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Rapid Mass Loss in West Antarctica Revealed by Swarm Gravimetry in the Absence of GRACE

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Key Points:

- Swarm mass anomalies estimates, though noisier, are consistent with GRACE estimates (correlation 0.78) in West Antarctic Ice Sheet (WAIS)
- Swarm reveals that WAIS returned to the rapid mass loss state (161.5 ± 48.4 Gt yr^{-1}) prevailed prior to 2015 in the GRACE intermission gap

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract GRACE observations revealed that rapid mass loss in the West Antarctic Ice Sheet (WAIS) abruptly paused in 2015, followed by a much lower rate of mass loss (21.3 ± 5.7 Gt yr^{-1}) until the decommissioning of GRACE in 2017. The critical 1-year GRACE intermission data gap raises the question of whether the reduced mass loss rate persists. The Swarm gravimetry data, which have a lower resolution, show good agreement with GRACE/GRACE-FO observations during the overlapping period, i.e., high correlation (0.78) and consistent trend estimates. Swarm data efficiently bridge the GRACE/GRACE-FO data gap and reveal that WAIS has returned to the rapid mass loss state (161.5 ± 48.4 Gt yr^{-1}) that prevailed prior to 2015 during the GRACE intermission data gap. The changes in precipitation patterns, driven by the climate cycles, further explain and confirm the dramatic shifts in the WAIS mass loss regime implied by the Swarm observations.

Plain Language Summary The West Antarctic Ice Sheet (WAIS) rests largely below sea level, and so is particularly vulnerable to anthropogenic climate change. The space gravimetry mission GRACE revealed that WAIS mass loss had accelerated until rapid mass loss abruptly paused in 2015. The much-reduced rates of ice mass loss prevailed until the middle of 2017, when the GRACE mission terminated, leaving a 1-year data gap before GRACE-FO resumed the measurement time series. We find the lower resolution Swarm gravimetry data have good consistency with GRACE and can be used to span this data gap. The Swarm observations reveal that WAIS has returned to the rapid mass loss state (observed prior to 2015) during the 2017–2018 data gap. Atmosphere pressure data suggest that a persistent low air pressure near Antarctic Pacific sector during 2015–2017, led to increased precipitation over West Antarctica. It then sharply transitioned into a high-pressure state during 2017–2019, which prevented the inflow of warm and moist air to West Antarctica. The resulting changes in precipitation and extreme El Niño to La Niña transition can jointly explain the major changes in the mass loss regime observed by Swarm in West Antarctica.

1. Introduction

Changes in the mass balance of polar ice sheets and glaciers are the key drivers of global sea level change. The mass loss of ice sheets in Antarctica and Greenland has been estimated to contribute to around 2 cm global mean sea level rise over the last three decades (IMBIE, 2018, 2019). Among them, the West Antarctic Ice Sheet (WAIS) is the most critical and vulnerable piece, since it sits on the terrain >2 km below the present sea level and has the potential to raise the global mean sea level by about 5 m if it completely melts. Generally, three techniques are commonly used to estimate the ice sheet mass balance (Rignot et al., 2019). The input-output method estimates the mass balance by subtracting the ice discharge (output) from the sum of accumulation and ablation at the ice sheet surface. The altimetry method observes the ice volume change and then converts it to mass change with appropriate firn compaction and density correction models. The third method is the gravimetric method, which directly measures the gravitational change induced by ice mass change after accounting for the signals from the solid Earth mass changes.

Since the launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 (Tapley et al., 2004, Tapley et al., 2019), and its successor mission GRACE Follow-On (GRACE-FO) in 2018 (Landerer et al., 2020),

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the temporal gravity observed by GRACE and GRACE-FO, have been intensively used to study the polar ice sheets mass balance and their respective contributions to the global sea level rise (Bevis et al., 2019; Bodart & Bingham, 2019; Chen, 2006; Chen et al., 2009; Groh et al., 2019; Harig & Simons, 2015; Jacob et al., 2012; Lee et al., 2012; Loomis et al., 2020; Luthcke et al., 2006; Sasgen et al., 2020; Su et al., 2018; Talpe et al., 2017; Velicogna, 2006; Velicogna et al., 2014; Williams et al., 2014; Wouters et al., 2013). These extensive studies revealed rapid and even accelerating patterns of mass loss over the polar ice sheets. Antarctica alone has lost around 2,000 Gt of ice during the GRACE and GRACE-FO era (Velicogna et al., 2020). WAIS alone contributed >90% of the Antarctica mass loss (IMBIE, 2018). The West Antarctica mass loss rate (5-year average) has also been observed to drastically increase from ~50 to ~150 Gt yr^{-1} during the recent two decades (IMBIE, 2018; Wang et al., 2021). However, the increased ice mass loss tendency is interrupted in late 2015, and no significant mass loss is observed until the cease of GRACE mission in July 2017 (Bodart & Bingham, 2019; Wang et al., 2021). The WAIS ice mass anomalies climate record thus has a critical data gap for around 1 year, as GRACE-FO was launched in May 2018 and did not deliver data until June 2018. We do not know exactly if the WAIS reduced mass loss lasts during this data gap, though, the offset between the last epoch of GRACE and the first epoch of GRACE-FO implies a possible rapid mass loss.

