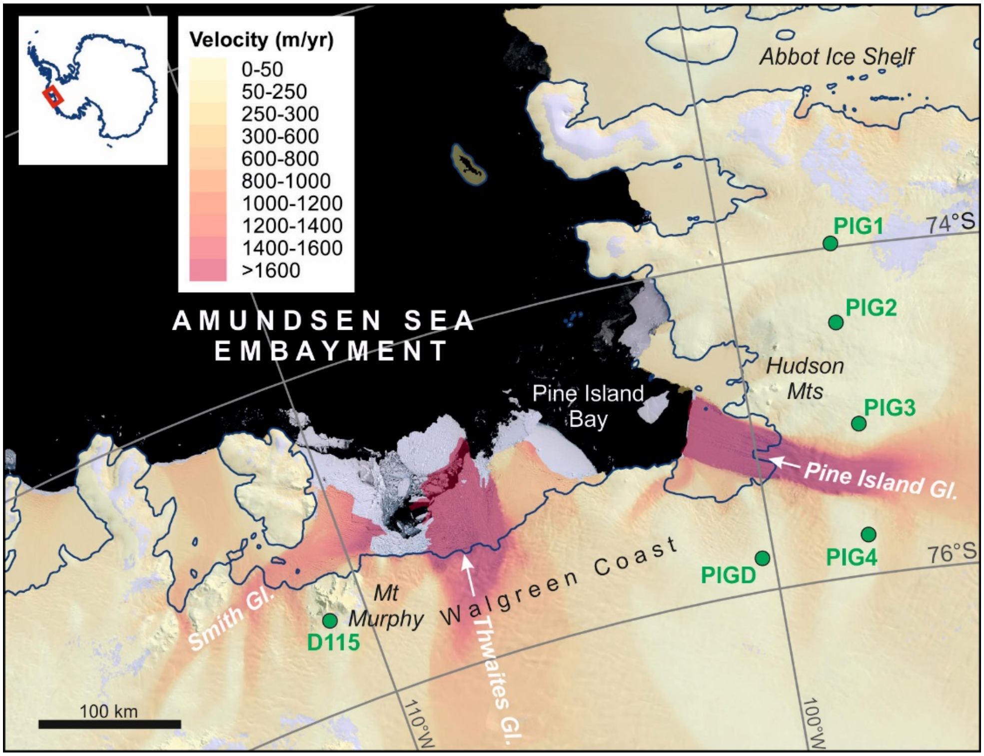

Velocity (m/yr)
0-50
50-250
250-300
300-600
600-800
800-1000
1000-1200
1200-1400
1400-1600
>1600
Abbot Ice Shelf
AMUNDSEN SEA
EMBAYMENT
PIG1
PIG2
PIG3
PIG4
PIGD
D115
74°S
76°S
Hudson
Mts
Pine Island
Bay
Pine Island Gl.
Walgreen Coast
Mt
Murphy
Smith Gl.
Thwaites Gl.
100 km
110°W
100°W

