

Estimating the Mass Balance of the Antarctic Ice Sheet from 1985 to 2021 using the Input-Output Method

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Abstract. Accurate monitoring of the Antarctic ice sheet's mass balance is crucial for comprehending its contribution to global sea level rise and climate patterns. We estimate the Antarctic mass balance from 1985 to 2021 using an input-output method. Ice discharge is estimated using an automated algorithm, while surface mass balance data is obtained from the RACMO2.3p2 model. We find a recent decrease in the rate of ice mass loss in Antarctica, consistent with the recent studies. The West Antarctic Ice Sheet (WAIS) drives the increase in ice discharge and mass loss, influenced by rising ocean temperatures and extreme weather events. The East Antarctic Ice Sheet (EAIS) shows stability in mass balance, except for an increase in discharge and mass loss in the Cp-D sub-region. The Antarctic Peninsula experiences increased ice discharge and mass loss, while the islands maintain a positive mass balance. The findings contribute to our understanding of the ongoing changes in ice mass and highlight the sensitivity of different regions to external factors.

Keywords: Antarctic Ice Sheet; Input-Output Method; Discharge; Mass Balance.

1. Introduction

The rapid advancement of satellite geodesy during the late 20th century and early 21st century has significantly transformed the monitoring methods for polar ice sheet mass balance (MB)[1, 2]. As one of the largest ice bodies on Earth, studying the MB of the Antarctic ice sheet (AIS) is crucial for understanding global mean sea-level fluctuations, global water circulation, climate patterns, and other related phenomena[3]. Consequently, the study of AIS ice discharge (D) and MB has become the focus of Antarctic scientific research.

In the past few decades, the monitoring of ice sheet MB has primarily relied on three main methods: the gravity method, the altimetry method, and input-output method. Among these, the gravity method, facilitated by satellite missions such as GRACE (Gravity Recovery and Climate Experiment) and its successor GRACE-FO (GRACE Follow-On), has emerged as a significant means of directly and effectively monitoring ice sheet mass changes [4-8]. However, due to its relatively low spatial resolution (approximately 300 km) and susceptibility to glacier dynamic adjustments, GRACE/GRACE-FO cannot provide accurate and high-precision estimations of ice sheet mass changes. The altimetry method, another important monitoring approach, utilizes radar or laser altimeters mounted on satellites to measure changes in the surface elevation of ice sheets and convert them into mass changes [9-12]. Data from satellites such as ERS (European Remote Sensing) and Envisat of the European Space Agency, as well as ICESat (The Ice, Clouds, and Land Elevation Satellite), have provided valuable observations for researchers [13]. However, the elevation changes obtained through this method encompass the combined effects of multiple factors, including snow accumulation, compaction, crustal uplift, and ice loss, making it challenging to accurately discern the contributions of these factors to the ice sheet elevation changes. This study focuses on the input-output method (IOM), which utilizes high-resolution data (100 m - 1 km) to quantify the differences between the mass gain caused by snowfall and the mass loss due to glacier discharge and meltwater runoff [14, 15]. The IOM's advantage lies in its ability to estimate MB changes at the scale of individual glacier drainage basins, providing more detailed spatiotemporal

information for research. Among different estimation methods, the IOM has garnered attention due to its high resolution and precise quantification of ice sheet mass changes. By estimating the MB of the AIS from 1985 to 2021, we provide new data on the contribution of different Antarctic scales to global sea level rise.

