Mass Balance Assessment of the Amery Ice Shelf Basin, East Antarctica

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Abstract The Lambert Glacier-Amery Ice Shelf (AIS) System is the largest glacial system in East Antarctica. Accurate estimation of its mass balance is imperative for reducing the uncertainty in evaluating the sea-level contribution from the East Antarctic Ice Sheet. Here, we present a comprehensive investigation of the mass balance of the AIS basin. We measured the ice velocity with Sentinel-1 synthetic-aperture radar data acquired in 2016. The ice thickness data from the radio echo-sounding measurements were combined with the surface mass balance data from the new Regional Atmospheric Climate Model, from which the mass balance of the AIS basin was estimated. Our estimates suggest a slight positive mass balance of 3.1 ± 9.4 Gt/year in 2016. We found that the short-term fluctuations in the surface mass balance dramatically affect the AIS mass balance. A comparison with previous estimates confirms the long-term positive mass balance trend.

1. Introduction

Estimating the mass balance of ice sheets is important because of their potential contribution to sea-level rise. In response to global climate warming, the mass loss from the Antarctic and Greenland ice sheets has increased since the early 1990s and has contributed ~19% of the total observed global sea-level rise in the period of 1993–2010 (Church et al., 2013). Recent research shows that Antarctica has the potential to raise the global sea level by more than 1 m by 2100 and more than 15 m by 2500 (DeConto & Pollard, 2016). Although remote-sensing technologies enable us to estimate the regional and temporal changes in ice sheets, considerabe uncertainties related to the evaluation of the absolute value of ice sheet mass loss continue to persist (Vaughan et al., 2013; Zwally et al., 2015). The accurate assessment of the ice sheet mass balance is imperative to better understand the ice sheet response to global warming and its contribution to sea-level rise.

The Lambert Glacier-Amery Ice Shelf System (LG-AIS) is the largest glacial system in East Antarctica (Figure 1; Fricker et al., 2000). It drained more than 60 Gt/year of ice in 2008–2015, which accounts for ~7% of East Antarctica’s total ice output (Gardner et al., 2018; Shen et al., 2018a). LG-AIS has three large tributary glaciers, the Lambert, Fisher, and Mellor glaciers, which converge at the grounding zone of the Amery Ice Shelf (AIS). Since the 1960s, the ice surface velocity of the LG-AIS has been measured with different techniques, including terrestrial surveys, GPS measurements (Allison, 1979; Budd et al., 1982; King et al., 2007), and satellite-based measurements (Joughin, 2002; Mouginot et al., 2017; Pritchard et al., 2015; Rignot, 2002; Rignot et al., 2011; Tong et al., 2018; Young & Hyland, 2002). Compared with GPS measurements that can precisely demonstrate three-dimensional ice motion of a single point, ice surface velocity maps derived from remote-sensing data have a much larger spatial coverage. Overall, observations and modeling studies show that the LG-AIS has been stable since the 1960s (Gong et al., 2014; Pritchard et al., 2017; Tong et al., 2018). Moreover, complicated interactions between the modified Circumpolar Deep Water and the AIS occur at the ice-shelf cavity, which results in different basal melting/freezing conditions between the western and eastern sections of the AIS (Fricker et al., 2001; Galton-Fenzi et al., 2012; Wen et al., 2010).

Several studies have been carried out to evaluate the mass balance of the AIS basin, either for individual AIS basins (Wen et al., 2008; Wen et al., 2014; Xie et al., 2016; Yu et al., 2010) or for all of Antarctica, which includes the AIS basin (Gardner et al., 2018; Martin-Espanol et al., 2016; McMillan et al., 2014; Rignot et al., 2008; Rignot et al., 2019; Shen et al., 2018a). Broadly, three different techniques are used to assess ice sheet mass balances (Hanna et al., 2013). The first technique is the mass budget method, also known...
as the input-output method, which estimates the difference between the net surface mass balance (SMB) of an ice sheet (input) and the ice discharge across the grounding line (output). The second technique is the repeated altimetry method, which measures the surface elevation change in the ice sheet. The third technique is the gravity method, which directly estimates the ice mass change at a spatial resolution of ~300 km. Each technique has its own sensitivities to errors relative to the observational data. For example, the mass budget method is highly sensitive to the modeled SMB, the main uncertainty of the gravity method emanates from the glacial isostatic adjustment correction, while the repeated altimetry method is affected by both of these biases (Hanna et al., 2013). For the AIS basin, discrepancies among different mass balance studies remain large (Xie et al., 2016). Therefore, it is crucial to reduce the uncertainty in mass balance measurements and examine the sensitivity of the mass balance to the variability in the observations.

