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# Observing Antarctic Bottom Water in the Southern Ocean

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Dense, cold waters formed on Antarctic continental shelves descend along the Antarctic continental margin, where they mix with other Southern Ocean waters to form Antarctic Bottom Water (AABW). AABW then spreads into the deepest parts of all major ocean basins, isolating heat and carbon from the atmosphere for centuries. Despite AABW's key role in regulating Earth's climate on long time scales and in recording Southern Ocean conditions, AABW remains poorly observed. This lack of observational data is mostly due to two factors. First, AABW originates on the Antarctic continental shelf and slope where *in situ* measurements are limited and ocean observations by satellites are hampered by persistent sea ice cover and long periods of darkness in winter. Second, north of the Antarctic continental slope, AABW is found below approximately 2 km depth, where *in situ* observations are also scarce and satellites cannot provide direct measurements. Here, we review progress made during the past decades in observing AABW. We describe 1) long-term monitoring obtained by moorings, by ship-based surveys, and beneath ice shelves through bore holes; 2) the recent development of autonomous observing tools in coastal Antarctic and deep ocean systems; and 3) alternative approaches including data assimilation models and satellite-derived proxies. The variety of approaches is beginning to transform our understanding of AABW, including its formation processes, temporal variability, and contribution to the lower limb of the global ocean meridional overturning circulation. In particular, these observations highlight the key role played by winds, sea ice, and the Antarctic Ice Sheet in AABW-related processes. We conclude by discussing future avenues for observing and understanding AABW, impressing the need for a sustained and coordinated observing system.

KEYWORDS

**Antarctic Bottom Water (AABW), Southern Ocean, ice shelves, ocean warming, ocean freshening, Antarctic sea ice, observations**

# 1 Introduction

Antarctic Bottom Water (AABW) plays a primary role in the climate system, as it supplies the lower branch of the global Meridional (i.e., north–south) Overturning Circulation (MOC; Lumpkin and Speer, 2007; Talley, 2013). The process of AABW formation near the Antarctic coast and its northward spreading allows ventilation of most of the abyssal (>2 km depth) ocean (Johnson, 2008), supplying oxygen (Gordon, 2013) and storing heat and carbon at depth for centuries (de Lavergne et al., 2017; Holzer et al., 2021). Sinking AABW also carries nutrients that have not been utilized by marine organisms due to local light and iron limitation and thereby affects global primary production and the efficiency of the biological carbon pump (Marinov et al., 2006). Changes in AABW formation and circulation are thus thought to influence atmospheric carbon dioxide, and consequently Earth's climate, on centennial to millennial time scales (Sigman and Boyle, 2000; Ferrari et al., 2014; Marzocchi and Jansen, 2019).

AABW originates on the Antarctic continental shelf (Figure 1), where extremely cold and salty waters are produced. Seawater that is near the surface freezing point and has absolute salinities higher than 34.6 g/kg is known as high-salinity shelf water (HSSW) and is produced on the shelf as a result of surface heat loss and salt input through brine rejection when sea ice forms. Sea ice formation is enhanced near the Antarctic coast, especially in ice-free coastal polynyas where sea ice is continuously formed and advected away by katabatic winds (see Figure 2B for locations of the main Antarctic coastal polynyas). In some locations (e.g., Ross and Weddell Seas, Prydz Bay), HSSW is further cooled by ice–ocean interaction at the base of ice shelves, producing supercooled water colder than the surface freezing point, known as Ice Shelf Water (ISW) that is typically below −2°C. Once formed, a fraction of