Although a variety of statistical methods (e.g., machine learning and singular spectrum analysis) have been used to fill the GRACE and GRACE-FO data gap, most of them focused on hydrology studies (Forootan et al., 2020; Humphrey & Gudmundsson, 2019; Li et al., 2020; Sahour et al., 2020; Sun et al., 2020; Wang et al., 2021), excepting Richter et al. (2021) and Yi and Sneeuw (2021), who also discussed the application on cryosphere studies. Bonin et al. (2018) investigated the possibility of using satellite laser ranging (SLR) inverted temporal gravity to fill the data gap in polar ice sheets. But they found the ice mass anomalies derived from SLR data had a relatively high uncertainty at the interannual time scale and could be hardly used to fill the data gap. Alternatively, Velicogna et al. (2020) used the input-output method to fill the data gap in the two polar ice sheets. They indicated the GRACE/GRACE-FO (here after GRACE(FO)) mass anomalies aligned well with input-output method both at continental and regional scales after adjusting for small trend offset. Here, we intend to directly use independent and alternative gravimetry data to assess the viability to bridge the GRACE data gap and study the contemporary transient ice sheet mass balance over WAIS. As it is a purely data-driven approach, we can avoid the implicit assumption in most statistical methods that there is no potential bias between GRACE and GRACE-FO data, and the need to introduce empirical covariance information to enable extrapolation over the data gap. The Swarm mission, a three-satellite constellation, equipped with geodetic quality GNSS receivers, could be a unique and promising source to bridge the data gap (Baur, 2013; Friis-Christensen et al., 2008; Teixeira da Encarnação et al., 2020). Here, we use the high-low GNSS-Swarm tracking data collected by the Swarm mission to invert monthly temporal gravity solutions (2015–2020) to fill the data gap. The mass anomalies estimated from Swarm show good agreement with GRACE(FO) during the overlapping period, 2015–2020. The biennial trend estimates reveal that the WAIS has returned to the intensive mass loss state during the data gap. We further elucidate the possible cause and identify the responsible climate driver that brings WAIS back to its previous rapid mass loss trajectory prior to 2015.

2. Data and Methods

2.1. GRACE(FO) and Swarm Temporal Gravity Solutions

The Center for Space Research (CSR) at the University of Texas at Austin routinely delivers the Release 6 (RL06) Level-2 (L2) temporal gravity field solutions in terms of spherical harmonics for GRACE and GRACE-FO missions (Bettadpur, 2018). Here, we use the CSR L2 solutions to compute the WAIS mass anomalies. The degree 1 coefficients, or geocenter corrections provided in Technical Note 13 (TN-13) are used. In addition, the degree 2 order 0 (C20) coefficients are replaced with CSR satellite laser ranging (SLR) derived monthly solutions (Cheng et al., 2011). The degree 3 order 0 (C30) coefficients are problematic and recommended to be replaced by SLR solutions after August 2016 (Loomis et al., 2020). For consistency, we also replace C30 between 2012 and July 2016, though its impact on WAIS mass anomalies estimation is very small (Figure S5, also Loomis et al., 2020; Su et al., 2020). The ICE6G-D glacial isostatic adjustment (GIA) model (Peltier et al., 2018) is used to correct the GIA signal. Then, the GGM05C mean field is removed from the monthly gravitational spherical harmonic coefficients (SHCs) and converted to the surficial "mass" SHCs (Wahr et al., 1998). The 300-km radius Gaussian smoothing (Guo et al., 2010; Jekeli, 1981) is applied to diminish the stripe error. Finally, the forward modeling

(FM) method (Chen et al., 2015) is used to restore and minimize the signal leakage in the WAIS study region. The open-source MATLAB package GRAMAT (Feng, 2018) is modified and used for both Swarm and GRACE(FO) data postprocessing.

