AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL118142

Oxygen Isotope Insights Into the Impact of Amundsen Sea Freshwater on Ross Sea Freshening

Guanghui Chen[1,2], Shunan Cao[3], You Jiang[1,4], Yi Wang[1], Minfang Zheng[1], Mengya Chen[1], Jianfeng He[3], and Min Chen[1]

[1]College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, [2]School of Oceanography, Shanghai Jiao Tong University, Shanghai, China, [3]Polar Research Institute of China, Shanghai, China, [4]Polar and Marine Research Institute, College of Harbor and Coastal Engineering, Jimei University, Xiamen, China

Key Points:

- Lower $\delta^{18}O$ in the Antarctic Slope Current (ASC) indicates the influence of Amundsen Sea winter water (WW)
- The Modified Circumpolar Deep Water on the Ross Sea shelf is formed from upwelled Upper Circumpolar Deep Water and WW of ASC
- Freshening in the Ross Sea is attributed to increased freshwater input from the Amundsen Sea and local glacial meltwater discharge

Supporting Information:

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

Correspondence to:

M. Chen,
mchen@xmu.edu.cn

Citation:

Chen, G., Cao, S., Jiang, Y., Wang, Y., Zheng, M., Chen, M., et al. (2025). Oxygen isotope insights into the impact of Amundsen Sea freshwater on Ross Sea freshening. *Geophysical Research Letters*, *52*, e2025GL118142. https://doi.org/10.1029/2025GL118142

Received 15 JUL 2025
Accepted 7 NOV 2025

Author Contributions:

Conceptualization: Shunan Cao, Jianfeng He, Min Chen
Data curation: Guanghui Chen, Minfang Zheng, Min Chen
Formal analysis: Guanghui Chen, You Jiang, Yi Wang, Min Chen
Funding acquisition: Shunan Cao, Min Chen
Investigation: You Jiang, Yi Wang
Methodology: Guanghui Chen, You Jiang, Yi Wang
Project administration: Jianfeng He
Resources: Minfang Zheng, Mengya Chen
Software: Minfang Zheng, Mengya Chen
Supervision: Min Chen
Validation: Minfang Zheng
Visualization: Guanghui Chen, Mengya Chen

Abstract

Over the past five decades, the Ross Sea has freshened, but the mechanisms remain unclear. This study uses oxygen isotopes to trace freshwater transport from the Amundsen Sea to the Ross Sea. Results show that Winter Water (WW) in the Antarctic Slope Current (ASC) has lower $\delta^{18}O$ values (<-0.7‰) due to glacial meltwater (GMW) inputs from the Amundsen Sea shelf. Modified Circumpolar Deep Water (mCDW) in the Ross Sea, formed by mixing upwelled Upper Circumpolar Deep Water and ASC WW, has intermediate salinity and $\delta^{18}O$ values. High Salinity Shelf Water (HSSW) forms from mCDW during sea ice formation and is further modified by mixing with GMW, resulting in distinctly low $\delta^{18}O$ of <-0.8‰. In 2020, HSSW $\delta^{18}O$ averaged 0.25‰ lower than in 2000, suggesting freshwater from the Amundsen Sea and local ice shelf melting contribute to the Ross Sea's freshening. This highlights the importance of understanding marginal sea interactions in climate change.

Plain Language Summary

Extensive evidence shows that the Ross Sea has been undergoing continuous freshening over the past 50 years, yet the mechanisms behind this freshening remain unclear. This study provides oxygen isotope evidence from both the Amundsen Sea and the Ross Sea, indicating that freshwater input from the upstream Amundsen Sea significantly contributes to this freshening. The winter water (WW) in the Amundsen Sea Antarctic Slope Current (ASC) has lower $\delta^{18}O$ values, indicating its origin from the continental shelf affected by glacial meltwater. The relationship between salinity and $\delta^{18}O$ further suggests that the modified Circumpolar Deep Water on the Ross Sea shelf is formed by the mixing of upwelled Upper Circumpolar Deep Water and WW from the ASC. The recent increase in freshwater discharge from melting ice shelves in the Amundsen Sea, transported through the ASC, contributes to the Ross Sea's freshening. Additionally, the $\delta^{18}O$ values indicate that local ice shelf melting plays an important role in the freshening of High Salinity Shelf Water. This study offers a new perspective on the interactions among different marginal seas of Antarctica in the context of climate change.

1. Introduction

The Antarctic Ice Sheet has the potential to raise global sea levels by 58 m if it were to melt completely (Fretwell et al., 2013). Over the past two decades, mass loss from the Antarctic Ice Sheet has been accelerating, particularly in West Antarctica (The IMBIE team, 2018). Significant mass loss from ice shelves in West Antarctica is primarily due to basal melting, where warm modified Circumpolar Deep Water (mCDW) intrudes onto the continental shelves and reaches the bases of the ice shelves (Dutrieux et al., 2014; Nakayama et al., 2018; Pritchard et al., 2012; Rignot et al., 2013). In the Amundsen Sea, glacial meltwater (GMW) from coastal ice shelves promotes phytoplankton booms in coastal polynyas by providing bioavailable micronutrients, such as Fe, thereby enhancing the efficiency of the biological carbon pump (Arrigo et al., 2012; Sherrell et al., 2015). Additionally, the continuous release of GMW has freshened seawater over the Amundsen Sea shelf (Hennig et al., 2024). Model simulations suggest that freshwater from the Amundsen Sea spreads onto the Ross Sea shelf within 1 year, facilitated by the Antarctic Slope Current (ASC) and the Antarctic Coastal Current (Nakayama et al., 2020).

The Ross Sea is a crucial region for the formation of Antarctic Bottom Water (AABW), contributing 20%–40% of AABW in the global ocean (Orsi et al., 2002; Schmidt et al., 2023). AABW ($\gamma^n > 28.27$ kg/m^3) originating from the Ross Sea is formed from a mixture of mCDW and Shelf Water (SW) (Orsi et al., 1999). SW in the Ross Sea is primarily produced in coastal polynyas in Terra Nova Bay (TNB) and adjacent to the Ross Ice Shelf (RIS) (Amblas & Dowdeswell, 2018). Persistent katabatic winds and strong sea ice formation generate cold, saline

Writing – original draft: Guanghui Chen
Writing – review & editing: Shunan Cao, Jianfeng He, Min Chen