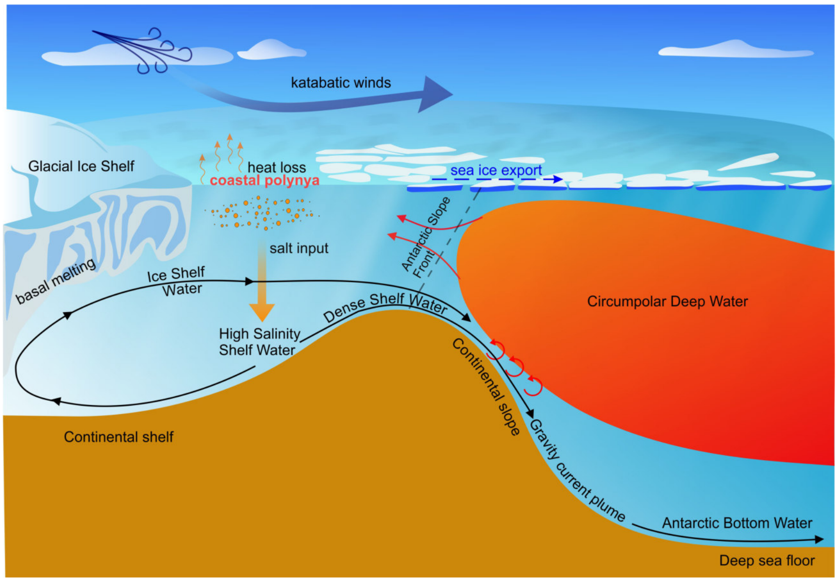


FIGURE 1
Schematic diagram summarizing Antarctic Bottom Water (AABW) formation. AABW originates on the Antarctic continental shelf where intense surface cooling and salt input occur during sea ice formation. Enhanced sea ice formation in coastal polynyas allows high-salinity shelf water (HSSW) formation. In some regions, HSSW interacts with the ice shelf base to produce supercooled (below the surface freezing point) Ice Shelf Water (ISW). These cold shelf waters are often referred to as Dense Shelf Water (DSW), as they are dense enough to descend down the continental slope as a gravity plume. Entrainment with Southern Ocean waters during their descent produces AABW.

HSSW/ISW escapes the continental shelf and cascades into the abyssal Southern Ocean. Dense waters produced on the continental shelf (HSSW and ISW) are usually referred altogether to as Dense Shelf Water (DSW). While sinking as a gravity plume down the continental slope, DSW mixes with other Southern Ocean waters, mostly with warmer (approximately 1°C to 2°C) Circumpolar Deep Water (CDW) and fresher (absolute salinity<34.6 g/kg) Antarctic Surface Water (Orsi et al., 1999; Akhoudas et al., 2021). This mixing process produces AABW, which is water that is colder than 0°C with neutral densities (Jackett and McDougall, 1997) greater than 28.27 kg/m$^3$ (Figure 1). AABW properties and formation rates can also be influenced by offshore polynyas, as the one observed in the 1970s in the Weddell Sea causing convection up to 3,000 m depth (Gordon, 1978). However, such offshore vigorous deep convective events have not been observed since the 1970s, indicating that the present-day main source region of AABW is the Antarctic continental shelf (see Figures 2B, 3).

AABW forms in localized areas around the Antarctic continent (see Figures 2B, 3). After sinking into the deep ocean, AABW flows along isobaths on the lower continental slope until its flow is diverted northward along deep western boundary currents (Stommel, 1958; see Figure 3). AABW's unique cold and fresh signature is steered topographically through the Southern Ocean and can be found over much of the global ocean abyss. Within the Antarctic Circumpolar Current (ACC), distinct varieties of AABW are homogenized before moving north, with more recent modeling work suggesting the Weddell and Cape Darnley regions primarily feed the Atlantic basin, while the Ross and Adélie regions feed the Indian and Pacific basins (Solodoch et al., 2022). North of the ACC, AABW is seen moving north in all ocean basins along deep western boundary currents and recirculating into the interior of these basins (Reid, 1989; Reid, 1994; Reid, 1997; Purkey et al., 2018). Along its northward pathway, AABW encounters sills and narrow passages, and its properties are further modified by mixing (Bryden and Nurser, 2003). This mixing causes AABW to become more buoyant (Figure 3A) and warmer (Figure 3B) as it spreads northward.

AABW has been historically challenging to monitor. The remote location of Antarctica and its harsh weather conditions imply long, expensive, often risky, and logistically demanding expeditions to collect *in situ* measurements. Oceanographic campaigns are further hampered by sea ice cover over the polar Southern Ocean (south of approximately 60°S) during austral winter and in many Antarctic coastal regions during austral summer (see Figure 2A). Sea ice cover also limits the ability of satellites to measure ocean surface properties. Similar and further limitations apply north of the seasonal sea ice zone, where AABW is found below ~2 km depth. At these depths, ocean properties can be neither directly measured by satellites nor reached by regular Argo floats (Riser et al., 2016). Observation of AABW thus has mostly relied on *in situ* measurements requiring time-consuming and expensive oceanographic expeditions.