We compute the monthly Swarm temporal gravity solutions using the modified decorrelated acceleration approach (Text S1 in Supporting Information S1, also Zhang, 2020; Zhang et al., 2019). It is updated from the original approach first developed by Bezděk et al. (2014). This approach is based on the linear relation between the gravitational acceleration and second-order time derivative of the satellite position determined by GNSS tracking data. Then two linear transformations are used to account for the correlation error induced by the time derivative and the correlation error among GNSS positioning. In addition to the original approach, we rigorously combine the solutions from each gravity component (along-track, cross-track, and radial direction) of all three satellites based on variance component estimation. Also, the relative variances are introduced to account for the positioning precision variations. For details of the approach see Supplementary Text S1 in Supporting Information S1 as well as Bezděk et al. (2014, 2016) and Zhang (2020). A series of monthly gravity solutions up to degree 40 are computed between 2015 and 2020, omitting the degraded solutions before 2015 (Text S1 in Supporting Information S1). We identify that there is an offset between GRACE(FO)/SLR and Swarm C40 coefficients (Figure S7 in Supporting Information S1). The offset is empirically removed by fitting Swarm C40 to SLR C40 with a constant term. As the Swarm solutions higher than degree 20 are generally 1 order of magnitude worse than GRACE(FO) solutions and dominated by noise (Figure S4 in Supporting Information S1), the Swarm solutions postprocessing (i.e., the processing from temporal gravity to mass anomalies) is limited to spherical harmonic degree 20, as opposed to the use of degree 60 for GRACE(FO) solutions. The corresponding Gaussian smoothing radius is enlarged to 1,100 km.

Eventually, all the "mass" SHCs are converted to the spatial domain in the regular half-degree by half-degree grids. The WAIS mass anomaly time series is the weighted (by cosine of grid latitude) mean anomalies of all the grids within the WAIS as defined by Zwally et al. (2012), e.g., Figure 2a. We follow the method of Scanlon et al. (2016, 2018) to estimate the uncertainty of GRACE(FO) time series. We first fit and remove linear trend and seasonal terms (annual and semiannual). Then we apply a 13-month moving average on the residuals and remove it to obtain the final residuals. The GRACE(FO) uncertainty is estimated from the root mean square (RMS) of the final residual. This method tend to overestimate the uncertainty as the final residuals can still include subseasonal signals (Scanlon et al., 2016). As the GRACE(FO) observation system is superior and the observation has a much lower noise level, we use the RMS of the difference between Swarm and GRACE(FO) time series to measure Swarm uncertainty. To have a better presentation and quantitative understanding of the mass variation in a shorter time interval, we split the total time span into consecutive 2-year segments and use the biennial trend to measure the ice sheet mass change tendency within the time interval, starting from April 2003 (Sasgen et al., 2020). Within each segment, the bias, linear trend, and seasonal terms (annual and semiannual) are fitted to estimate the biennial trend. The uncertainties of the biennial trend are measured by the postfit formal error. For Swarm, we shift the two years period to both sides of the time axis for 2 months and average the five trend estimates to obtain a stable biennial trend estimate.

2.2. Surface Mass Balance Model

The ice sheet surface mass balance (SMB) is the summation of precipitation, snow sublimation, snow erosion, and meltwater run-off (Van Wessem et al., 2018). SMB combined with the glacial discharge gives the total mass variation over the ice sheet. SMB alone plays a key role in the total ice sheet mass balance at the interannual time scale because the glacial discharge does not change considerably at interannual time scale (Zhang et al., 2021). Thus, the SMB anomalies provide us insight into the mass anomalies observed by satellite gravimetry and, therefore, help us to interpret the gravimetric observation. We use the SMB output from the Antarctic Regional Atmospheric Climate Model, RACMO2.3p2 (Van Wessem et al., 2018). This model has a one-quarter (0.25) degree horizontal resolution and at a monthly sampling rate. The latest version of the RACMO2.3p2 model is forced by the ERA5 reanalysis data (Hersbach et al., 2020).

We fit and remove bias, linear trend, and seasonal terms (annual and semiannual) from the GRACE, Swarm, and SMB time series. The remaining (residual) signals mainly represent their interannual variations (e.g., Su et al., 2015). Because Swarm residual time series is shorter than the other two, a constant and linear term is used to adjust Swarm time series to fit the GRACE and SMB for the overlap period. The uncertainty of SMB model is considered difficult to estimate. We attempt to do so by taking the difference between RACMO2.3p2 and another SMB model, MARv3.11 (Agosta et al., 2019) and using the RMS of their difference to quantify the uncertainty of RACMO model. Considering that the two models share the same forcing, the uncertainty estimates may be optimistic. In this study, we use these residual time series to investigate WAIS mass variability at the interannual time scale.

2.3. Atmosphere Model

Over Antarctica, precipitation, one of the major SMB components, contributes to >90% of the total mass budget (Van Wessem et al., 2014). As the precipitation is the result of the atmosphere circulation and variation, we used the ERA5 pressure field (Hersbach et al., 2019) to assess the climate drivers of mass anomalies as observed by satellite gravimetry. More specifically, we use the geopotential height of 500 hPa (e.g., Zhang et al., 2021). The data resolution is 0.25° at the monthly sampling rate.

Since the pressure anomalies are more interested here, we remove the climatology (the mean, trend, and seasonality between1979 and 2020) of each grid to obtain the geopotential height anomalies. Following the biennial segments as defined in the evolution of WAIS mass anomalies, we calculate the biennial mean geopotential height by averaging all the monthly anomalies over each 2-year interval for each grid.