In this study, we conducted a comprehensive investigation of the LG-AIS by using Sentinel-1 and airborne radio echo-sounding (RES) data. First, we produced an ice velocity mosaic of the AIS derived from 7 Sentinel-1 image pairs. Then, we obtained the ice discharge of the AIS basin by combining the ice thickness data, mostly from the RES data, with the ice surface velocity at the grounding line position. Finally, the mass balance of the AIS basin in 2016 was evaluated by the input-output method. We discuss the differences between our results and those from previous studies. Moreover, we present the importance of variability in the SMB to understand mass balance calculations. Combined with the results from previous studies, the mass trend of the AIS basin was determined.
Table 1
The Usage of Sentinel-1 Images in This Study

| Scene | Platform | Orbit   | Date             |
|-------|----------|---------|------------------|
| 1     | Sentinel-1A | 12500   | 7 August 2016    |
| 2     | Sentinel-1A | 12675   | 19 August 2016   |
| 3     | Sentinel-1A | 12500   | 7 August 2016    |
| 4     | Sentinel-1A | 12675   | 19 August 2016   |
| 5     | Sentinel-1A | 11567   | 4 June 2016      |
| 6     | Sentinel-1A | 11917   | 28 June 2016     |
| 7     | Sentinel-1A | 11567   | 4 June 2016      |
|       | Sentinel-1A | 11917   | 28 June 2016     |

2. Data and Methods

2.1. Ice Surface Velocity Measurements

The ice surface displacement was measured by using Sentinel-1 single look complex synthetic-aperture radar (SAR) images acquired in interferometric wide swath mode. This mode acquires data with large swath widths (250 km) at a spatial resolution of 5 × 20 m for single look data. Scenes acquired between 4 June 2016 and 19 August 2016 were used to generate a velocity mosaic that covers the entire AIS. The details of the SAR image pairs are listed in Table 1.

We performed the widely used intensity offset tracking method (Strozzi et al., 2002) of GAMMA remote-sensing software (Werner et al., 2000) with repeat Sentinel-1 data to retrieve the ice surface velocity. This method computes the cross-correlation function between two matching windows in the master and slave SAR images to estimate the azimuth and range displacements. Compared with the interferometric synthetic-aperture radar method that provides ice surface displacement only in the line-of-sight direction, the offset tracking technique can provide two-dimensional displacements. First, the coregistration procedure was performed between selected pairs of images. This step started with rough coregistration using a lookup table that considered the terrain topography of the scene. We resampled the slave image to the geometries of the master image based on a lookup table. Afterwards, a residual offset between the two images was calculated by using cross-correlation matching. Furthermore, we applied a spectral diversity method that uses the double difference phase in burst overlap regions to refine the coregistration (Scheiber & Moreira, 2000). With this result, we obtained the precise coregistered Sentinel-1 SAR image pair and used them to calculate the two-dimensional offsets with a correlation matching window size of 640 × 128 pixels. The final generated velocity maps had a spatial resolution of 200 m both in the azimuth and range directions.

Although the geolocation accuracy is high with the available Sentinel-1 precise orbit data (Nagler et al., 2015), the residual geolocation errors in the ice velocity estimation are a few tens of meters per year, assuming a 0.1 pixel displacement error (Mougnot et al., 2017). Therefore, velocity calibration is necessary for the Sentinel-1 offset tracking procedure to improve the accuracy of the ice velocity measurement. Here, velocity calibration was conducted by taking advantage of the abundant rock outcrops in the AIS region. First, outliers were excluded by applying a median filter. Then, quadratic plane fitting was performed by using the velocity at the rock outcrops. Finally, calibration was achieved by subtracting the fitted plane from the original velocity field.