Here, we review progress made during the past decades in measuring AABW, from its formation around Antarctica to its northward transport through the Southern Ocean. In Section 2, we describe observations in the open ocean through ship-based surveys, through moorings, and within the ice shelf cavities through bore holes. Section 3 introduces new tools developed in recent years, while Section 4 illustrates indirect approaches that can be used to monitor AABW. In each section, we outline important

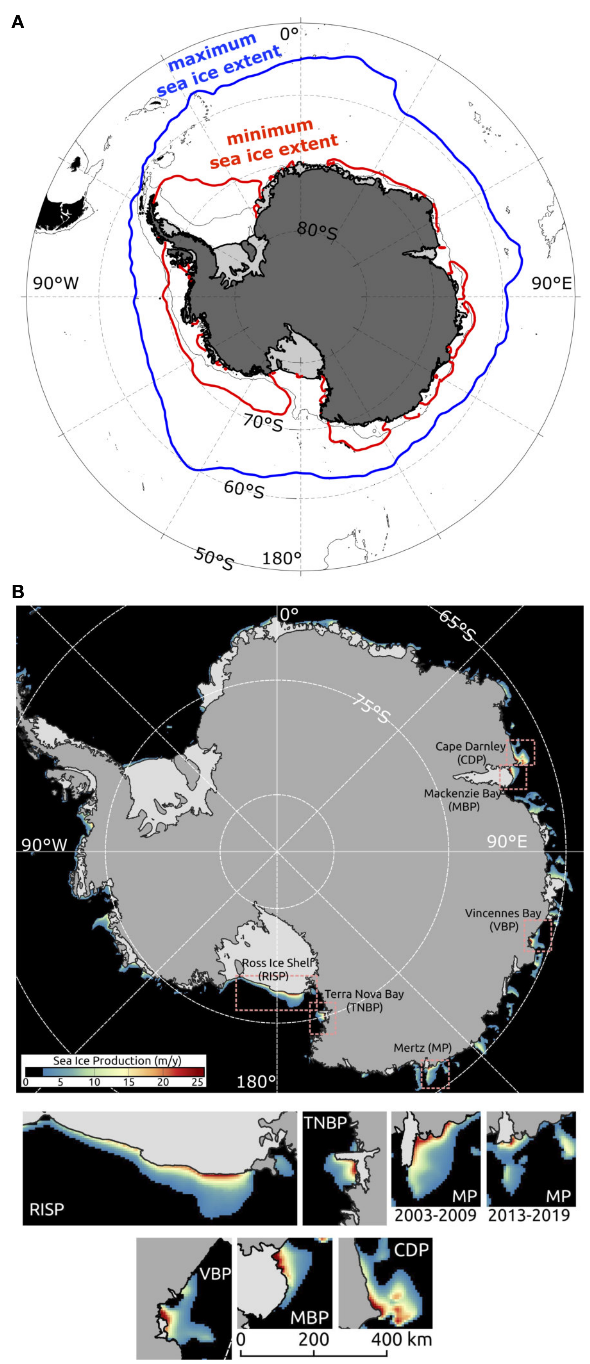


FIGURE 2
Maps showing Antarctic sea ice coverage and production. **(A)** Map of summer minimum (February, red line) and winter maximum (September, blue line) Antarctic sea ice extent (defined by the 15% sea ice concentration threshold from the 1978–2018 climatological sea ice values; Meier et al., 2017). **(B)** Map of annual sea ice production (m/year) during the freezing period (March–October) averaged over the period 2003–2019, updated by Nakata et al. (2021). The lower panels are close-up maps for the polynyas (red dashed rectangles in the main panel) that can create Antarctic Bottom Water (AABW) dense precursors.

scientific discoveries associated with the different tools. Section 5 delineates knowledge gaps in understanding AABW and the observational needs required to address them. Section 6 provides concluding remarks.