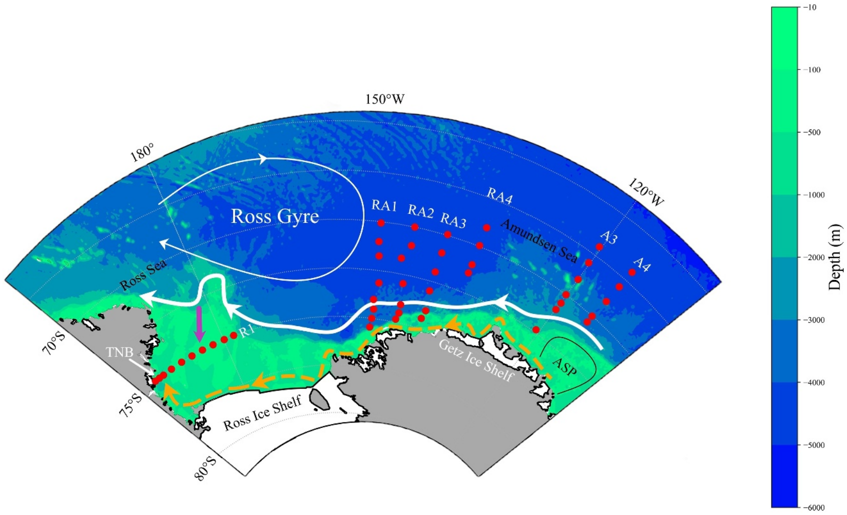

Figure 1. Map showing the sampling stations (red circles) for δ^{18}O in this study. All transects are labeled. White areas denote coastal ice shelves, with only the Ross Ice Shelf and Getz Ice Shelf specifically labeled. The yellow dashed line along the coast represents the Antarctic Coastal Current. The thick and thin white lines represent the Antarctic Slope Current and the Ross Gyre, respectively. The purple arrow indicates the path of UCDW intrusion onto the continental shelf through Jodies Trough (Kohut et al., 2013). The black curve delineates the area of the Amundsen Sea Polynya in January 2020 (Chen et al., 2024). The white arrow marks the location of Terra Nova Bay in the Ross Sea.

surface water, which sinks and aggregates to form new, dense SW ($\theta < -1.85$°C, $S > 34.80$) (Jacobs et al., 1970; Orsi & Wiederwohl, 2009). Long-term observations have shown a continuing decline in the salinity of High Salinity Shelf Water (HSSW) from the 1950s to 2020 (Jacobs et al., 2022). This freshening is thought to be associated with multiple processes, such as enhanced precipitation, weakened sea ice production, and melting of the West Antarctica Ice Sheet (Jacobs et al., 2002; Xie et al., 2025). Among these, freshwater released by the West Antarctica Ice Sheet is thought to play a dominant role in freshening the Ross Sea SW (Castagno et al., 2019; Jacobs & Giulivi, 2010; Jacobs et al., 2022).

Seawater oxygen isotopes serve as reliable and sensitive tracers for freshwater inputs (Kim and Timmermann, 2024; Weiss et al., 1979). These isotopes are typically used in combination with salinity (S) and mass balance models to quantify freshwater proportions and sea ice formation intensities in the Southern Ocean (Jia et al., 2022; Meredith et al., 2010; Qi et al., 2025). In the Amundsen Sea, GMW derived from basal melting of ice shelves constitutes a major component of freshwater, as estimated by δ^{18}O, dissolved oxygen, and physical parameters (potential temperature θ, S) (Biddle et al., 2019; Chen et al., 2024; Randall-Goodwin et al., 2015). Measurements of δ^{18}O and S for HSSW in the Ross Sea showed significantly reduced δ^{18}O and S levels in 2000 compared to the previous century, indicating persistent freshening of Ross Sea SW (Jacobs et al., 2002). Influenced by GMW from the upstream Amundsen and Bellingshausen Seas, the salinity of HSSW in the Ross Sea declined by 0.17 from 1957 to 2020 (Castagno et al., 2019; Jacobs & Giulivi, 2010; Jacobs et al., 2022). Although extensive spatiotemporal observations of physical oceanographic parameters exist for the Ross Sea (Castagno et al., 2019; Orsi & Wiederwohl, 2009), studies involving δ^{18}O are limited. As δ^{18}O is a sensitive indicator for freshwater inputs, investigations in the Ross Sea are crucial for monitoring the influence of the West Antarctic Ice Sheet on the region.

In this study, we present δ^{18}O values of seawater samples collected along a zonal transect at 75°S in the Ross Sea and six meridional transects in the Amundsen Sea in January 2020 (Figure 1). Four of the six meridional transects cross the continental slope allow us to verify the hypothesis that the ASC transports freshwater from the Amundsen Sea to the Ross Sea shelf (Castagno et al., 2019; Guo et al., 2021; Jacobs & Giulivi, 2010; Nakayama et al., 2020). We analyze δ^{18}O and other physical parameters (θ, S) in the zonal transect in the Ross Sea to identify water masses and investigate how the freshwater from the Amundsen Sea impacts the Ross Sea HSSW. Finally, we illustrate the evolution of HSSW in terms of δ^{18}O and S, indicating the persistent freshening of the Ross Sea from 1977 to 2020.

2. Materials and Methods

2.1. Sampling and Measurements

Seawater samples for $\delta^{18}O$ analysis were collected from Niskin bottles mounted onto a SeaBird 911plus conductivity-temperature-depth (CTD) instrument aboard the R/V *Xuelong* in January 2020. Two-milliliter glass vials were rinsed three times with in situ seawater, then filled to overflow and sealed with silicone gaskets. The sealed samples were stored at 4°C until analysis at Xiamen University.

The oxygen isotope ratios (^{18}O:^{16}O) of the seawater samples were analyzed using wavelength-scanning cavity ring-down spectroscopy in a laser spectroscopy analyzer (Picarro L2140-I, USA) (Chen et al., 2024; Hutchings & Konecky, 2022; Li et al., 2017). Each sample was analyzed eight times, and to prevent contamination, only the last five measurements were averaged to yield the final ^{18}O:^{16}O value. Oxygen isotopic compositions are expressed in the delta-notation ($\delta^{18}O$ in per mil) relative to the Vienna Standard Mean Ocean Water:

$$\delta^{18}\text{O}\ (‰) = \left[\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{VSMOW}}} - 1\right] \times 1,000 \tag{1}$$

To ensure measurement accuracy, three laboratory seawater references were included in the measurement sequence of 20 samples. The seawater reference results were consistent within each measurement batch ($R^2 > 0.99$). Duplicate measurements indicate an analytical precision better than ±0.03‰.

2.2. Potential Temperature and Salinity

Seawater temperature and salinity were measured by the SeaBird 911plus CTD with precisions of ±0.001°C and ±0.0003 S/m, respectively. In this study, potential temperature (θ) was calculated using Gibbs function for seawater thermodynamics (Feistel, 2008).

3. Results

3.1. Water Masses and $\delta^{18}O$ in the Amundsen Sea

In Figures 2a and 2b, Upper Circumpolar Deep Water (UCDW) is identified by its elevated θ ranging from 0.5 to 2°C at depths of 200–1,500 m (Talley et al., 2011). Below the UCDW lies the Lower Circumpolar Deep Water, characterized by slightly lower θ and higher density (28.18 kg/m^3 < γ^n < 28.27 kg/m^3) compared to UCDW (Orsi et al., 1999; Talley et al., 2011). The densest AABW is found at γ^n greater than 28.27 kg/m^3 (Orsi et al., 1999). The cold waters above the UCDW are referred to winter water (WW), found at depths of ≥50 m with γ^n less than 27.80 kg/m^3. WW extends down to 300 m along the density surface of $\gamma^n = 27.80$ kg/m^3 at the continental slope (Figures 2a and 2b and Figure S1 in Supporting Information S1). In comparison, offshore WW reaches a depth of approximately 200 m.