2.2. Ice Thickness from Radio Echo Sounding

Numerous high spatial density airborne RES measurements over the AIS region (hereafter referred to as Australian Antarctic Data Centre [AADC] data) have been collected by the Australian National Antarctic Research Expedition and the Russian/Soviet Antarctic Expedition through several campaigns from 1968 to 2004 (Figure 2). The ice thickness datasets acquired in 1990–2004 have smaller uncertainties than the datasets acquired in 1968–1989. Consequently, we selected only the RES measurements collected in 1990–2004, with thickness precision values ranging from 75 to 30 m and coordinate precision values ranging from 100 to 20 m. The datasets from later campaigns not only provide better accuracy than earlier datasets but also exclude potential temporal changes in the ice thickness. Previous studies have demonstrated that the average ice thickness change in the AIS in 1994–2012 was small, at approximately 1.6 ± 1.1 m per decade (Paolo et al., 2015). Hence, temporal changes in the ice thickness are negligible compared with the magnitude of the ice thickness uncertainty.

The ice thickness data acquired by the Prince Charles Mountains Expedition of Germany and Australia (PCMEGA) aerogeophysical campaign during the Antarctic season of 2002/2003 were also used. This dataset covers an area of more than 100,000 km², from 60°E to 70°E and from 73°S to 77.5°S, with thickness precision values ranging from 50 to 1 m (depending on the selected pulse length) and coordinate precision better than 1 m (Damm, 2007). It considerably filled the sparse ice thickness point measurements at the southernmost part of the AIS in the AADC data.
In this study, all RES measurements were merged with a procedure similar to that described by Allison and Hyland (2010). The PCMEGA data were first included because of their higher precision than AADC data. Then, the RES measurements from 12 different campaigns in the AADC data were sequentially introduced according to a priority order specified by Allison and Hyland (2010). For example, the Priority 1 dataset was introduced following the PCMEGA data. All points in the dataset were then tested and accepted on two conditions: either there were no existing points within the 1-km radius of the point being tested or the ice thickness of the point being tested was within ±400 m/km when compared to the closest point. Otherwise, the points were rejected. Subsequently, the Priority 2 dataset was introduced, and points were accepted or rejected based on the above criteria. By using this method, most of the ice thickness outliers were removed.

2.3. Basin Mass Balance

The ice sheet mass balance was evaluated by the mass budget method, which quantifies the difference between the mass input (i.e., the integration of ice SMB over the catchment basin) and the mass output (i.e., the ice discharged $D$ from the ice sheet). The total mass balance ($MB$) is defined as

$$MB = SMB - D.$$  \hspace{1cm} (1)

The method has the advantage of separately measuring the ice dynamics (by using satellite remote-sensing data) and the surface processes (e.g., runoff, snow, rain, and sublimation from the model output) at the individual basin scale (van den Broeke et al., 2009). In this study, the AIS basin was delineated based on the 500-m digital elevation model of Antarctica (Zwally et al., 2012). The entire basin was further subdivided into three subbasins.

The SMB is the sum of accumulation by precipitation (snow or rain) and ablation by sublimation and runoff. Here, the SMB in 2016 was estimated by using the output of the newest Regional Atmospheric Climate Model, Version 2.3p2 (RACMO2.3p2), with a horizontal resolution of 27 km (van Wessem et al., 2018).
The updated model improves the simulated SMB and surface energy balance over the ice sheet, particularly at lower elevations. A recent work (Rignot et al., 2019) suggested that RACMO2.3p1 (Van Wessem et al., 2014) may perform better than the updated RACMO2.3p2 for some Antarctic basins. Therefore, the SMB product from RACMO2.3p1 was also used to evaluate the results.

The ice discharge \(D\) was computed by combining the ice thickness data and the ice velocity data along the grounding line. In this study, a new grounding line product (Lei et al., 2017) was used for the ice discharge calculation, derived from the Sentinel-1 constellation data from 2016. First, the grounding line was cut into 3,852 flux gates with maximum widths of less than 1 km. Then, the amount of ice flow across each flux gate was calculated at the middle point of each gate (defined as the flux node). The total ice volume discharge \(D\) can then be defined as

\[
D = \sum_{i=1}^{n} V_i H_i W_i, \tag{2}
\]

where \(n\) is the number of flux gates along the grounding line. \(H_i\), \(W_i\), and \(V_i\) are the ice-equivalent thickness, flux gate width, and ice velocity at the \(i\)th flux node, respectively. We assume that the measured ice surface velocity is approximately equal to the depth-averaged velocity, which will introduce a negligible bias of \(<0.4\%\) (Gardner et al., 2018). In this case, \(V_i\) is regarded as the ice surface velocity at the \(i\)th flux node that is perpendicular to the flux gate.