# 2 Multidecadal *in situ* observations

## 2.1 Ship-based hydrography

This section describes hydrographic (i.e., temperature and salinity) measurements of shelf and abyssal waters collected by ships in the Southern Ocean. We begin with early expeditions from the 18th century that spanned almost three centuries of ocean explorations. We then focus on more recent observations from the second half of the 20th century to the present, which have collected measurements on the continental shelf and in the deep Southern Ocean (i.e., equatorward of the continental shelf break).

### 2.1.1 Early measurements

While ocean surface currents have been known since the days when sailing ships formed the basis of trade (more than 1,000 years ago) and refined during the 15th to 17th centuries of exploration, little was known about the ocean properties or circulation below the surface. From the 18th century, this started to change (Wüst, 1964; Wüst, 1968; Warren, 1981). In 1750, Captain Henri Ellis, aboard the *Earl of Halifax*, found that there were indications of cold water below the subtropical Atlantic sea surface. By extrapolation to the sea floor, J. Otto in 1800 and A. von Humboldt in 1814 speculated that near the deep seafloor, the temperature would be approximately 0°C and of polar origin. Wüst (1968) reported that this was partially verified in 1837 with an observation of 1.7°C water at 3,741 m depth in the tropical Pacific made by the French frigate *Venus*. During the same period, in 1800, Count Rumford proposed a meridional circulation of the ocean whereby water sinks near the poles and rises near the equator, a view shared later by E. von Lenz in 1845.

Systematic study of the ocean below the surface began with the *Challenger* expedition (1873 to 1876; Thompson and Murray, 1895), which is considered the start of the "Era of Exploration" (1873 to 1914). The *Challenger* expedition, with widely spaced stations in each ocean basin, produced the first large-scale coherent picture of the water masses in the deep ocean. Other expeditions during this exploration era coarsely revealed the spatial pattern of ocean circulation within its deep and abyssal parts.

The hemispheric abyssal circulation pattern (sinking at the poles and upwelling at the equator) of von Lenz in the 19th century was still in vogue 50 years later in 1902. At this time, G. Schott published a diagram of the oceanic meridional circulation of the Atlantic Ocean based on the *Valdivia* Expedition (1898 to 1899), including cross-equator flow from south to north below 2,000 m (Richardson, 2008; Figure 4A). In the 1920s, a more complete view of the meridional exchange emerged. Analyses by Brennecke (1921); Merz and Wüst (1922), and Merz (1925) revealed the asymmetry of the North and South Atlantic Oceans.

In 1925, an "Era of National Systematic and Dynamic Ocean Surveys" began and lasted until 1940 (Wüst, 1964). This era was initiated with a new and detailed view of the South Atlantic stratification from the German Atlantic Expedition on the Research Vessel *Meteor* in the period 1925 to 1927. This expedition collected sections of closely spaced hydrographic