The $\delta^{18}O$ distribution, similar to θ, shows the highest values (−0.4‰ to 0.1‰) in the deep waters and relatively lower values in the WW (Figures 2c and 2d, Figure S2 and S3 in Supporting Information S1). In contrast to θ, $\delta^{18}O$ in WW is heterogeneous, with lower $\delta^{18}O$ values at the continental slope and higher values in the northern regions (Figures 2c and 2d and Figure S2 in Supporting Information S1).

3.2. Water Masses and $\delta^{18}O$ in the Ross Sea

In the Ross Sea, the elevated θ and relatively low S in surface waters are caused by solar radiation and sea ice melt (Figures 3a and 3b), consistent with the characteristics of Antarctic Surface Water (AASW) (Chen et al., 2024). Beneath the AASW lies HSSW and mCDW, identified by their distinct hydrological properties. HSSW (γ^n > 28.27 kg/m^3) has the highest salinity ($S > 34.62$) and the lowest θ ($\theta < -1.85$°C) (Orsi & Wiederwohl, 2009), occupying the majority of the water column in TNB (Figures 3a and 3b). The presence of HSSW aligns with previous studies indicating that TNB is a significant region for HSSW formation (Castagno et al., 2019; Jacobs et al., 1985). The mCDW, characterized by relatively higher θ and lower S compared to HSSW, is mainly observed in the water column between $\gamma^n = 27.8$ and 28.27 kg/m^3 east of 173°E (Budillon et al., 2011; Orsi & Wiederwohl, 2009). Stations with mCDW signals are near Jodies Trough, an important CDW

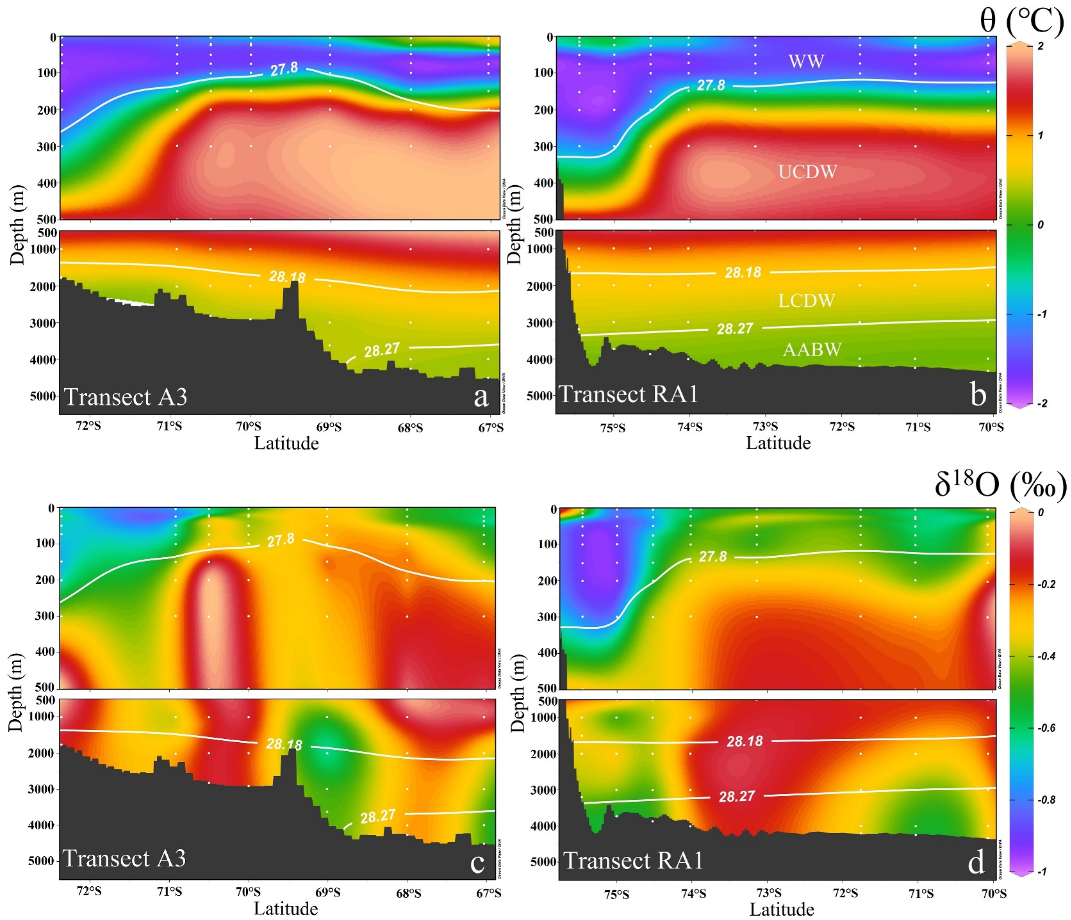

Figure 2. Meridional distribution of θ (a, b) and δ^{18}O (c, d) at 120°W (transect A3) and 150°W (transect RA1) in the Amundsen Sea. White dots indicate the sampling depths at each station. White lines represent neutral density surfaces of γ^n = 27.8, 28.18, and 28.27 kg/m^3.

intrusion path in the Ross Sea (Figure 1) (Kohut et al., 2013; Smith et al., 2014). The modified Shelf Water (MSW), defined by ($\gamma^n > 28.27$ kg/m^3 and $\theta > -1.85$°C), is found at the bottom layer west of 175°E (Figure 3a).

The subsurface distribution of δ^{18}O resembles that of θ. δ^{18}O values in HSSW are typically lower than those in mCDW. For AASW, the δ^{18}O values at stations in TNB are lower than those at stations to the east (Figure 3c).