We obtained the ice thickness value of each flux node by initially obtaining the nearest RES measurements. If no RES points exist within the 1-km radius of the flux node, then the ice thickness values were interpolated from the Bedmap2 ice thickness dataset (Fretwell et al., 2013). In this way, 40.9% of the ice thickness values at each flux node were derived from the RES data. Then, the ice thickness was converted into the ice-equivalent thickness \(H\) after accounting for the firn air content. The firn air content is defined as the variation in the thickness if the firn column is compressed to the density of glacier ice, and it was estimated from the Institute for Marine and Atmospheric Research Firn Densification Model (Ligtenberg et al., 2011; Ligtenberg et al., 2014). Finally, the ice mass discharge was calculated using equation (2) with an ice density of 917 kg/m\(^3\), favoring high-coverage RES data and an accurate grounding line position.

### 2.4. Uncertainties in the Mass Balance Calculation

The ice discharge error \(\Delta D\), which mainly depends on the errors in the ice surface velocity \(\Delta v\) and the ice thickness \(\Delta H\), can be defined as:

\[
\Delta D = v\Delta H + H\Delta v, \tag{3}
\]

where \(v\) is the ice surface velocity (Mouginot et al., 2015).

When measuring the ice surface velocity with the offset tracking method, three factors typically affect the final accuracy: coregistration errors, ionospheric disturbances, and geocoding errors (Nagler et al., 2015). In this study, we evaluated the ice velocity error based on the velocity values of the rock outcrops in the AIS region. In theory, these places should have velocity values of zero. However, because of the errors described above, some biases were introduced at the rock outcrops. Hence, the root-mean-square error of the velocity over those rock outcrops was used to represent the error in the ice surface velocity.

Given that the ice-equivalent thickness was a combination of RES data and the Bedmap2 dataset, we evaluated the thickness error at each flux node based on these data sources. For the RES data, the thickness precision ranges from 75 to 1 m (depending on the campaign). For the error associated with the Bedmap2 dataset, we used a range from 150 to 50 m. Overall, a mean ice-equivalent thickness uncertainty of ~50 m was estimated, which is similar to the value estimated by Wen et al. (2014).

The error in the SMB is provided by the product as a function of surface elevation (Favier et al., 2013; Van Wessem et al., 2014). Here, we calculated the error in the SMB over the AIS basin \(\Delta SMB\) based on the SMB bias \(SMB_{\text{bias}}\) and its combined uncertainty \(SMB_{\text{bias}}\)uncertainty\) for each elevation bin reported by van Wessem et al. (2018). Assuming that \(SMB_{\text{bias}}\)uncertainty\) and \(SMB_{\text{bias}}\) are independent, the total SMB error can be calculated as follows (Li et al., 2016):
3. Results

3.1. Ice Velocity Mosaic of the AIS

The ice velocity mosaic of the AIS (Figure 3a) was obtained on the basis of the ice flow velocity derived from seven pairs of Sentinel-1 SAR images. The gap in the northern part of the AIS without velocity measurements can be attributed to the loss of coverage by the Sentinel-1 images in 2016. Since mass balance estimation only requires the ice velocity data at the grounding line, which was already included in our estimate, the gap did not affect our final results. By using a relatively short time interval between image pairs, we avoided the decorrelation caused by surface changes and transformations in most parts of the AIS region. Nonetheless, other measurement gaps were apparent due to low correlations. The affected regions mainly consisted of the shear margins of ice streams and the fast-flowing areas with strong velocity gradients and surface feature changes.