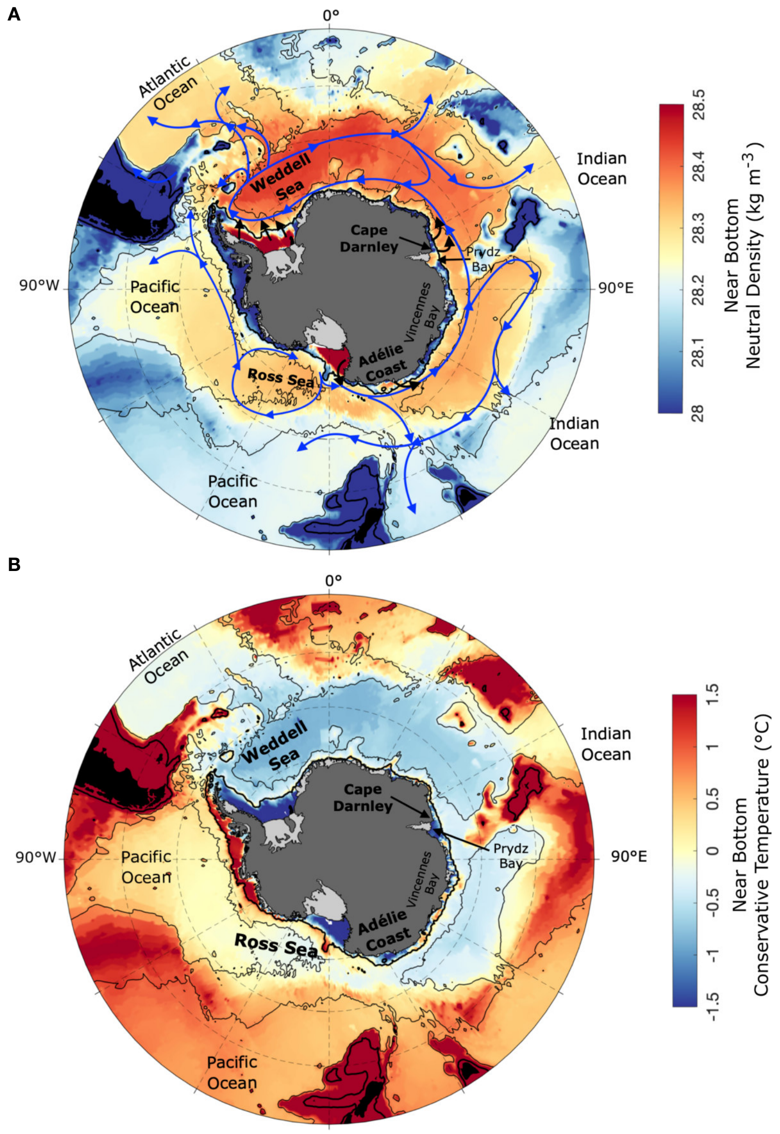


FIGURE 3
Maps of Antarctic Bottom Water (AABW) properties and spreading in the Southern Ocean. Climatological near bottom **(A)** neutral density (kg/m$^3$) and **(B)** conservative temperature (°C) derived from the World Ocean Experiment (WOCE; Gouretski and Koltermann, 2004). AABW formation regions are highlighted in **(A)** by black arrows, while blue arrows show the main pathways of AABW through the Southern Ocean (from Orsi et al., 1999; Talley, 2013; Van Sebille et al., 2013; Purkey et al., 2018; Solodoch et al., 2022). AABW and its precursor DSW are characterized by dense (red in panel **A**) and cold (blue in panel **B**) water properties near the seafloor. The 1,000-m isobath is in thick black and roughly delimits the continental shelf, while the 4,000-m isobath is in thin black (Gouretski and Koltermann, 2004). The Antarctic coastline is from BedMachine (Morlighem et al., 2020).

stations across the Atlantic Ocean between 20°N and 65°S, with subsurface observations reaching the deep seafloor up to 6 km deep. Based on the *Meteor* expedition and other hydrographic data, Wüst (1935) produced schematics of the spreading of the sub-thermocline circulation of the Atlantic Ocean between 60°S and 60°N, including AABW (Figure 4B), which remain qualitatively similar to modern schematics of the deep Atlantic circulation (Talley, 2013).

Circum-Antarctic surveys in the 1920s and 1930s conducted under the auspices of the *Discovery* investigations (Deacon, 1937) and 1960s and 1970s by the *Eltanin* (Gordon, 2012) provided new details of the formation sites of AABW along the continental margins of Antarctica and its spreading across the ACC into the major ocean basins. Combining observations from these expeditions and others around the world ocean, Lynn and Reid (1968) provided a global overview of the characteristics of abyssal waters.

The International Geophysical Year (1957 to 1959) marked the beginning of a new era of observational ocean research, providing a transition from a more-or-less independent national research work of one ship to systematic multi-ship, multi-national surveys. A notable example is the World Ocean Circulation Experiment (WOCE) surveys that covered the global ocean during the 1990s, producing an atlas series that included detailed views of the bottom