3. Results

3.1. Gravimetric Mass Anomalies

Figures 1a and 1b show trend maps estimated from Swarm and GRACE(FO) for 2015–2020. Both solutions are limited to degree 20 and applied 1,100 km Gaussian smoothing. Swarm trend estimates have good agreement with GRACE(FO), where their differences are generally smaller than several mm/yr (in equivalent water height or EWH, Figure 1c). The gravimetric data indicate that the Amundsen Sea sector and Wilkes Land sector were experiencing mass loss while Queen Maud Land was gaining mass. Though, with only degree 20, we lose some details that are captured by degree 60 GRACE (with 300 km smoothing radius, Figure 1d), the prominent signals such as Amundsen Sea sector are well captured. Figure 1e highlights the WAIS mass anomalies time series estimated from degree 20 GRACE(FO) and Swarm solutions. As we can expected, the Swarm mass anomalies are noisier than GRACE(FO), showing as higher month to month variations (e.g., Richter et al., 2021; Teixeira da Encarnação et al., 2020, also Figure S8 in Supporting Information S1). Nonetheless, Swarm mass anomalies still have a great consistency with GRACE(FO). Their correlation is 0.78 after applying a simple three epoch moving average on Swarm time series (not shown). Both Swarm and GRACE(FO) observed a consistent WAIS mass loss rate for the overlapping period, at 27.0 ± 5.2 and -31.0 ± 2.6 Gt yr^{-1}, respectively (1 sigma). The excellent coherence indicates that Swarm is a good candidate for WAIS mass balance study in the absence of GRACE(-FO). Although the Swarm spatial resolution (degree 20) is coarser than GRACE (degree 60), e.g., Figure 1a versus Figure 1c, after proper leakage reduction, we find that the degree 20 (1,100 km smoothing) and degree 60 (300 km smoothing) GRACE(FO) mass anomalies only show subtle subseasonal difference and little difference in longer term variation (Figure S6 in Supporting Information S1) in WAIS. Figure 2a delineates the WAIS mass anomalies observed by degree 20 Swarm and degree 60 GRACE(FO) with leakage reduction. The time series are much steeper and mass loss rate are around 2.5 time higher at 82.6 ± 9.9 Gt yr^{-1} (Swarm) and 80.2 ± 3.9 Gt yr^{-1} (GRACE(FO)) compared with Figure 1d and its estimates for 2015–2020. In additional to the consistent trend estimates from Swarm and GRACE(FO), we should also note that while leakage reduction processing restores the signal, it can also amplify the noises that cannot be mitigated by Gaussian smoothing. It is especially clear for the Swarm case, comparing Figures 1e and 2a. Because Swarm temporal gravity solutions generally have higher noises in full spectrum compared with GRACE(FO), e.g., Figure S4.

The mass anomalies observed by GRACE reveal an accelerated mass loss in West Antarctica (Figure 2a, blue) since 2003. This steep mass loss tendency suddenly abates in the middle of 2015 and becomes flat until the decommissioning of GRACE mission. The drastic change is more prominent in the biennial trend plot (Figure 2a, light blue), where the mass loss rate drops from the peak 157.8 ± 8.3 Gt yr^{-1} (Figure 2b) between 2009 and 2011 to a mild 21.3 ± 5.7 Gt yr^{-1} between 2015 and 2017. Bodart and Bingham (2019) attributed this sharp change to the enhanced precipitation over West Antarctica. They found this period coincided with the strongest 2015 El Niño event during the GRACE period, which began in late 2014 and ended in the middle of 2016. As the GRACE