The AIS is primarily fed by several large glaciers. The Lambert Glacier flows the fastest among all the glaciers in this region, with a velocity of ~800 m/year at the grounding line. The second fastest glacier is the Mellor Glacier (~700 m/year at the grounding line), followed by the Fisher Glacier on the western side (~550 m/year at the grounding line). These three glaciers converge and join the AIS at its southernmost end, draining the majority of the ice in the AIS basin. On the eastern side of the AIS, the Kronshtadtskiy Glacier and the Lepekhin Glacier have the largest flow velocities, reaching ~350 and ~240 m/year at the grounding line, respectively. Other glaciers flow with velocities less than 200 m/year. The Scylla Glacier is the largest glacier that drains into the AIS from the west (~180 m/year at the grounding line).

To evaluate the quality of the AIS ice velocity mosaic, we compared our ice velocity results with the MEaSUREs Annual Antarctic Ice Velocity Maps (hereafter the MEaSUREs annual velocity) for the period covering July 2015 to June 2016 (Mouginot et al., 2017) and another high-resolution Antarctic ice velocity map (Shen et al., 2018b; hereafter the Shen velocity). Figure 3b shows the distribution of the velocity map differences, which are calculated as the MEaSUREs annual velocity or the Shen velocity minus our result. The mean differences in the velocity are 1.8 and 7.3 m/year, and the standard deviations are 10.6 and 17.4 m/year, respectively. Moreover, we compared the ice velocities of the three fastest glaciers (the Lambert Glacier, Mellor Glacier, and Fisher Glacier) with those two products and the Global Land Ice Velocity Extraction from Landsat 8 (GoLIVE) result (Fahnestock et al., 2016; Scambos et al., 2016), which represents the ice velocity in 2016 (Figures 4 and 5). The velocity profiles, both along the flowline

\[
\Delta \text{SMB} = \sqrt{\text{SMB}_{\text{bias}}^2 + \text{bias}_{\text{uncertainty}}^2}.
\]
Figure 4. (a) Ice surface velocities of the Lambert Glacier, Mellor Glacier, and Fisher Glacier. The red curves BB’, CC’, and DD’ indicate the positions of the velocity profiles corresponding to the (b) Lambert Glacier, (c) Mellor Glacier, and (d) Fisher Glacier. GoLIVE = Global Land Ice Velocity Extraction from Landsat 8.

(Figure 4) and the grounding line (Figure 5b), derived from our results agree well with other results. Overall, our analysis of velocity over the rock outcrops indicates that the uncertainty in the velocity is 10 m/year, which is comparable to the errors of the Sentinel-1-derived ice velocity reported in other studies (Mouginot et al., 2017; Nagler et al., 2015; Sánchez-Gámez & Navarro, 2017).

3.2. Estimation of the Mass Balance

The ice flux discharged into the AIS in 2016 was 61 ± 5.0 Gt/year. For the individual subbasins, Subbasin 10 drains the majority of the ice into the AIS at 37.0 ± 1.8 Gt/year, accounting for 60.7% of the total AIS basin ice discharge. The ice fluxes of Subbasins 9 and 11 are 13.1 ± 3.6 and 10.9 ± 2.9 Gt/year, respectively.

The integrated SMB of the entire AIS basin in 2016 from the RACMO2.3p2 model is 64.1 ± 8 Gt. By combining this result with the ice discharge values of 61.0 ± 5.0 Gt/year, a positive mass balance of 3.1 ± 9.4 Gt/year for the AIS basin in 2016 can be derived. The three subbasins differed in their mass balance states. Subbasins 9 and 11 both exhibited positive mass balances in 2016 with values of 2.4 ± 4.5 and 4.3 ± 3.4 Gt/year, respectively. In contrast, the mass balance of Subbasin 10 in 2016 was slightly negative at −3.6 ± 4.8 Gt/year.
4. Discussion

4.1. Comparison of the AIS Ice Discharge Estimates with Those from Previous Studies

A comparison of our results with those of previous studies (Table 2) suggests similar ice discharge values for the AIS basin when the ice thickness at the flux gate is mostly derived from airborne RES data (Gardner et al., 2018; Wen et al., 2014; Yu et al., 2010). However, the ice discharge estimations from Wen et al. (2008), Rignot et al. (2008), Depoorter et al. (2013), Shen et al. (2018a), and Rignot et al. (2019) are higher than our results. The most possible reason for the differences is the overestimation of the grounding line ice thickness. These studies use ice thickness data at the grounding lines derived from the surface elevation assuming hydrostatic equilibrium to calculate the AIS ice discharge. However, the hydrostatic equilibrium at the narrow southern part of the AIS is likely invalid.