4. Discussion

4.1. Freshwater Transported From the Amundsen Sea to the Ross Sea via ASC

The ASC is prevalent at the shelf break around Antarctica, playing a crucial role in the stability of Antarctic ice sheets (Thompson et al., 2018). In East Antarctica, the strong ASC effectively blocks CDW from intruding onto the continental shelf (Nakayama et al., 2021). Conversely, in West Antarctica, especially in the Eastern Amundsen and Bellingshausen Seas, the weak ASC allows CDW to easily intrude onto the shelf and enter ice shelf basal cavities (Dutrieux et al., 2014; Nakayama et al., 2018). The strong ASC is characterized by the deepened isopycnals at Antarctic slope (Thompson et al., 2018). Deepened isopycnals were observed at the shelf break along transects A3, RA1, RA2, and RA3 (Figure 2 and Figure S2 in Supporting Information S1), indicating a strong ASC from 120°E to 150°E. To confirm this inference, we extracted water current velocities and directions from the Hybrid Coordinate Model (HYCOM), a high-resolution (1/12°) eddy-resolving, data-assimilative ocean circulation model (https://www.hycom.org/). Model outputs showed a strong westward current (exceeding 0.1 m/s) along the shelf break from 130°E to 160°E (Figure S4 in Supporting Information S1). Combined with our observations, we infer a strong ASC flowing from the Amundsen Sea to the Ross Sea. The ASC was relatively weak

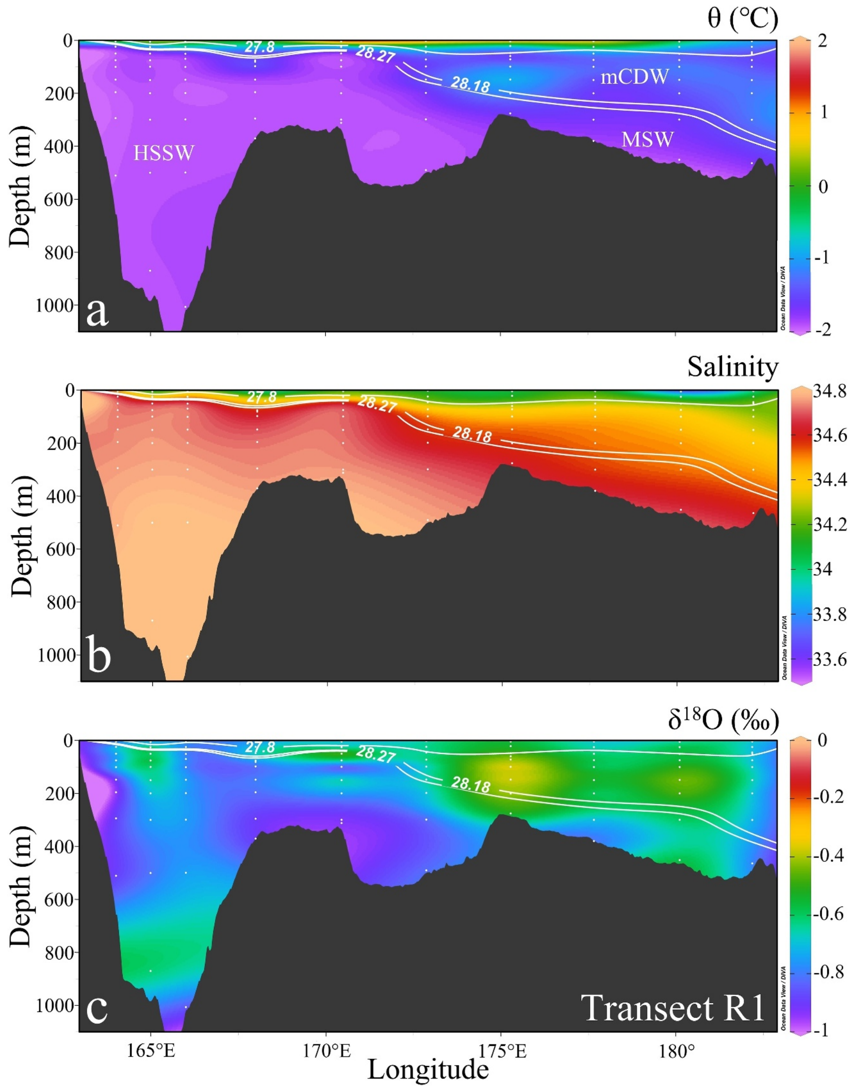

Figure 3. Zonal distribution of θ (a), S (b), and $\delta^{18}O$ (c) at 75°S (transect R1) in the Ross Sea. The white dots indicate the sampling depths for each station. The white lines represent the neutral density surfaces of γ^n = 27.8, 28.18, and 28.27 kg/m^3.

in the eastern Amundsen Sea (Figure S4 in Supporting Information S1), where CDW typically upwells onto the shelf (Biddle et al., 2019; Chen et al., 2024). In contrast, CDW signals were absent on the shelf in the eastern Amundsen Sea (Figures S1 and S2 in Supporting Information S1), due to the ASC acting as a barrier to CDW intrusion (Nakayama et al., 2021; Thompson et al., 2018).

The ASC is believed to play a key role in transporting freshwater from the upstream Amundsen and Bellingshausen Seas to the Ross Sea, and even to East Antarctica (Guo et al., 2021; Jacobs & Giulivi, 2010; Nakayama et al., 2020). Our $\delta^{18}O$ observations support this hypothesis. The $\delta^{18}O$ values in the WW of ASC (defined as depth ≥50 m and γ^n < 27.8 kg/m^3) were comparable to those in the WW of the Amundsen Sea Polynya (ASP) (Figure 4; Chen et al., 2024), implying that the WW of ASC originated from the Amundsen Sea shelf. Additionally, northward GMW outflows in the Amundsen Sea shelf were observed at depths of <400 m (Biddle et al., 2019; Chen et al., 2024). This depth range was consistent with the WW of ASC, which exhibited low $\delta^{18}O$ values (<−0.7‰). In contrast, elevated $\delta^{18}O$ in the WW layer north of the ASC was due to the influence of upwelling CDW with high $\delta^{18}O$ (Figures 2c and 2d, Figures S2 and S3 in Supporting Information S1).

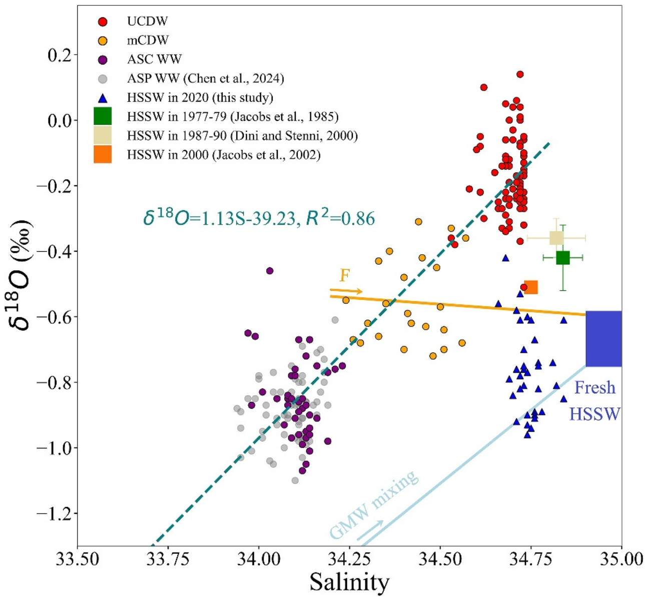

Figure 4. The relationship between S and δ^{18}O in Upper Circumpolar Deep Water (UCDW), Modified Circumpolar Deep Water (mCDW) and Antarctic Slope Current (ASC) winter water (WW). Squares represent the average values of reported High Salinity Shelf Water (HSSW) from other studies, with one standard deviation (±1 SD). The dashed line indicates the linear regression of S and δ^{18}O in UCDW, mCDW, and ASC WW, with the mathematic expression shown. The orange line indicates seawater oxygen isotope fractionation during sea ice freezing (F). The light blue line represents the mixing between fresh HSSW and glacial melt water with S = 0 and δ^{18}O = −32‰ (Kim and Timmermann, 2024). Note that the S and δ^{18}O ranges of fresh HSSW are not precise.