2. Data

2.1 Ice velocity data

The Antarctic ice velocity data encompass information from various sources (Table 1) and cover multiple time periods, utilizing different remote sensing techniques and processing methods to gain insights into the motion characteristics of polar ice sheets. Firstly, the MEaSUREs program provides Antarctic ice velocity data (NSIDC 0720) from July 1, 2000, to June 30, 2021, with a temporal resolution of one year and a spatial resolution of 1 km. This dataset integrates multiple satellite data sources. Secondly, we utilized Landsat 8 Antarctic ice velocity data (NSIDC 0733) as part of the Global Land Ice Velocity Extraction (GoLIVE) project, covering the period from July 1, 2013, to April 30, 2017, with a temporal resolution of one year and a spatial resolution of 750 m. Additionally, we applied the ITS_LIVE Antarctic ice velocity data, spanning from 1985 to 2020, with a spatial resolution of 240 m and obtained through the auto-RIFT feature tracking processing chain. Finally, the European Space Agency's (ESA) Antarctic Ice Sheets Climate Change Initiative (CCI) project provides monthly ice velocity data from October 1, 2014, to December 31, 2021, using Sentinel-1 synthetic aperture radar (SAR) imagery and feature tracking techniques, offering high-quality products of monthly average velocities. The combined use of these datasets provides a multi-temporal information base for a comprehensive understanding of the AIS MB.

Table 1. Summary of ice velocity data

Dataset Name	Time Span	Temporal, Spatial Resolution	Reference
NSIDC 0720	2000,2005-2021	Annual、 1 km	Mouginot et al.[16]
NSIDC 0733	2013-2017	Annual、 750m	Scambos et al.[17]
ITS_LIVE	1985-2020	Annual、 240m	Gardner et al.[18]
Sentinel-1	2014.10 – 2021.12	Monthly、 200m	Mouginot et al. [19]

2.2 Ice thickness, surface elevation change, and drainage basins data

This study utilized ice thickness data from BedMachine Antarctica, part of the MEaSUREs program [20]. The dataset covers the AIS from January 1970 to October 2019, providing information on subglacial topography, ice thickness, surface elevation, and more, with a spatial resolution of 500 m. The ice thickness data was derived from 47 airborne radar surveys spanning 1967 to 2020, along with other data, to improve accuracy near grounding lines and ice sheet margins.

Surface elevation change data for the grounded AIS was obtained from airborne surveys conducted between 1991 and 2021 by ESA radar altimetry missions [21-23]. These measurements, collected by the Airborne Topographic Mapper (ATM), offer at a spatial resolution of 5 km and 5-year intervals.

For systematic and different region scales analysis, we used Antarctic drainage basins data from Mouginot et al [24] (NSIDC 0709). This dataset divides the Antarctic into four regions, further subdivided into 18 subregions. This data allows for region-specific and precise analysis.

2.3 Surface mass balance Data

In the process of surface mass balance (SMB) estimation for the AIS, climatic processes such as snowfall and rainfall play a crucial role. Regional atmospheric climate models (RACMO) have become indispensable tools for assessing SMB. Developed collaboratively by the Royal

Netherlands Meteorological Institute (KNMI) and the Danish Meteorological Institute, RACMO is based on high-resolution limited-area models (HIRLM) and numerical weather prediction models. Two versions of the RACMO 2.3 model, namely RACMO 2.3 p1 and RACMO 2.3 p2, have been released [25, 26]. In this study, we utilized the RACMO 2.3 p2 model, which has a temporal resolution of one month and a spatial resolution of 27 km. By simulating and computing processes such as snowfall, the RACMO 2.3 p2 model provides SMB data for the AIS. The application of climate models allows for a comprehensive understanding of the spatial and temporal distribution of SMB, providing critical information for subsequent analyses of mass changes.

3. Methodology

3.1 Discharge

Ice discharge refers to the mass of ice passing through the grounding line per unit time. Due to the continuous retreat of the grounding line, calculating ice discharge presents challenges. In this study, we adopted an automatic and adaptable method proposed by Mankoff et al. (2019) to generate ice discharge gate. The algorithm details can be found in https://github.com/GEUS-Glaciology-and-Climate/ice_discharge/. The formula for calculating the discharge can be expressed as follows:

$$D = \sum_{n=1}^N \rho w_n V H \quad (1)$$

where ρ represents the ice density with a value of 917 kg/m³, w represents the width of the discharge gate, n represents the number of discharge gate, V represents the ice velocity at the discharge gate, and H represents the thickness at the discharge gate.