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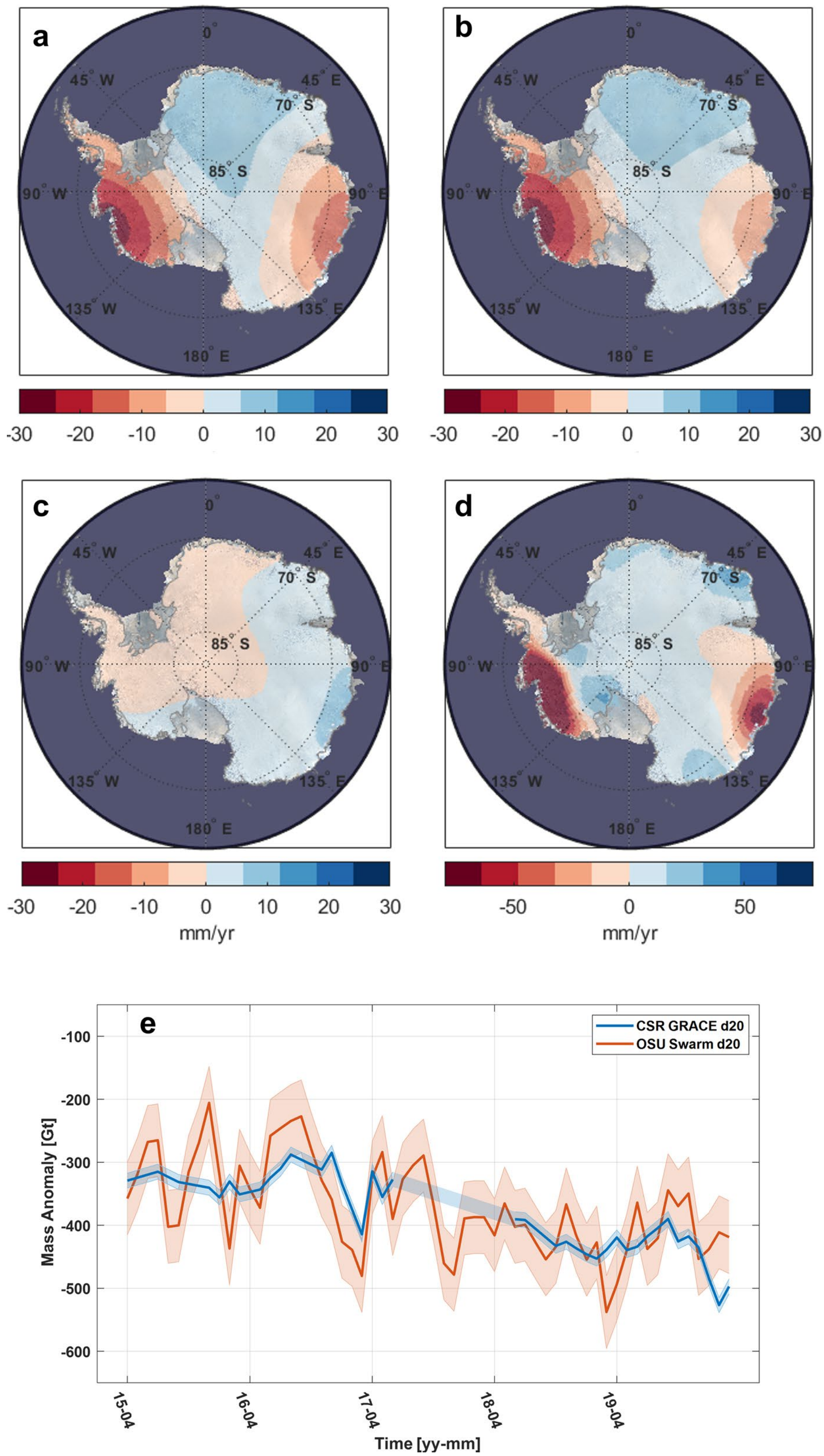

Figure 1. Mass anomalies trends (2015–2020) in Antarctica estimated from (a) degree 20 Swarm solutions with 1,100 km smoothing, (b) degree 20 GRACE(FO) with 1,100 km smoothing, (c) the difference between (a) and (b), and (d) degree 60 GRACE(FO) with 300 km smoothing. (e) Highlights the West Antarctic Ice Sheet (WAIS) mass anomalies time series estimated from degree 20 Swarm and degree 20 GRACE(FO).