Figure 1

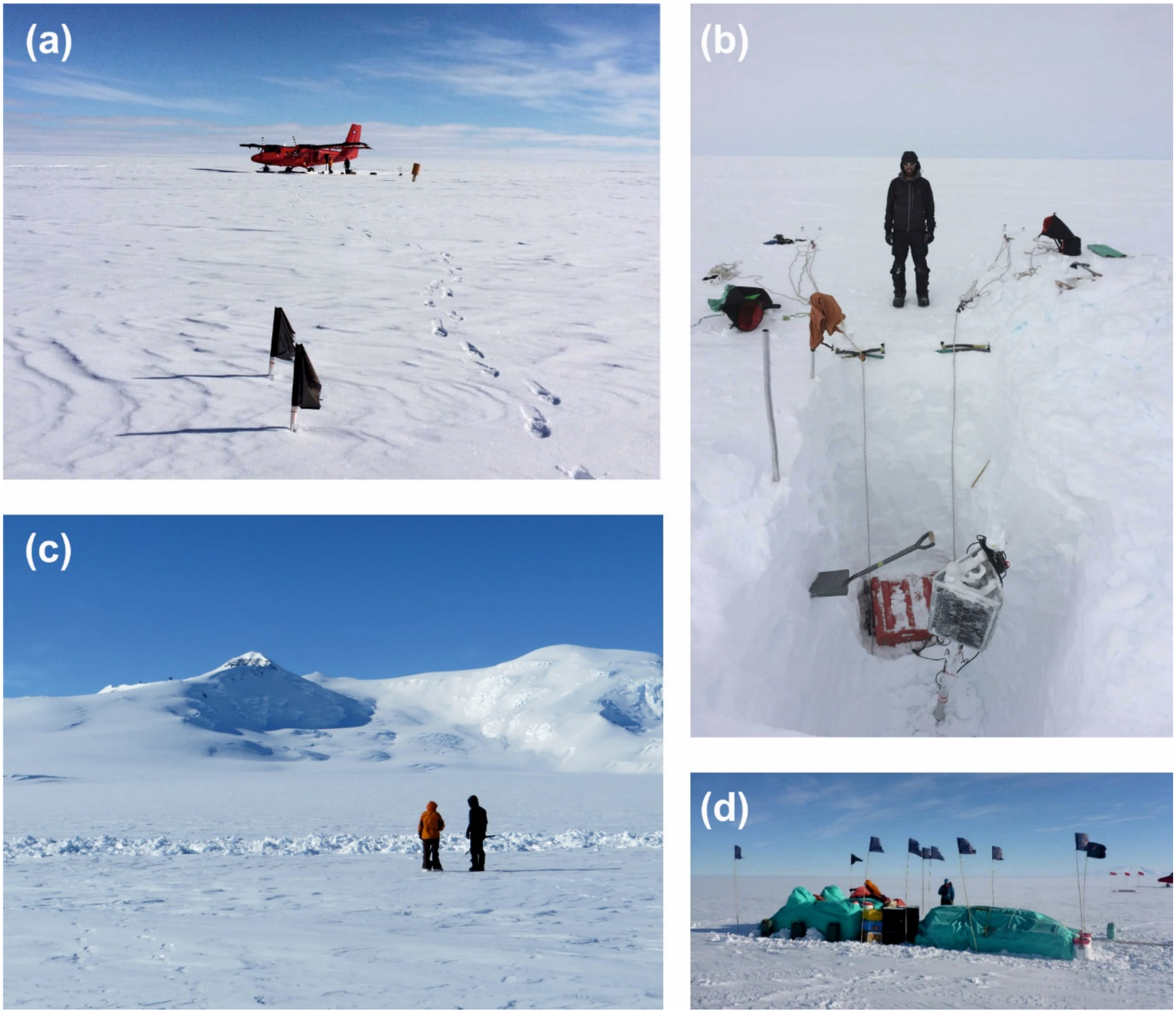


Figure 2