3.2 Mass balance

The MB calculation in this study is performed using the IOM, which estimates the surface accumulation and mass loss of the AIS. The surface mass accumulation, also known as SMB, is obtained through estimation using RACMO2.3p2 model. It represents the net accumulation of snowfall on the surface. It is estimated that over 90% of the mass loss from the AIS occurs in the form of ice discharge (section 3.1 describes how the variable D is calculated) into the ocean [27]. The MB of the AIS can be obtained by subtracting the mass loss (D) from the surface mass accumulation (SMB). The calculation formula is as follows:

$$MB = SMB - D \quad (2)$$

4. Results and analysis

4.1 Antarctic ice discharge

This study calculated the ice discharge for various basins in the AIS from 1985 to 2021, as shown in Table 2. The ice discharge for the East AIS (EAIS) exhibited an increasing trend from 1985 to 2014 but showed a decreasing trend from 2015 to 2021. In terms of specific subregions, except for the C-Cp, Cp-D, D-Dp, and Jpp-K subregions near the Indian Ocean and Filchner Ice Shelf, the discharge for other subregions was below 85 Gt/year. Among them, the Cp-D subregion had the highest discharge in the AIS from 1985 to 1994. In recent decades, the changes in ice discharge in the EAIS did not exceed 15 Gt/year. Therefore, overall, the ice discharge in the EAIS remained relatively stable.

Over the entire period from 1985 to 2021, the ice discharge in the West AIS (WAIS) showed a continuous increasing trend, with a total increase of approximately 150 Gt/year. Relative to the area of the EAIS, the WAIS had a much smaller area, especially the F-G, G-H, and H-Hp subregions

near the Amundsen Sea, which had relatively small areas but high discharge. Among them, the discharge in the G-H subregion exceeded that of the C-Cp subregion in the EAIS from 1995 to 2021, becoming the highest-discharging subregion in the entire AIS. Overall, the discharge in various subregions in the WAIS showed an increasing trend, and this region dominated the overall increase in ice discharge in the AIS.

The Antarctic Peninsula (AP) exhibited an increasing trend from 1985 to 2021. For various subregions within the AP, the Hp-I subregion accounted for over 50% of the discharge and also drove the increasing trend of ice discharge in the entire AP.

Previous studies[27] often overlooked the discharge from islands near AIS. This study's estimation indicates that the discharge from islands near AIS showed an increasing trend from 1985 to 2014 but a decreasing trend from 2015 to 2021.

Table 2. Ice discharge in AIS from 1985 to 2021 (Unit: Gt/year)

Region	1985-1994	1995-2004	2005-2014	2015-2021
A-AP	83.36	84.64	85.10	85.90
Ap-B	79.31	82.45	78.30	79.38
B-C	71.57	75.23	79.61	72.46
C-Cp	125.72	130.42	129.47	131.94
Cp-D	269.51	279.74	289.35	281.04
D-Dp	116.61	118.00	117.86	116.41
Dp-E	41.30	42.48	44.19	44.27
E-Ep	37.09	37.33	37.66	37.39
Jpp-K	109.37	107.70	102.20	98.38
K-A	45.11	51.54	60.57	50.78
EAIS	978.95	1009.52	1024.32	997.95
Ep-F	102.47	103.20	105.36	99.53
F-G	146.07	149.77	163.36	163.02
G-H	265.28	295.87	359.32	384.98
H-Hp	83.42	85.14	86.72	88.56
J-Jpp	162.72	165.73	169.49	171.25
WAIS	759.96	799.70	884.27	907.35
Hp-I	126.01	129.44	133.91	140.20
I-Ipp	93.54	96.22	103.35	107.66
Ipp-J	10.48	10.72	11.26	10.91
AP	230.03	236.38	248.52	258.77
Islands	72.34	79.61	84.90	57.38
AIS	2041.27	2125.22	2242.01	2221.45

4.2 Antarctic mass balance

To assess the validity of the AIS MB changes estimated in this study, a comparison was made with the findings of Rignot et al. (2019) and the IMBIE team. The results of this study, along with those of other studies, are shown in Figure 1. It should be noted that Rignot et al. (2019) used the average SMB data from RACMO2.3p1 for the period 1978-2008, which may introduce some inaccuracies when estimating the MB. To address this issue, we improved this study by replacing the average SMB data with annual data from RACMO2.3p2.