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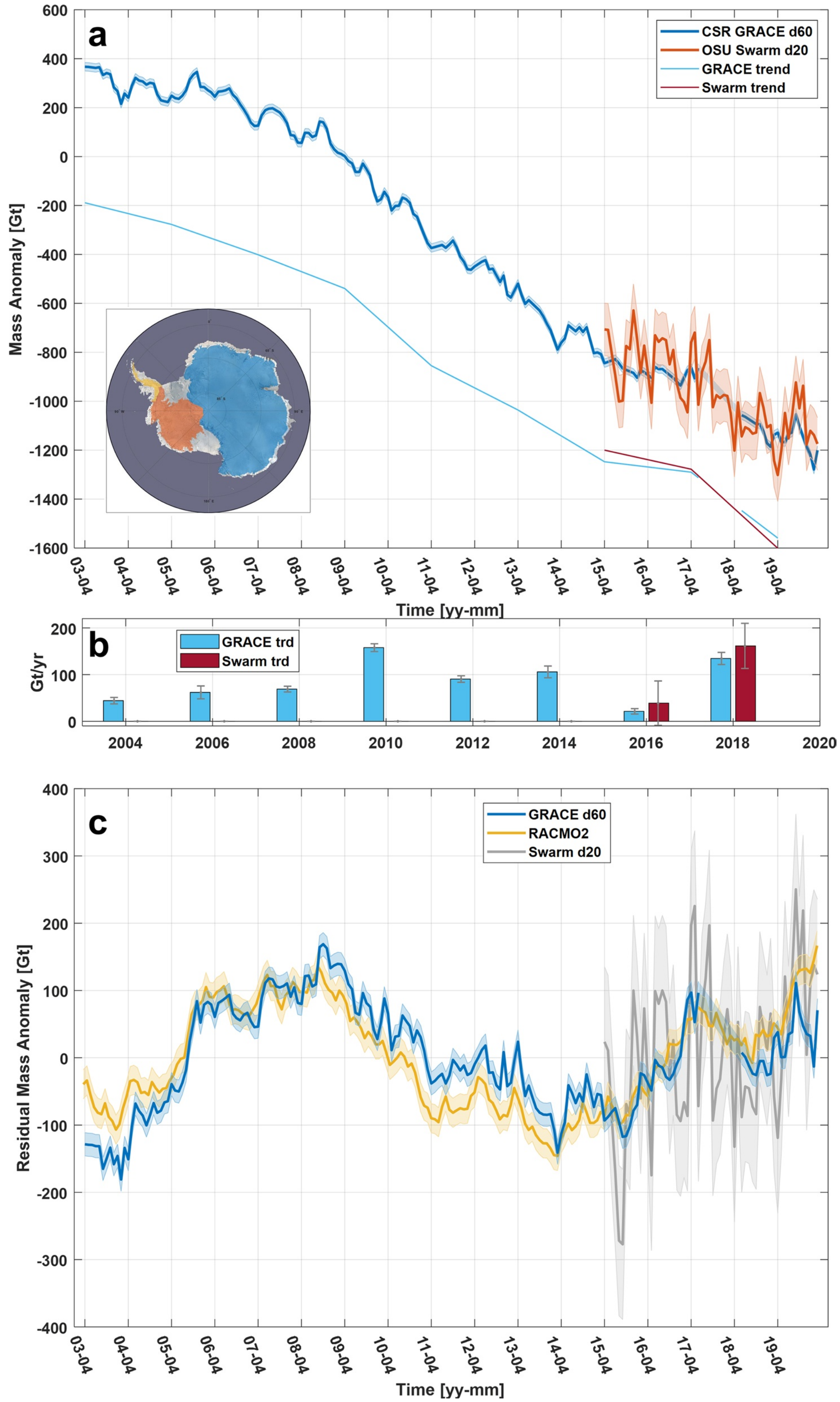

Figure 2.

mission ended in June 2017, and the GRACE-FO mission did not deliver data until May 2018, the one-year data gap raised the question of whether this low mass loss rate would continue in the absence of GRACE(FO) gravimetry observations? Apparently, there is an offset between the last GRACE epoch and the first GRACE-FO epoch (Figure 2a, blue). Without considering the data gap, the biennial trend estimated from GRACE and GRACE-FO mass anomalies between 2017 and 2019 is -134.6 ± 13.0 Gt yr^{-1}, which may suggest the mass loss rate has returned to the rapid mass loss periods prior to 2015 or may be attributed to a potential systematic bias between GRACE and GRACE-FO. In other words, GRACE and GRACE-FO may inherently provide biased mass estimates, at least in WAIS, which cannot be ruled out unless independent data confirm the return of the rapid mass loss state prevailed prior 2015. To unravel this mystery, we use the mass anomalies observed by Swarm mission to bridge this gap (Figure 2a, red). Though the Swarm time series is nosier than GRACE(FO), the mass loss tendency is consistent with GRACE(FO) during the overlapping period. The Swarm biennial trend estimate is -38.9 ± 47.5 Gt yr^{-1} for 2015–2017, which is within the GRACE trend estimate uncertainty. Both suggest a mild mass change rate. For the biennial period that covers the data gap (2017–2019), Swarm mass rate is -161.5 ± 48.4 Gt yr^{-1} which confirms the mass rate observed by GRACE(FO) (-134.6 ± 13.0 Gt yr^{-1}). The agreement also implies that the offset between GRACE and GRACE-FO is mainly from the ice mass loss rather than a systematic bias between these two missions. Compared with the mass loss rate prior to 2015, both GRACE(FO) and Swarm biennial trends suggest that WAIS has abruptly returned to the rapid mass loss state at the end of GRACE mission. Next, we investigate the plausible origin attributable to the observed shift in mass loss rate in West Antarctica.