4.2. Impacts of ASC WW and GMW on HSSW in the Ross Sea

In the Southern Ocean, S and δ^{18}O are reliable proxies for water mass mixing (Helly et al., 2015; Hennig et al., 2024; Jia et al., 2022; Weiss et al., 1979). In Figure 4, S and δ^{18}O exhibit a linear relationship (R^2 = 0.86) in UCDW, mCDW, and ASC WW, implying that mCDW in the Ross Sea is formed through the mixing of UCDW and ASC WW. Despite the strong ASC at the shelf break, abnormally high θ of mCDW has been observed on the shelf in Prydz Bay, East Antarctica (Guo et al., 2019; Williams et al., 2016). Similarly, UCDW can flow across the shelf break into the inner shelf through deep troughs in the Ross Sea (e.g., Jodies Trough at 170−175°E in Figure 3; Kohut et al., 2013). The mCDW signals between 172 and 180°E are consistent with previous studies (Kohut et al., 2013). Therefore, we propose that the southward-flowing UCDW encounters the westward ASC during its intrusion, producing the mCDW observed at 75°S in the Ross Sea (Figure 3a).

HSSW in Antarctica is primarily produced through intense sea ice formation in polynyas during the austral winter (Jacobs et al., 1985; Williams et al., 2016; Yoon et al., 2020). Sea ice formation simultaneously alters the salinity and δ^{18}O of seawater. The release of brine raises the salinity of surface seawater, thereby enhancing vertical mixing. Additionally, isotopically heavy oxygen is preferentially incorporated into sea ice during formation, causing a relative enrichment of lighter oxygen isotopes in the surface seawater (Kim and Timmermann, 2024; Melling & Moore, 1995). Consequently, the precursor of HSSW is characterized by lower salinity and higher δ^{18}O compared to HSSW. Such surface seawater in TNB is likely sourced from mCDW during the austral winter. The first piece of evidence is the consistent characteristics of S and δ^{18}O between mCDW and the precursor of HSSW (Figure 4). The second piece of evidence is the presence of the mCDW signal at depths of 50 and 75 m at 170°E in transect R1, identified by elevated δ^{18}O and corresponding densities (Figure 3). In Prydz Bay, Guo et al. (2019) also reported mCDW upwelling to depth of 50 m. Based on these observations, we suggest that mCDW with relatively low S and high δ^{18}O upwells to the mixing layer in TNB, where it is transformed into newly formed HSSW through sea ice formation during the austral winter. To model this process, an equilibrium fractionation curve of seawater oxygen isotopes during sea ice formation was plotted in Figure 4. The slope of the fractionation line is associated with the fractionation factor (α) of seawater oxygen isotopes during seawater freezing (Jacobs et al., 1985; Weiss et al., 1979). Jacobs et al. (1985) used a slope of −0.08‰ for the fractionation line, based on an α value of 1.00270 determined by Craig and Hom (1968). Following Jacobs et al. (1985), we plotted the fractionation line with a slope of −0.08‰ passing through the mean δ^{18}O-S point of mCDW (Figure 4). The intercept at the δ^{18}O axis is 2.2‰, consistent with δ^{18}O measurements of 2.1‰ for sea ice in Antarctica (Randall-Goodwin et al., 2015). However, only HSSW with relatively high δ^{18}O (>−0.8‰) is well interpreted by the process of sea ice formation, suggesting that other processes may lower δ^{18}O of HSSW in TNB (Figure 4).

In the Weddell Sea and Prydz Bay, where SW is produced, S and δ^{18}O of SW decline due to mixing with GMW (Jia et al., 2022; Weiss et al., 1979). Similarly, in the Ross Sea, the salinity and δ^{18}O of HSSW adjacent to ice shelves are somewhat lower due to the injection of glacial meltwater, compared to those farther from ice shelves (Jacobs et al., 1985). Several studies have observed significant basal melting of the Nansen Ice Shelf and Drygalski Ice Tongue in TNB (Depoorter et al., 2013; Liu et al., 2015; Rignot et al., 2013). Kim et al. (2023) proposed that newly formed HSSW in the austral winter intrudes into the cavity beneath the Nansen Ice Shelf, promoting basal melt. Consequently, local GMW input has the potential to modify HSSW properties through water mass mixing in the TNB. Besides local GMW, HSSW in the TNB may also be influenced by GMW from the Amundsen Sea and the area in front of the RIS, transported to the TNB by the Antarctic Coastal Current (Figure 1). To evaluate the impact of GMW on HSSW properties, we assign values of 0‰ and −32‰ for S and δ^{18}O, respectively, as endmembers for GMW, following Kim and Timmermann (2024). The observed HSSW with δ^{18}O < −0.8‰ resulted from the mixing of fresh HSSW with GMW (Figure 4).

In addition to sea ice formation and GMW discharge, precipitation is generally considered an important factor affecting the S and $\delta^{18}O$ of seawater in Antarctica (Meredith et al., 2010). However, a recent study suggests that the influence of net precipitation (precipitation minus evaporation) on mixed layer S and $\delta^{18}O$ is negligible compared to Antarctic ice sheet loss and sea ice formation/melting in the Ross Sea, due to the relatively lower amount of precipitation with higher $\delta^{18}O$ of −18‰ compared to GMW (Kim and Timmermann, 2024). Consequently, the influence of precipitation on the S and $\delta^{18}O$ of HSSW is not considered in this study.

Overall, S and $\delta^{18}O$ of HSSW in the TNB are primarily influenced by two processes: sea ice formation and GMW inputs. During the austral winter, fresh HSSW is formed from mCDW through intense sea ice formation, which leads to brine release and a slight enrichment of isotopically light oxygen isotopes in the fresh HSSW. Once formed, the fresh HSSW directly mixes with GMW transported by the Antarctic Coastal Current and/or circulates into the ice shelf cavities, where it mixes with local GMW beneath the ice shelves. This mixing with GMW leads to declines in both S and $\delta^{18}O$ of the fresh HSSW (Figure 4).