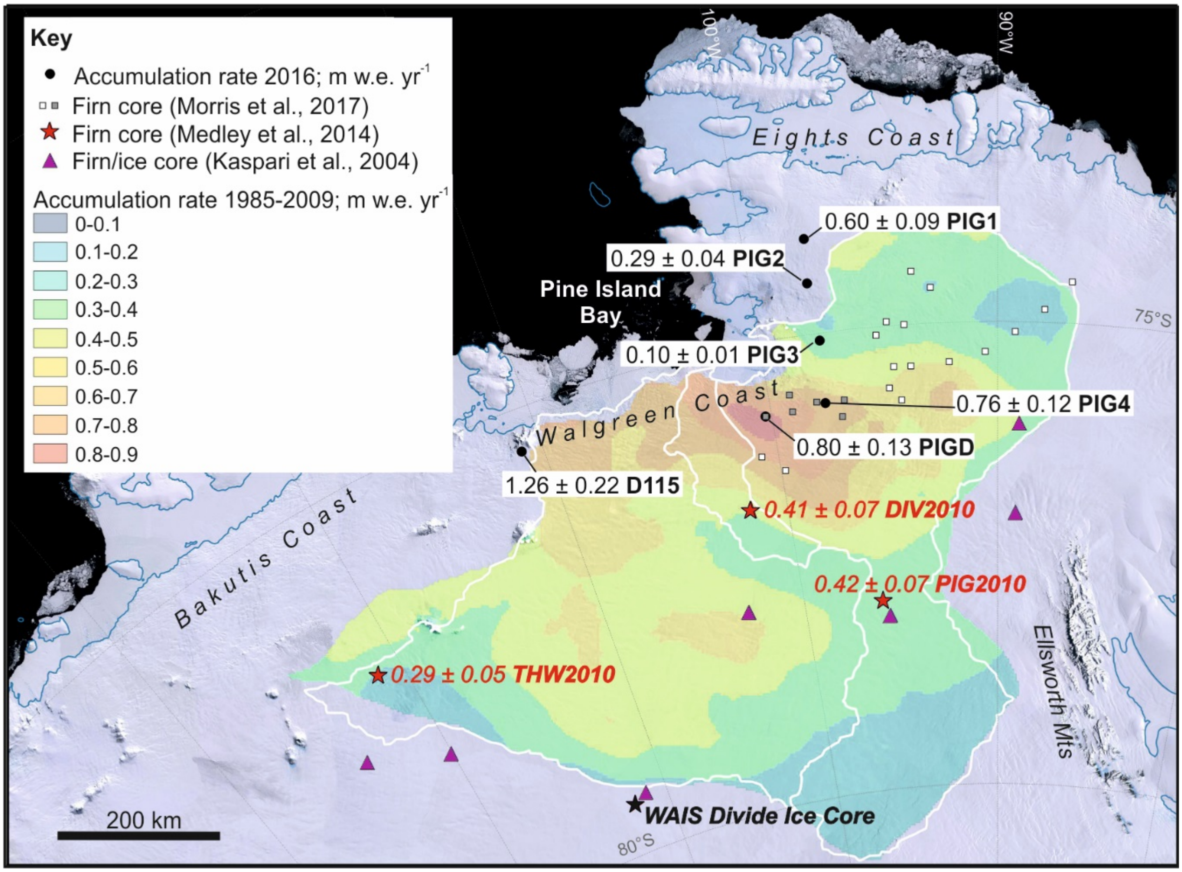
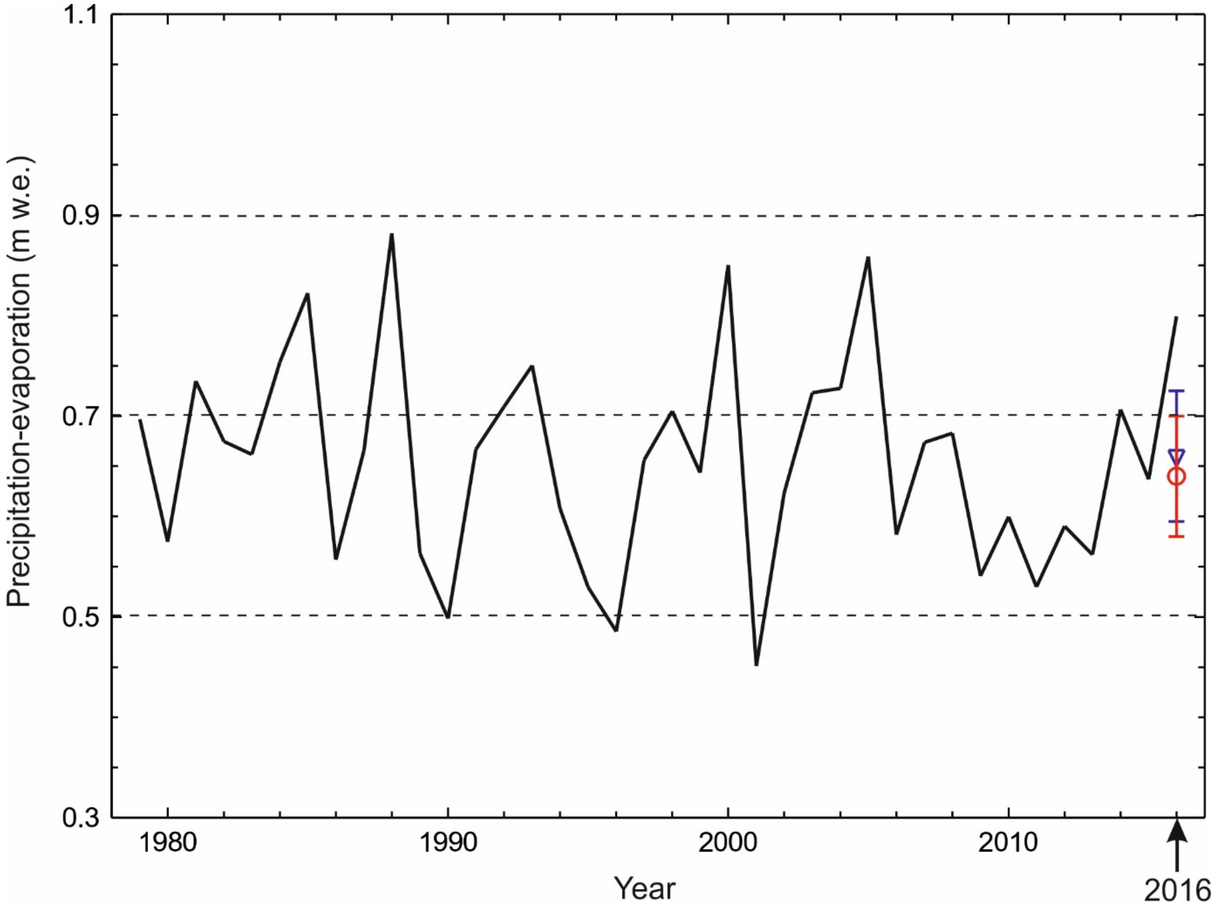