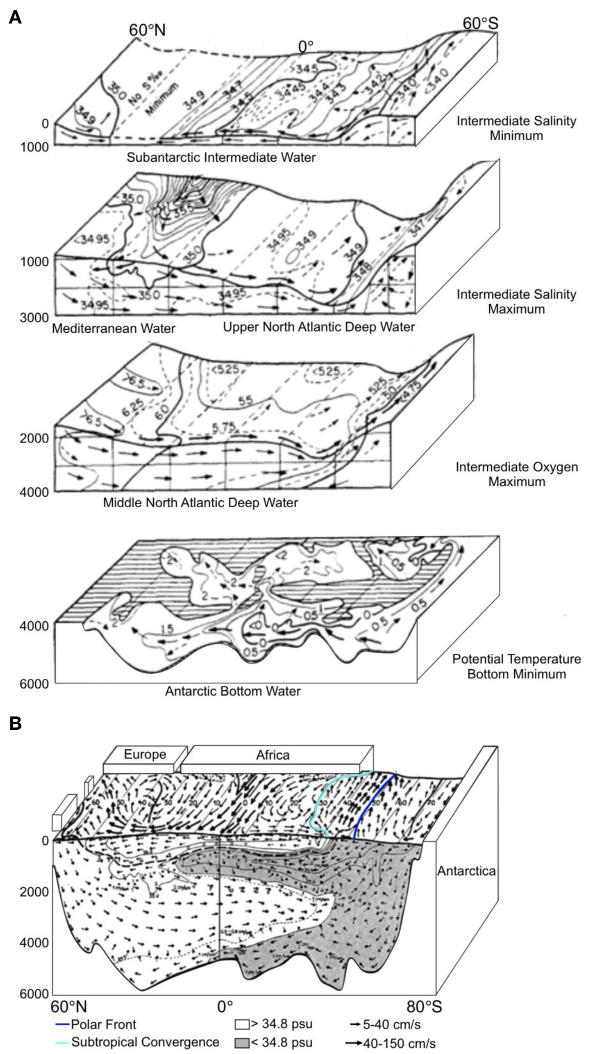


FIGURE 4
Schematic diagrams showing meridional spreading of water mass in the Atlantic Ocean. **(A)** Spreading of main water masses of the Atlantic Ocean in four core layers adapted from Wüst, 1964. **(B)** Surface currents, salinity contours, and the meridional circulation along a section in the western Atlantic by Wüst (1935); Wüst (1949). Small numbers are geostrophic speeds in cm/s. Dashed line is the 9° C boundary between warm and cold layers. Polar Front and Subtropical Convergence are depicted as blue and cyan lines, respectively. Adapted from Richardson (2008).

water characteristics and the extent of interocean exchange (Orsi and Whitworth, 2005).

As described below, with the expansion of observations from ships, moorings, Argo floats, and new platforms along with geochemical tracers, we now have a much more refined view of the spatio-temporal variability of AABW along with estimates of ventilation times associated with its spread across the global ocean. Wüst (1964) said of ocean research: "As in all sciences, progress is not continuous. Most of the ideas, instruments and methods influencing research work in the laboratories are conceived in the preparation and in the accomplishment of great expeditions. At the same time new theoretical concepts are also formed." So it is today, as we can now view in increasing detail, the cold waters near the seafloor that emanate from Antarctica.

### 2.1.2 Antarctic continental shelf

Here, we focus on the four main continental shelf regions around Antarctica where AABW originates (Weddell Sea, Ross Sea, Adélie Coast, and Prydz Bay/Cape Darnley).

#### 2.1.2.1 Weddell Sea

Ship-based hydrographic observations in the southern and western Weddell Sea are hampered year-round due to a vast sea ice cover (Figure 2A). Thus, observations are austral summer-biased and limited (with a few exceptions) to areas around the Filchner Trough, near the tip of the Antarctic Peninsula, and to coastal polynyas formed by offshore winds across the ice shelf fronts. The first systematic observations were collected in the 1970s during Norwegian expeditions (Foldvik et al., 1985a) and continued in the following decades, including multiple hydrographic surveys on the southern continental shelf by German-led expeditions onboard the RVIB *Polarstern* (Janout et al., 2021). The multiple conductivity–temperature–depth (CTD) surveys provide information about the variability, pathways, and modifications of the shelf water masses (HSSW, ISW, and modified Circumpolar Deep Water (mCDW), with the latter resulting from the mixing of CDW with cooler and fresher waters near the coast) all contributing to the AABW formation (see Nicholls et al., 2009, for a comprehensive review). ISW forms beneath the Filchner-Ronne Ice Shelf and is transported toward the continental slope in the Filchner Trough on the south-eastern continental shelf. Multidecadal observations have shown that while ISW exhibits considerable variability in temperature and salinity (depending on the ice shelf cavity circulation), its density has remained stable over the past five decades (Figure 5E).