4.3. Variations in $\delta^{18}O$ of HSSW in the Last Forty Years

HSSW in the Ross Sea has experienced freshening over the past ∼40 years (Figure 4). The most significant decline in S occurred in the 1990s, with a rate of 0.007 per year. The $\delta^{18}O$ of HSSW also decreased from −0.36 ± 0.06‰ to −0.51 ± 0.02‰, at a rate of 0.015‰ per year (Dini & Stenni, 2000; Jacobs et al., 2002). However, from 2000 to 2020, the salinity of HSSW only decreased by an average of 0.001, due to a rebound in HSSW salinity in the Ross Sea starting in 2014 (Castagno et al., 2019; Jacobs et al., 2022). Castagno et al. (2019) suggested that the shift to saltier HSSW could be attributed to enhanced sea ice formation and a reduction in freshwater input. The mass loss of the West Antarctic Ice Sheet has indeed remained low since 2012 (Jenkins et al., 2018), which would result in reduced freshwater discharge into the Ross Sea. However, during the period from 2000 to 2020, the $\delta^{18}O$ of HSSW continued to drop, averaging a decline of 0.25‰. The sharp decline in $\delta^{18}O$ is largely attributed to the impact of GMW (Figure 4).

Overall, both the salinity and $\delta^{18}O$ of HSSW in the Ross Sea have decreased over the last approximately 40 years. These variations in S and $\delta^{18}O$ were largely controlled by freshwater input from the Amundsen Sea, sea ice formation, and local GMW discharge. Under the influence of global warming, the ice shelves around the Amundsen Sea and the Ross Sea continue to melt at an accelerating rate (The IMBIE team, 2018). Sea ice coverage reached its lowest level in 2023 since 1980 and is predicted to continue decreasing (Purich & Doddridge, 2023; https://earthobservatory.nasa.gov/world-of-change/sea-ice-antarctic). Increased GMW discharge will contribute to the reduction of S and $\delta^{18}O$ of HSSW. Weakened sea ice formation will similarly affect the S of HSSW but will have a minor impact on $\delta^{18}O$ of HSSW (Kim and Timmermann, 2024; Zhang et al., 2024). Consequently, HSSW freshening will continue. Long-term observations of $\delta^{18}O$ in the changing Ross Sea are required to investigate the influences of GMW discharge in the Amundsen and Ross Seas on HSSW freshening.

Although precipitation is not considered a factor in the decline of $\delta^{18}O$ in HSSW, climate change-induced increases in precipitation and more intense precipitation events will decrease the $\delta^{18}O$ of precipitation (Weisser et al., 2024), potentially lowering the $\delta^{18}O$ of HSSW in the Ross Sea. Conversely, a latitudinal effect will result in more positive $\delta^{18}O$ values for precipitation at higher latitudes due to the poleward shift of precipitation. Therefore, the impact of precipitation on HSSW $\delta^{18}O$ remains uncertain in the context of global warming.

The Ross Sea shelf contributes 20%−40% of the AABW in the global ocean (Meredith, 2013; Oris et al., 2002). The precursor of AABW, MSW, is formed by the mixing of HSSW and mCDW in the Ross Sea (Orsi & Wiederwohl, 2009). Previous studies have observed that AABW is becoming fresher and less dense, attributing this continuous freshening to the increasing melt of Antarctic coastal ice shelves (Menezes et al., 2017; Rintoul, 2007; Williams et al., 2016; Xie et al., 2025). With persistent and increasing freshwater inputs from the upstream Amundsen Sea and local ice shelves, mCDW and HSSW in the Ross Sea tend to become fresher, thereby contributing to the further freshening of AABW.

5. Conclusions

The persistent freshening in the Ross Sea since the 1960s is closely linked to the rapid mass loss of West Antarctica Ice Sheet. Freshwater discharged by the Amundsen Sea coastal ice shelves is entrained by the ASC and flows westward to the Ross Sea. In this study, we utilized oxygen isotopes in seawater to trace the transport path of the ASC. The $\delta^{18}O$ values in the WW of ASC were consistent with those in the ASP during the same year, indicating that the origin of ASC WW is the Amundsen Sea shelf. The linear relationship between S and $\delta^{18}O$ suggests that the WW of ASC mixed with upwelled UCDW to form mCDW on the Ross Sea shelf. During the austral winter, when sea ice production in the TNB polynya was significant, HSSW was formed from upwelled mCDW at the surface and modified by mixing with glacial meltwater in the TNB. The variability in $\delta^{18}O$ of HSSW aligns with S, suggesting continuous freshening on the Ross Sea shelf over the past approximately 40 years. As a reliable and sensitive tracer for freshwater inputs, monitoring $\delta^{18}O$ variations in the Ross Sea can provide insights into the region's responses to global warming.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study..

Data Availability Statement

Data representation was performed using Ocean Data View (Schlitzer, R., Ocean Data View, http://odv.awi.de) and matplotlib with python (https://matplotlib.org/). All relevant data in this article are available in Chen (2025).

Acknowledgments

The authors express their gratitude to the captains and crews of the R/V *Xuelong* for their assistance with sampling. We also thank the three anonymous reviewers for their constructive comments, which significantly improved the manuscript. We also acknowledge the Hybrid Coordinate Model (HYCOM) (https://www.hycom.org/) for providing water current. This work was funded by the Polar Research Institute of China (Grants IRASCC 02-01-01 and IRASCC 01-01-02C).

References

Amblas, D., & Dowdeswell, J. A. (2018). Physiographic influences on dense shelf-water cascading down the Antarctic continental slope. *Earth-Science Reviews*, *185*, 887–900. https://doi.org/10.1016/j.earscirev.2018.07.014

Arrigo, K. R., Lowry, K. E., & van Dijken, G. L. (2012). Annual changes in sea ice and phytoplankton in polynyas of the Amundsen Sea Antarctica. *Deep-Sea Research Part II Topical Studies in Oceanography*, *71*, 5–15.

Biddle, L. C., Loose, B., & Heywood, K. J. (2019). Upper ocean distribution of glacial meltwater in the Amundsen Sea Antarctica. *Journal of Geophysical Research: Oceans*, *124*(10), 6854–6870. https://doi.org/10.1029/2019jc015133

Budillon, G., Castagno, P., Aliani, S., Spezie, G., & Padman, L. (2011). Thermohaline variability and Antarctic bottom water formation at the Ross Sea shelf break. *Deep-Sea Research Part I Oceanographic Research Papers*, *58*(10), 1002–1018. https://doi.org/10.1016/j.dsr.2011.07.002

Castagno, P., Capozzi, V., DiTullio, G. R., Falco, P., Fusco, G., Rintoul, S. R., & Budillon, G. (2019). Rebound of shelf water salinity in the Ross Sea. *Nature Communications*, *10*(1), 5441. https://doi.org/10.1038/s41467-019-13083-8

Chen, G. (2025). Oxygen isotope insights into the impact of Amundsen Sea freshwater on Ross Sea Shelf Water freshening [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.15745747

Chen, G., Jiang, Y., Wang, Y., Zhao, J., Qiu, Y., Zheng, M., et al. (2024). Changes in glacial meltwater system around Amundsen Sea Polynya illustrated by radium and oxygen isotopes. *Progress in Oceanography*, *229*, 103367. https://doi.org/10.1016/j.pocean.2024.103367

Craig, H., & Hom, B. (1968). Relationships of deuterium, oxygen-18, and chlorinity in the formation of sea ice. *Transactions - American Geophysical Union*, *49*, 216–217.

Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, T. M., Ligtenberg, S. R. M., van den Broeke, M. R., & Moholdt, G. (2013). Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature*, *502*(7469), 89–92. https://doi.org/10.1038/nature12567

Dini, M., & Stenni, B. (2000). Oxygen isotope characterization of Terra Nova Bay seawater. In F. M. Faranda, L. Guglielmo, & A. Ianora (Eds.), *Ross Sea ecology*. Springer.

Dutrieux, P., De Rydt, J., Jenkins, A., Holland, P. R., Ha, H. K., Lee, S. H., et al. (2014). Strong sensitivity of Pine Island ice-shelf melting to climatic variability. *Science*, *343*(6167), 174–178. https://doi.org/10.1126/science.1244341

Feistel, R. (2008). A Gibbs function for seawater thermodynamics for −6 to 80°C and salinity up to 120 g kg^{-1}. *Deep-Sea Research Part I: Oceanographic Research Papers*, *55*(12), 1639–1671. https://doi.org/10.1016/j.dsr.2008.07.004

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., et al. (2013). Bedmap2: Improved ice bed surface and thickness datasets for Antarctica. *The Cryosphere*, *7*(1), 375–393. https://doi.org/10.5194/tc-7-375-2013

Guo, G., Gao, L., & Shi, J. (2021). Modulation of dense shelf water salinity variability in the western Ross Sea associated with the Amundsen Sea Low. *Environmental Research Letters*, *16*(1), 014004. https://doi.org/10.1088/1748-9326/abc995

Guo, G., Shi, J., Gao, L., Tamura, T., & Williams, G. D. (2019). Reduced sea ice production due to upwelled oceanic heat flux in Prydz Bay East Antarctica. *Geophysical Research Letters*, *46*(9), 4782–4789. https://doi.org/10.1029/2018gl081463

Helly, J. J., Vernet, M., Murray, A. E., & Stephenson, G. R., Jr. (2015). Characteristics of the meltwater field from a large Antarctic iceberg using $\delta^{18}O$. *Journal of Geophysical Research: Oceans*, *120*(3), 2259–2269. https://doi.org/10.1002/2015jc010772

Hennig, A. N., Mucciarone, D. A., Jacobs, S. S., Mortlock, R. A., & Dunbar, R. B. (2024). Meteoric water and glacial melt in the southeastern Amundsen Sea: A time series from 1994 to 2020. *The Cryosphere*, *18*(2), 791–818. https://doi.org/10.5194/tc-18-791-2024

Hutchings, J. A., & Konecky, B. L. (2022). Optimization of the Picarro L2140-i cavity ring down spectrometer for routine measurement of triple oxygen isotope ratios in meteoric waters. *Atmospheric Measurement Techniques Discussions*, *16*, 1663–1682.

Jacobs, S. S., Amos, A. F., & Bruchhausen, P. M. (1970). Ross Sea oceanography and Antarctic bottom water formation. *Deep-Sea Research*, *17*(6), 935–962. https://doi.org/10.1016/0011-7471(70)90046-x

Jacobs, S. S., Fairbanks, R. G., & Horibe, Y. (1985). Origin and evolution of water masses near the Antarctic continental margin: Evidence from $H_2^{18}O/H_2^{16}O$ ratios in seawater. In S. S. Jacobs (Ed.), *Antarctic Research Series (Oceanology of the Antarctic Continental Shelf)* (p. 43). American Geophysical Union.

Jacobs, S. S., & Giulivi, C. F. (2010). Large multidecadal salinity trends near the Pacific–Antarctic continental margin. *Journal of Climate*, *23*(17), 4508–4524. https://doi.org/10.1175/2010jcli3284.1

Jacobs, S. S., Giulivi, C. F., & Dutrieux, P. (2022). Persistent Ross Sea freshening from imbalance West Antarctic ice shelf melting. *Journal of Geophysical Research: Oceans*, *127*(3), e2021JC017808. https://doi.org/10.1029/2021jc017808

Jacobs, S. S., Giulivi, C. F., & Mele, P. A. (2002). Freshening of the Ross Sea during the late 20th century. *Science*, *297*(5580), 386–389. https://doi.org/10.1126/science.1069574

Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T. W., Lee, S. H., et al. (2018). West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. *Nature Geoscience*, *11*(10), 733–738. https://doi.org/10.1038/s41561-018-0207-4

Jia, R., Chen, M., Pan, H., Zeng, J., Zhu, J., Liu, X., et al. (2022). Freshwater components track the export of dense shelf water from Prydz Bay Antarctica. *Deep-Sea Research Part II Topical Studies in Oceanography*, *196*, 105023. https://doi.org/10.1016/j.dsr2.2022.105023

Kim, H., & Timmermann, A. (2024). Seawater oxygen isotopes as a tool for monitoring future meltwater from the Antarctic ice-sheet. *Communications Earth & Environment*, *5*(1), 343. https://doi.org/10.1038/s43247-024-01514-4

Kim, T., Hong, J.-S., Jin, E. K., Moon, J.-H., Song, S.-K., & Lee, W. S. (2023). Spatiotemporal variability in ocean-driven basal melting of cold-water cavity ice shelf in Terra Nova Bay, East Antarctica: Roles of tide and cavity geometry. *Frontiers in Marine Science*, *10*, 1249562. https://doi.org/10.3389/fmars.2023.1249562

Kohut, J., Hunter, E., & Huber, B. (2013). Small-scale variability of the cross-shelf flow over the outer shelf of the Ross Sea. *Journal of Geophysical Research: Oceans*, *118*(4), 1863–1876. https://doi.org/10.1002/jgrc.20090

Li, Q., Chen, M., Jia, R., Zeng, J., Lin, H., Zheng, M., & Qiu, Y. (2017). Transit time of river water in the Bering and Chukchi Seas estimated from δ^{18}O and radium isotopes. *Progress in Oceanography*, *159*, 115–129. https://doi.org/10.1016/j.pocean.2017.08.004

Liu, Y., Moore, J. C., Cheng, X., Gladstone, R. M., Bassis, J. N., Liu, H., et al. (2015). Ocean-driven thinning enhances iceberg calving and retreat of Antarctic Ice Shelves. *Proceedings of the National Academy of the United States of America*, *112*(11), 3263–3268. https://doi.org/10.1073/pnas.1415137112

Melling, H., & Moore, R. M. (1995). Modification of halocline source waters during freezing on the Beaufort Sea shelf: Evidence from oxygen isotopes and dissolved nutrients. *Continental Shelf Research*, *15*(1), 89–113. https://doi.org/10.1016/0278-4343(94)p1814-r