We exhibit a consistent trend with the improved SMB from Rignot et al. (2019) and are numerically closer to the mass balance estimation of the IMBIE team (as shown in Figure 1). The estimated results indicate a decreasing trend in the mass loss rate of AIS over time. Specifically, there are periods of mass gain in 1985, 1991-1993, and 2016, which align with the observations of

Rignot et al. (2019). From 1996 to 2014, the mass loss of AIS accelerates, indicating that the ice discharge surpasses the accumulation of SMB. However, since 2015, the mass loss rate of AIS has remained at a low level, consistent with the trend observed by the GRACE/GRACE-FO gravity satellite [28].

In conclusion, to analyze the validity of the estimated AIS MB changes in this study, a comparison was made with the findings of Rignot et al. (2019) and the IMBIE team. The results demonstrate a consistent trend with the improved SMB from Rignot et al. (2019) and are numerically closer to the MB estimation of the IMBIE team. The analysis of the AIS MB indicates a decreasing mass loss rate over time, with periods of mass gain and accelerated mass loss in alignment with previous research.

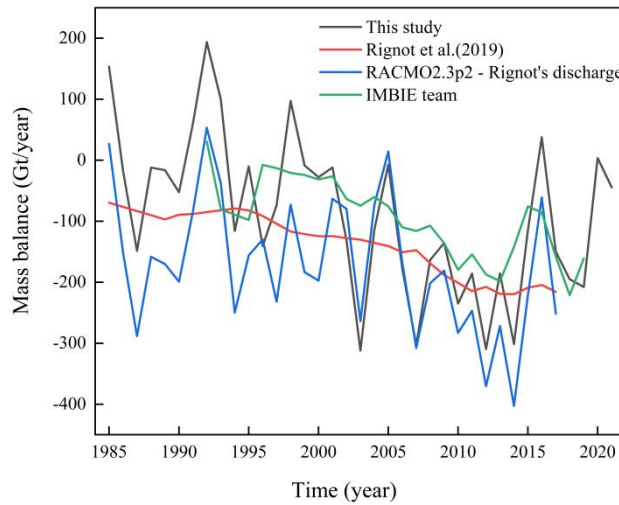


Figure 1: Comparison of the results of ours with existing studies.

The black line represents the MB estimated in this study. The red line represents the ice discharge provided by Rignot et al. (2019) along with the SMB data used in this study for the period 1978-2008. Additionally, to improve the accuracy of the MB estimation, this study incorporates the improved SMB data from RACMO2.3p2 and combines it with the ice discharge from Rignot et al. (2019), as shown by the blue line. The green line represents the MB curve from the IMBIE team [29].