On the western Weddell Sea shelf (i.e., north of the Ronne Ice Shelf), heavy sea ice conditions and icebergs (Rackow et al., 2017) have precluded systematic surveys. Measurements from opportunistic surveys during favorable sea ice conditions or from drift experiments such as Ice Station Weddell-1 (ISW-1; Gordon and Ice Station Weddell Group of Principal Investigators and Chief Scientists, 1993) and Ice Station POLarstern (ISPOL; Hellmer et al., 2008; Huhn et al., 2008) provide evidence of HSSW near the shelf break, confirming the western Weddell Sea as a source of AABW.

#### 2.1.2.2 Ross Sea

HSSW in the Ross Sea is mainly produced in two coastal polynyas in the western sector of the continental shelf: the Terra Nova Bay and Ross Ice Shelf Polynyas. Summer hydrographic measurements of these water masses started in 1957 (Jacobs et al., 2022) and were conducted in most subsequent years near Ross Island during expeditions by the United States, New Zealand, and South Korea (see Figure 5E). Key locations of repeated measurements are Terra Nova Bay, Hayes Bank, and Bay of Whales (Jacobs et al., 2022). In Terra Nova Bay, oceanographic observations began in 1978 with the United States icebreaker USCGC *Burton Island* (Jacobs et al., 2022) and since 1994 have been continued almost yearly by the Italian Antarctic Program (Castagno et al., 2019; Silvano et al., 2020). Systematic observations have been carried out by the South Korean Antarctic Program since 2014 as well, in both the Ross (Yoon et al., 2020) and Amundsen