Menezes, V. V., Macdonald, A. M., & Schatzman, C. (2017). Accelerated freshening of Antarctic Bottom Water over the last decade in the Southern Indian Ocean. *Science Advances*, *3*(1), e1601426. https://doi.org/10.1126/sciadv.1601426

Meredith, M. P. (2013). Replenishing the abyss. *Nature Geoscience*, *6*(3), 166–167. https://doi.org/10.1038/ngeo1743

Meredith, M. P., Wallace, M. I., Stammerjohn, S. E., Renfrew, I. A., Clarke, A., Venables, H., et al. (2010). Changes in the freshwater composition of the upper ocean west of the Antarctic Peninsula during the first decade of the 21st century. *Progress in Oceanography*, *87*(1–4), 127–143. https://doi.org/10.1016/j.pocean.2010.09.019

Nakayama, Y., Greene, C. A., Paolo, F. S., Mensah, V., Zhang, H., Kashiwase, H., et al. (2021). Antarctic slope current modulates ocean heat intrusions towards Totten Glacier. *Geophysical Research Letters*, *48*(17), e2021GL094149. https://doi.org/10.1029/2021gl094149

Nakayama, Y., Menemenlis, D., Zhang, H., Schodlok, M., & Rignot, E. (2018). Origin of Circumpolar Deep Water intruding onto the Amundsen and Bellingshausen Sea continental shelves. *Nature Communications*, *9*(1), 3403. https://doi.org/10.1038/s41467-018-05813-1

Nakayama, Y., Timmermann, R., & Hellmer, H. (2020). Impact of West Antarctic ice shelf melting on Southern Ocean hydrography. *The Cryosphere*, *14*(7), 2205–2216. https://doi.org/10.5194/tc-14-2205-2020

Orsi, A. H., Johnson, G. C., & Bullister, J. L. (1999). Circulation mixing and production of Antarctic Bottom Water. *Progress in Oceanography*, *43*(1), 55–109. https://doi.org/10.1016/s0079-6611(99)00004-x

Orsi, A. H., Smethie Jr, W. M., & Bullister, J. L. (2002). On the total input of Antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements. *Journal of Geophysical Research*, *107*(C8), 3122. https://doi.org/10.1029/2001JC000976

Orsi, A. H., & Wiederwohl, C. L. (2009). A recount of Ross Sea waters. *Deep-Sea Research Part II Topical Studies in Oceanography*, *56*(13–14), 778–795. https://doi.org/10.1016/j.dsr2.2008.10.033

Pritchard, H., Ligtenberg, S. R., Fricker, H. A., Vaughan, D. G., van den Broeke, M. R., & Padman, L. (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature*, *484*(7395), 502–505. https://doi.org/10.1038/nature10968

Purich, A., & Doddridge, E. W. (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. *Communications Earth & Environment*, *4*(1), 314. https://doi.org/10.1038/s43247-023-00961-9

Qi, Q., Hao, Q., Yang, G., Cao, S., Kang, J., Hu, J., et al. (2025). Diverse impacts of sea ice and ice shelf melting on phytoplankton communities in the Cosmonaut Sea East Antarctica. *Environmental Research Letters*, *20*(1), 014003. https://doi.org/10.1088/1748-9326/ad975e

Randall-Goodwin, E., Meredith, M. P., Jenkins, A., Yager, P. L., Sherrell, R. M., Abrahamsen, E. P., et al. (2015). Freshwater distributions and water mass structure in the Amundsen Sea Polynya region Antarctica. *Elementa*, *3*, 000065. https://doi.org/10.12952/journal.elementa.000065

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013). Ice-shelf melting around Antarctica. *Science*, *341*(6143), 266–270. https://doi.org/10.1126/science.1235798

Rintoul, S. R. (2007). Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans. *Geophysical Research Letters*, *34*(6), GL028550. https://doi.org/10.1029/2006gl028550

Schmidt, C., Morrison, A. K., & England, M. H. (2023). Wind–and sea-ice–driven interannual variability of Antarctic Bottom water formation. *Journal of Geophysical Research: Oceans*, *128*(6), e2023JC019774. https://doi.org/10.1029/2023jc019774

Sherrell, R. M., Lagerström, M. E., Forsch, K. O., Stammerjohn, S. E., & Yager, P. L. (2015). Dynamics of dissolved iron and other bioactive trace metals (Mn Ni Cu Zn) in the Amundsen Sea Polynya Antarctica. *Elementa*, *3*, 000071.

Smith Jr, W. O., Dinniman, M. S., Hofmann, E. E., & Klinck, J. M. (2014). The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. *Geophysical Research Letters*, *41*(5), 1624–1631. https://doi.org/10.1002/2014gl059311

Talley, L. D., Pickard, G. L., Emery, W. J., & Swift, J. H. (2011). *Descriptive physical oceanography: An introduction*. Academic Press.

The IMBIE Team. (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, *558*(7709), 219–222. https://doi.org/10.1038/s41586-018-0179-y

Thompson, A. F., Stewart, A. L., Spence, P., & Heywood, K. J. (2018). The Antarctic slope current in a changing climate. *Reviews of Geophysics*, *56*(4), 741–770. https://doi.org/10.1029/2018rg000624

Weiss, R. F., Östlund, H. G., & Craig, H. (1979). Geochemical studies of the Weddell Sea. *Deep-Sea Research Part A Oceanographic Research Papers*, *26*(10), 1093–1120. https://doi.org/10.1016/0198-0149(79)90059-1

Weisser, O., De Vleeschouwer, D., & Strauss, H. (2024). The influence of climate change on the δ^{18}O and δ^{2}H signatures of meteoric waters in Europe and North America. *Modeling Earth Systems and Environment*, *10*(6), 6917–6930. https://doi.org/10.1007/s40808-024-02137-6

Williams, G. D., Herraiz-Borreguero, L., Roquet, F., Tamura, T., Ohshima, K. I., Fukamachi, Y., et al. (2016). The suppression of Antarctic bottom water formation by melting ice shelves in Prydz Bay. *Nature Communications*, *7*(1), 12577. https://doi.org/10.1038/ncomms12577

Xie, C., Zhang, Z., Chen, Y., & Wang, C. (2025). Substantial contraction of dense Shelf water in the Ross Sea under future climate scenarios. *Geophysical Research Letters*, *52*(6), e2024GL112581. https://doi.org/10.1029/2024gl112581

Yoon, S. T., Lee, W. S., Stevens, C., Jendersie, S., Nam, S., Yun, S., et al. (2020). Variability in high-salinity shelf water production in the Terra Nova Bay polynya Antarctica. *Ocean Science*, *16*(2), 373–388. https://doi.org/10.5194/os-16-373-2020

Zhang, Z., Xie, C., Castagno, P., England, M. H., Wang, X., Dinniman, M. S., et al. (2024). Evidence for large-scale climate forcing of dense shelf water variability in the Ross Sea. *Nature Communications*, *15*(1), 8190. https://doi.org/10.1038/s41467-024-52524-x