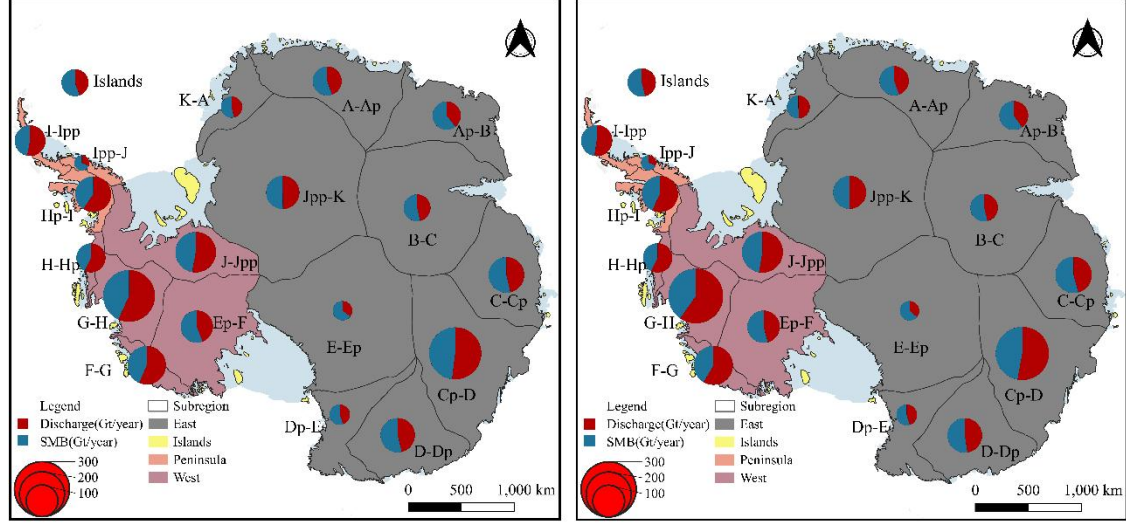
In addition, this study also estimated the MB of individual subregions within AIS (as shown in Figure 2). Among them, all subregions of EAIS, except for Cp-D subregion, show a trend of mass accumulation, where the mass loss in one subregion is offset by the mass gain in other subregions. Overall, the EAIS shows a trend of mass gain. The MB increased from 144.20 Gt/year in 1985-1994 to 147.99 Gt/year in 2015-2021. In contrast, the subregions of WAIS, except for Ep-F subregion, exhibit a trend of mass loss, and the rate of mass loss accelerates over time. The mass loss of the WAIS increased from 109.22 Gt/year to 246.81 Gt/year, with the G-H subregion being the primary contributor to this trend. The mass loss in the G-H subregion escalated from 63.58 Gt/year to 173.25 Gt/year. In general, the WAIS experienced substantial mass loss and instability from 1985 to 2021. The AP shows a trend of mass loss in all subregions except for Ipp-J subregion. Throughout the entire time series, the islands showed an accelerating trend of mass accumulation, which partially mitigated the trend of sea level rise.

Analyzing the MB of the subregions in AIS reveals that the mass loss is mainly concentrated in the WAIS and AP, consistent with current research findings. The accelerated mass loss rate in WAIS is attributed to basal melting of ice shelves and ocean temperature warming [30, 31]. Furthermore, studies indicate that the accelerated mass loss rate may further lead to the collapse of the WAIS [32]. In comparison, AP is more sensitive to ocean temperature changes, as the

freshwater anomaly stratifies the ocean in front of the ice shelves, modifying heat fluxes and increasing basal melt [33].