Figure 5. (a) Maps of the velocity differences between our result and the Global Land Ice Velocity Extraction from Landsat 8 (GoLIVE) results for the southernmost part of the Amery Ice Shelf. (b) A profile along the grounding line of Subbasin 10 shown in (a).
The negligible ice discharge change between 2000 and 2016 indicates the relatively stable dynamics of the AIS basin in recent decades. In fact, previous studies (King et al., 2007; Tong et al., 2018) have shown that the ice velocity in the AIS hardly changed in the past 45 years (1968–2014). An investigation of decade-scale ice-shelf thickness changes has also shown that the overall thickness change of the AIS is $1.6 \pm 1.1$ m per decade, which is close to zero (Paolo et al., 2015). In addition, model simulations and observations show that the grounding line of the AIS has not undergone significant changes and is unlikely to retreat substantially in the next 500 years (Lei et al., 2017; Pittard et al., 2017). Thus, we conclude that the ice discharge of the AIS basin has remained stable in the past few decades.

4.2. Analysis of the Mass Balance of the AIS Basin

The interannual variations in the integrated SMB can greatly affect the mass balance of the AIS basin catchment, as shown in Figure 6. Here, we analyzed the SMB anomalies in 2016 with respect to the mean SMB over 1979–2016. In general, the SMB of the AIS basin exhibited a negative anomaly in 2016 ($-17.9$ Gt/year) compared with the 38-year mean ($81.6$ Gt/year). Subbasins 9 and 10 showed similar time-series anomalies during the past 40 years, whereas the annual SMB of Subbasin 11 fluctuated less. As shown in Figure 6a, Subbasin 9 had a significant negative SMB anomaly in 2016. The strongest negative anomaly in 2016 occurred near the grounding zone and reached rates as high as $-126$ mm w.e./year. Given that Subbasin 9 demonstrated a positive mass balance of $2.4 \pm 4.5$ Gt/year in 2016, we can conclude that this subbasin has certainly gained mass in the long term and in 2016 despite the negative SMB anomalies. Moreover, a widespread negative SMB anomaly across Subbasin 10 resulted in the largest SMB anomaly of the subbasins at $-12$ Gt/year in 2016 (Figure 6b). We speculate that the negative mass balance of $-3.6 \pm 4.8$ Gt/year is mainly driven by the SMB anomaly in 2016, which is the second strongest negative anomaly since 1979. Some researchers have used the average SMB over a much longer period to explore long-term mass balance trends and reduce the annual fluctuation (Rignot et al., 2008). In this case, the SMB for Subbasin 10 is $45 \pm 4.3$ Gt/year instead of $33.4 \pm 4.3$ Gt/year when the 38-year mean SMB (1979–2016) is used. This results in a positive mass balance of $8.0 \pm 4.8$ Gt/year. Subbasin 11, with a value of $-1.3$ Gt/year, exhibited a much smaller SMB anomaly in 2016 than Subbasins 9 and 10.

The results from some previous studies of the entire AIS basin mass balance with the mass budget method are shown in Table 3. Here, we list both the ice discharge and the SMB components of each study to evaluate the importance of variability in the SMB in understanding the mass balance calculations. Note that the period here indicates the epoch of the velocity measurements, and the SMB in each study is estimated from different time periods. The negative mass balance of the AIS basin estimated by several studies is most likely related to the overestimated ice discharge or the SMB variability. Wen et al. (2008) and Yu et al. (2010) used the same Modified Antarctic Mapping Mission interferometric synthetic-aperture radar surface velocities and similar snow accumulation datasets (Glovinetto & Zwally, 2000; Vaughan et al., 1999) to calculate the mass balance, whereas Yu et al. (2010) used the RES data rather than hydrostatically derived ice thickness data and obtained a more accurate value of the ice discharge.
The version of RACMO used to constrain the SMB can considerably affect the results. Rignot et al. (2008) used a previous version of the RACMO SMB (RACMO2) and averaged over the period from 1980 to 2004. The SMB value from RACMO2.3p1 or RACMO2.3p2 averaged over the same epoch is 72 or 81 Gt/year, respectively. Similarly, the value of the RACMO2.3p1 SMB averaged over the period from 2008 to 2015 in Gardner et al. (2018) is 75 Gt/year, whereas the same epoch yielded an average of 81 Gt/year in RACMO2.3p2. The higher SMB likely indicates a larger amount of mass gain. Moreover, Shen et al. (2018a) and Rignot et al. (2019) used the long-term averaged RACMO2.3p1 SMB and obtained a slightly negative mass balance. In contrast, the use of the newer version RACMO2.3p2 SMB will result in a positive mass balance in both studies. In general, the SMB value of the AIS basin from RACMO2.3p2 is ~7 Gt/year greater than the value from RACMO2.3p1. Rignot et al. (2019) concluded that the measured ice fluxes of some basins agree more with RACMO2.3p1 than RACMO2.3p2. However, other studies have also demonstrated that RACMO2.3p2 SMB variations correlate better than RACMO2.3p1 with the temporal variation in the ice mass anomalies observed by GRACE (van Wessem et al., 2018). Therefore, additional studies are needed to determine the difference between the two versions of RACMO.