3.2. SMB Variation

The ice sheet mass balance is mainly controlled by ice discharge and SMB. At the interannual time scale, SMB dominates the WAIS mass balance, where its contribution can be around 10 times greater than ice discharge (Zhang et al., 2021). Figure 2c shows the WAIS residual mass anomalies after removing linear trend and seasonal terms, which is dominated by the interannual variations. The WAIS interannual mass variations (as observed by GRACE(FO) and Swarm) are mainly driven by the variation of the SMB, where they show a high correlation at 0.84 and 0.72, respectively (Figure 2c). As the key component of SMB, precipitation controls the variability of the Antarctic SMB (Van Wessem et al., 2014). A positive trend in SMB anomalies mostly manifests increased precipitation. In the opposite way, a negative trend in SMB reflects reduced precipitation (Bodart & Bingham, 2019). The fast mass loss biennial periods, e.g., 2009–2015 and 2017–2019, generally correlate with lower precipitation, shown as a negative trend in SMB (Figure 2c) while the mild mass loss period, e.g., 2003–2006 and 2015–2017, tend to happen during increased precipitation (Figure 2c). The enhanced precipitation between 2015 and 2017 may explain the mild mass loss observed by GRACE and Swarm (Figure 2a), where the SMB trend (Figure 2c) is shown to have sharply changed from -27 ± 2 Gt yr^{-1} (2009–2015) to around 74 ± 6 Gt yr^{-1} (2015–2017). Similarly, the anomalous high precipitation unexpectedly turned into low precipitation around May 2017, where the SMB trend turned from 74 ± 6 Gt yr^{-1} (2015–2017) to -18 ± 6 Gt yr^{-1} (2017–2019). This dramatic change in precipitation further explains and confirms the rapid mass loss observed by Swarm 161.5 ± 48.4 Gt yr^{-1} during the GRACE and GRACE-FO data gap. In summary, we find the WAIS has returned to the rapid mass loss trajectory prior to 2015 during the data gap. This transition can be mostly explained by the anomalous low precipitation between early 2017 and 2019.

4. Discussion

The Southern Annular Mode (SAM), also called Antarctica Oscillation, and the Pacific-South America patterns (PSA) are the leading atmospheric modes that vary on interannual time scales (Jin & Kirtman, 2009; Mo, 2000; Thompson & Wallace, 2000; Yu et al., 2011). Along with El Niño/Southern Oscillation (ENSO), they are the most

Figure 2. (a) West Antarctica mass anomalies time series and biennial trends estimated from degree 60 GRACE(FO) (blue and light blue) and degree 20 Swarm (red and dark red), after applied leakage reduction processing. The shifts between time series and biennial trends are for better and clear visualization. (b) The bar plots of the Swarm (dark red) and GRACE(FO) (light blue) biennial mass loss rate estimates with uncertainty. Each estimate is placed at the center of each 2-year period. (c) The West Antarctic Ice Sheet (WAIS) interannual mass anomalies from surface mass balance (SMB; yellow, RACMO2 model), GRACE (blue, CSR RL06 solutions), and Swarm (gray, OSU solutions). The shaded areas are uncertainty. The West Antarctic Ice Sheet ($\sim 2 \times 10^6$ km^2) is delineated in the left bottom corner of (a) in red. East Antarctica Ice Sheet is in blue and Antarctic Peninsula in yellow. The background is NASA blue marble.

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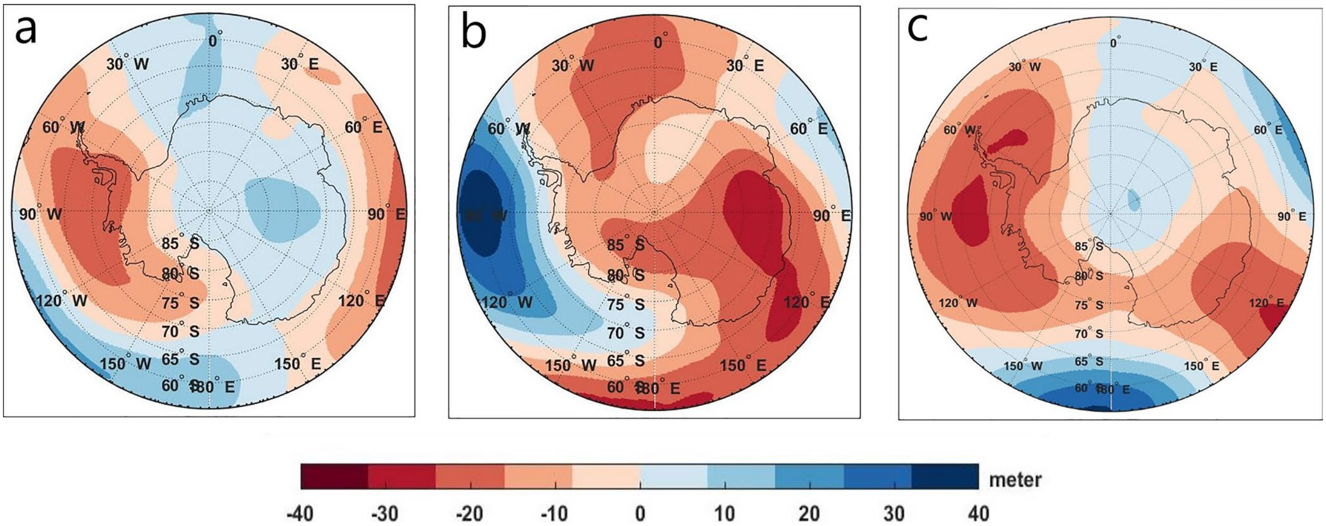