(a) 1985-1994 mass balane

(b) 1995-2004 mass balane



(c) 2005-2014 mass balane

(d) 2014-2021 mass balane

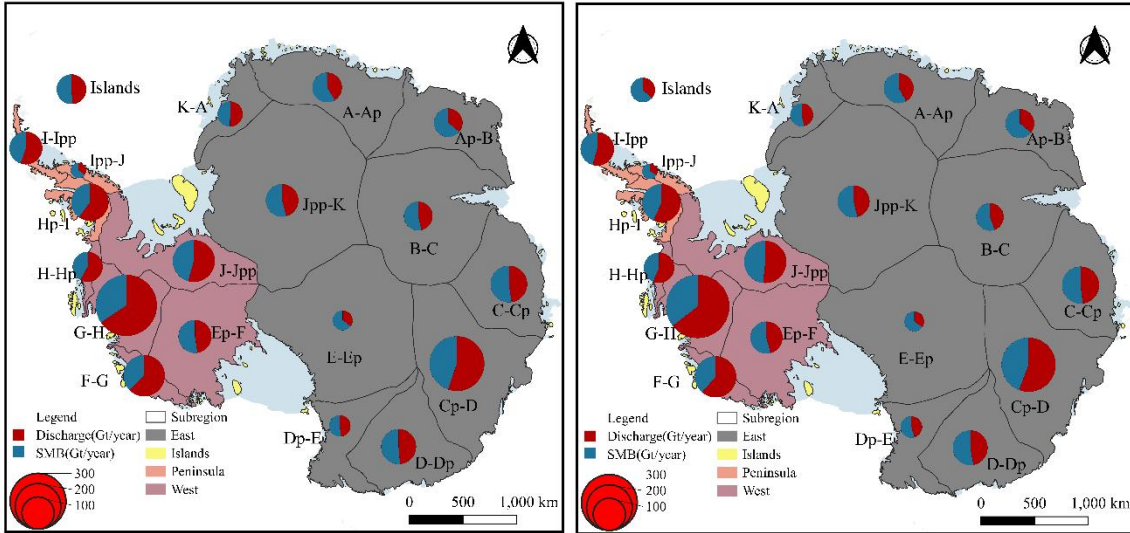


Figure 2: Estimation of AIS MB using IOM. (a) 1985-1994, (b) 1995-2004, (c) 2005-2014 and (d) 2015-2021.

5. Discussion and conclusion

This study investigates the AIS MB from 1985 to 2021 using IOM. Ice discharge is estimated using an automated generation of discharge gate algorithm, while SMB data is obtained from the RACMO2.3p2 model. The study compares the results with previous studies by Rignot et al. (2019) and the IMBIE team, finding consistent findings. Additionally, this study extends the time series and reveals a recent decrease in the rate of ice mass loss in AIS, which aligns with the observed trend from the GRACE/GRACE-FO study [28].

In terms of spatial distribution, the increase in ice discharge and intensification of mass loss in AIS are primarily driven by the WAIS. This is likely due to rising ocean temperatures and frequent extreme weather events [34-36] leading to ice shelf melting [37, 38], thereby increasing the discharge. The EAIS maintains stable ice discharge, showing an overall trend of mass accumulation,

except for an increase in discharge and mass loss in the Cp-D subregion, which is offset by reductions in other subregions. Furthermore, the EAIS demonstrates stability in MB during extreme weather events, possibly due to consistent internal glacier structure and ice flow direction [39], ensuring stability [40]. The AP experiences an increase in both ice discharge and mass loss, primarily driven by the I-Ipp and Hp-I subregions, indicating high sensitivity to temperature changes [41]. As for the islands, they maintain a positive MB throughout the entire time period. Furthermore, further analysis of the AIS MB indicates that this study extends the time series to 2021 and analyzes the interannual mass balance from 1985 to 2021, yielding results consistent with existing research [29, 42].

In summary, our analysis of 19 subregions of the AIS and reveals that the rate of mass loss in the G-H and H-Hp subregions of the Amundsen Sea sector in WAIS accelerates with increasing discharge, particularly with the G-H subregion exhibiting a mass loss rate of 170 Gt/year from 2005 to 2021. The accelerated mass loss in the Cp-D subregion of the EAIS is linked to the retreat of the Totten Glacier front and intensified basal melting caused by warm water intrusion. The A-Ap, Ap-B and E-Ep subregions show continuous mass accumulation. The AP, except for the Ipp-J subregion, experiences a mass loss trend with higher loss rates than accumulation rates, indicating an overall mass loss. The islands maintain a positive mass balance trend from 2015 to 2021. Overall, among the 19 subregions of AIS, the rate of mass loss far exceeds the accumulation rate, leading to an accelerated mass loss from the AIS.

In conclusion, we offer a comprehensive analysis of the AIS MB at both regional and subregional scales. The findings contribute to our understanding of the ongoing changes in ice mass and highlight the sensitivity of different regions to external factors such as ocean temperatures and extreme weather events. The results underscore the need for continued monitoring and research efforts to assess the implications of ice mass loss for global sea level rise and climate change.

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