In general, the overall mass balance of the AIS basin was slightly positive in 2016 according to our estimate. Given that the negative SMB anomaly was significant in 2016, we speculate that this basin has been gaining mass in recent years. The analyses of the mass balance assessed by previous studies also indicate that the AIS basin has been gaining mass since the start of the 21st century. Ice sheet modeling studies (Gong et al., 2014; Pittard et al., 2017) support this view and suggest that the positive mass trend will continue to the 22nd century.

![Figure 6](image)

**Figure 6.** (a) Spatial distribution of the surface mass balance (SMB) anomalies of the Amery Ice Shelf (AIS) basin in 2016 with respect to the mean SMB over 1979–2016. The boundaries of the three subbasins are delineated by black lines. (b) Annual SMB anomalies from 1979–2016. The dashed box highlights the anomaly of the three subbasins in 2016.

### Table 3

| Study            | Period | Ice discharge (Gt/year) | SMB (Gt/year) | Mass balance (Gt/year) |
|------------------|--------|------------------------|---------------|------------------------|
| Rignot et al. (2008) | 2000   | 77 ± 4                 | 73 ± 10 (81)  | −4 ± 11                |
| Wen et al. (2008)  | 2000   | 88.9 ± 8.9             | 84.8 ± 4.2    | −4.2 ± 9.8             |
| Yu et al. (2010)   | 2000   | 64.3 ± 3.2             | 87.2 ± 2.9    | 22.9 ± 4.4             |
| Gardner et al. (2018) | 2008–2015 | 63 ± 5               | 75 ± 9 (81)   | 7 ± 11                 |
| Shen et al. (2018a) | 2008–2015 | 76.4 ± 9.0           | 74.9 ± 4.7 (82) | −1.5 ± 10.2          |
| Rignot et al. (2019) | 2009–2017 | 77.4 ± 3.6           | 75.3 ± 4.4 (82) | −2.1 ± 5.7           |
| This study        | 2016   | 61.0 ± 5.0             | 64.1 ± 8      | 3.1 ± 9.4              |

*Note.* Values in parentheses in the SMB column are the RACMO2.3p2 SMB averaged for the same epoch. SMB = surface mass balance.
5. Conclusions

In this study, we present a mass balance estimate for the AIS basin in 2016 by using the mass budget method. We measured the ice surface velocity of the AIS in 2016 with Sentinel-1 SAR images. The precision of our ice velocity results was comparable to that of other studies. The performance level achieved by this study supports the use of Sentinel-1 data in monitoring ice surface motion. Combining the ice surface velocity estimate with precise ice thickness data, our study updates and reliably assesses the ice discharge of the entire AIS basin and its three subbasins. The basin typically drained 61.0 ± 5.0 Gt of ice into the AIS in 2016. The results indicate that the ice discharge of the AIS basin has not undergone significant changes in recent decades. Our analysis further reveals the importance of variability in SMB in understanding mass balance calculations. The AIS basin exhibited a slightly positive mass balance of 3.1 ± 9.4 Gt/year in 2016 despite the substantial negative SMB anomaly that year. We conclude that the AIS basin has gained ice mass from at least the 2000s and has continued to gain ice mass during our study period of 2016. This positive mass balance trend may continue in the future.

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