Key
Accumulation rate 2016; m w.e. yr-1
Firn core (Morris et al., 2017)
Firn core (Medley et al., 2014)
Firn/ice core (Kaspari et al., 2004)
Accumulation rate 1985-2009; m w.e. yr-1
0-0.1
0.1-0.2
0.2-0.3
0.3-0.4
0.4-0.5
0.5-0.6
0.6-0.7
0.7-0.8
0.8-0.9
100°W
90°W
Eights Coast
0.60 ± 0.09 PIG1
0.29 ± 0.04 PIG2
Pine Island Bay
0.10 ± 0.01 PIG3
75°S
Walgreen Coast
0.76 ± 0.12 PIG4
0.80 ± 0.13 PIGD
1.26 ± 0.22 D115
0.41 ± 0.07 DIV2010
Bakutis Coast
0.42 ± 0.07 PIG2010
Ellsworth Mts
0.29 ± 0.05 THW2010
200 km
WAIS Divide Ice Core
80°S

Figure 3



1.1
0.9
0.7
0.5
0.3
Precipitation-evaporation (m w.e.)
1980
1990
2000
2010
Year
2016

Figure 4

Table I. Locations of sites and details of snow depth measurements

Site	**Latitude**	**Longitude**	**Altitude** (m asl)	**Date measured**	**Time elapsed** (days)	**Difference in height of snow surface** (m)	**Acc. rate** (cm yr^{-1})	**Acc. rate*** (m w.e. yr^{-1})	**Error on acc. rate$** (m w.e. yr^{-1})
PIGD	-75.8024	-100.2758	844	31 Jan 2016					
				19 Dec 2016	324	2.2	90	0.80	0.13
PIG4	-75.7598	-97.5827	788	30 Jan 2016					
				21 Dec 2016	327	2.1	85	0.76	0.12
PIG3	-75.0839	-97.4746	649	30 Jan 2016					
				24 Dec 2016	330	0.25	11	0.10	0.01
PIG2	-74.4556	-97.6830	978	29 Jan 2016					
				26 Dec 2016	333	0.75	32	0.29	0.04
PIG1	-73.9781	-97.5751	1057	28 Jan 2016					
				28 Dec 2016	336	1.6	65	0.60	0.09
D115	-75.4575	-110.9213	736	29 Jan 2016					
				20 Dec 2016	327	3.8	141	1.26	0.22

* assuming snow bulk density based on average of six firn cores from Pine Island Glacier (grey squares in Fig. 3; see text)
$ based on standard deviation from six firn core records from Pine Island Glacier (grey squares in Fig. 3; see text) and also accounts for the uncertainty of up to 10 cm in the depth measurements