Figure 3. ERA5 biennial mean geopotential height at 500 hPa during 2013–2015 (a), 2015–2017 (b), and 2017–2019 (c).

prominent climate driving forces of interannual changes in West Antarctica (Paolo et al., 2018). ENSO, SAM, and PSA have been linked to the variations of sea ice extent (Pope et al., 2017; Raphael & Hobbs, 2014), surface air temperature (Steig et al., 2013), ice-shelf thickness (Paolo et al., 2018), surface melt (Wille et al., 2019), Circumpolar Deep Water and basal melting (Cook et al., 2016; Jacobs et al., 2011; Pritchard et al., 2012), precipitation and ice sheet surface mass balance (Nicolas et al., 2017; Scott et al., 2019; Zhang et al., 2021).

To investigate the climate drivers of the transition from mild mass loss (2015–2017) to intensive mass loss (2017–2019), we analyze the geopotential height anomalies of 500 hPa over Antarctica using ERA5 pressure data. Figures 3a and 3c shows the mean geopotential height anomalies at 500 hPa for three consecutive biennial periods (2013–2015, 2015–2017, and 2017–2019) from left to right. They are also corresponding to La Niña, El Niño, and La Niña. Especially the 2015–2017 period corresponds to the 2015 extreme El Nino event. All three biennial periods are dominated by the classical PSA (Jin & Kirtman, 2009; Yu et al., 2011), where high (low) pressure anomalies persist at the Pacific sector. The +PSA (−PSA) is also accompanied by El Niño (La Niña). As the air tends to flow from high-pressure zone to low-pressure zone, the anomalous low pressure over the Pacific sector during −PSA (Figures 3a and 3c) will cause the cold continental air outflow to the ocean, which will result in less precipitation over West Antarctica. On the contrary, the high pressure in Figure 3b is in favor of increased precipitation that is contributed from the warm and moist air driven by the meridional advection (Nicolas & Bromwich, 2011; Scott et al., 2019; Zhang et al., 2021). Compared with Figure 2, we interpret that the shifts of SMB from downward (2013–2015) to upward (2015–2017) and then back to downward trend (2017–2019) are mainly driven by the variation of the PSA along with the ENSO. Therefore, after the extreme El Niño (2015–2017), the +PSA turns into −PSA. The corresponding enhanced precipitation turns back to anomalous low precipitation, where we see the WAIS returns to the rapid mass loss state as observed by Swarm and GRACE(FO) (2017–2019).

5. Conclusions

Exact quantification and understanding of the complex ice sheet mass balance in WAIS is a critical component for viable and improved projections of global sea level change. During the past decade, progressively increasing mass loss in the WAIS was observed by the GRACE gravimetric satellites, until mass loss suddenly paused in 2015. A much lower rate of mass loss persisted until the decommissioning of the GRACE mission in 2017. The one-year gap between GRACE and GRACE-FO mission interrupted the high-accuracy gravimetric record of WAIS mass variation. We have estimated independent temporal gravity solutions using the Swarm GNSS tracking data to bridge that unfortunate data gap, allowing us to better follow the abrupt mass change episodes in WAIS. Because the nature of the observation system, the Swarm observed WAIS mass anomalies are noisier than GRACE measurements. However, the mass anomalies time series and trend estimates turn out to have a good agreement with GRACE(FO) during the overlapping period, which makes it a good candidate for bridging the data gap.

Using these Swarm estimates, we find that during the GRACE and GRACE-FO data gap, the WAIS has returned to the rapid mass loss state, observed prior to 2015. Indirectly, we also demonstrate that the large offset between GRACE and GRACE-FO WAIS mass anomalies are mainly attributed to transient changes in ice mass loss, rather than a potential intermission bias between GRACE and GRACE-FO. By comparing residual anomalies from gravimetry observation and SMB on interannual time scales, we infer that the shifting in the biennial trend was mainly caused by precipitation anomalies, which turned from the enhanced precipitation during 2015–2017 to anomalously low precipitation in 2017–2019. The biennial mean geopotential height at 500 hPa suggests that a shift from +PSA to −PSA modes, coupled with the unusually pronounced El Niño to La Niña transition, are the main drivers of the observed changes in the WAIS biennial ice mass loss trends.

The 2015–2017 pause in WAIS mass loss is reminiscent of the 18-month pause in the mass loss in the Greenland Ice Sheet, which began in mid-2013. The Greenland pause was caused by a dramatic shift in another climate cycle, i.e., the North Atlantic Oscillation (Bevis et al., 2019). What we learn from both studies, is to take no comfort in short pauses in ice loss, caused by one or more climate cycles that "temporarily" oppose a persistent climate trend. Over many decades the cycles will have little net effect, whereas ongoing global warming of the oceans and the atmosphere certainly will drive accelerating ice loss, and sea level rise, for many decades to come.

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