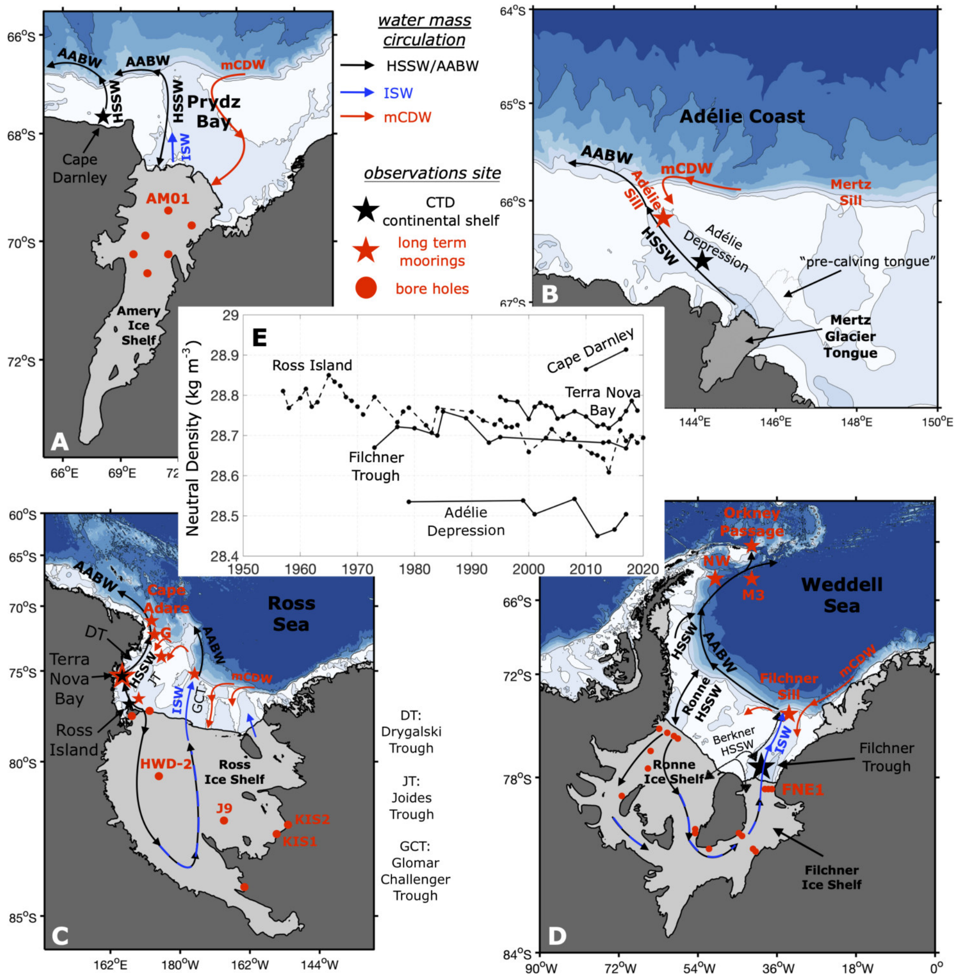

FIGURE 5
Maps showing circulation in **(A)** Prydz Bay, **(B)** Adélie Coast, **(C)** Ross Sea, and **(D)** Weddell Sea **(D)**. Circulation of water masses and locations of oceanographic measurements are depicted by arrows, dots, and stars (according to the legend). **(E)** Time series of neutral density (kg/m$^3$) observed near the seafloor in the main areas of high-salinity shelf water (HSSW)/Ice Shelf Water (ISW) sourcing Antarctic Bottom Water (AABW). mCDW refers to modified Circumpolar Deep Water. From lighter to denser: Adélie Depression (location is indicated by the black star in panel **B**), Filchner Trough (black star in panel **D**), Terra Nova Bay/Ross Island (black stars in panel **C**), and Cape Darnley (black star in panel **A**).

Seas (Kim et al., 2021; Yang et al., 2022). These long time series have reported both statistically significant long-term decreasing trends for salinity and density (Jacobs and Giulivi, 2010; Jacobs et al., 2022) and interannual variability of these parameters with 5-year to 10-year fluctuations and a strong rebound after 2014 (Castagno et al., 2019; Silvano et al., 2020; Yoon et al., 2020; Figure 5E). Furthermore, ship-based hydrographic observations have provided significant insights into the processes involved in the production, pathways, and outflow of HSSW, ISW, and AABW (Bergamasco et al., 2002; Budillon et al., 2003; Gordon et al., 2004; Smethie and Jacobs, 2005; Whitworth and Orsi, 2006; Gordon et al., 2009; Orsi and Wiederwohl, 2009; Budillon et al., 2011; Rusciano et al., 2013; Gordon et al., 2015; Castagno et al., 2017). HSSW directly contributes to AABW formation, escaping the continental shelf primarily through the Drygalski Trough, while ISW formed beneath the Ross Ice Shelf contributes by being exported via the Glomar Challenger Trough.

### 2.1.2.3 Prydz Bay/Cape Darnley

AABW originates from the Cape Darnley Polynya, located to the northwest of Prydz Bay (Ohshima et al., 2013), and to a lesser extent from the McKenzie Bay Polynya within Prydz Bay (Williams et al., 2016). Compared to the Weddell and Ross Sea continental shelves, detailed hydrographic observations started relatively late around Prydz Bay. After the early cruises by the Soviet Union, Australian cruises in the 1980s established the general circulation pattern in Prydz Bay (Smith et al., 1984; Nunes Vaz and Lennon, 1996). Australian hydrographic projects further clarified the water mass structure (Herraiz-Borreguero et al., 2015; Herraiz-Borreguero et al., 2016). From the 2000s, Japanese, Chinese, Russian, and Indian voyages collected hydrographic observations in most years (e.g., Yabuki et al., 2006; Antipov and Klepikov, 2017; Liu et al., 2018). Off Cape Darnley, a series of hydrographic and mooring observations have been made intermittently since the 2010s by the Japanese Antarctic Research Expedition (Aoki et al., 2020a; Aoki et al., 2022).

No statistically significant long-term trends have been reported for temperature and salinity so far (Schmidtko et al., 2014), although trends and interannual/decadal variability may emerge as more data are collected and the time series are extended (Figure 5E).

#### 2.1.2.4 Adélie Land/George V Land

Oceanographic sampling along the Adélie Land and George V Land coasts completed by the USNS *Eltanin* in 1969 showed that a relatively fresh AABW variety was formed in the region and could be tracked offshore (Gordon and Tchernia, 1972). The continental shelf was rarely visited in following years, with the notable exception of the GLACIER79 voyage (Jacobs and Haines, 1982), until the World Ocean Circulation Experiment program began in the early 1990s. Rintoul (1998) brought together the new WOCE measurements and historical data to show that dense water exported from the Adélie Depression made a substantial contribution to the abyssal waters of the Australian Antarctic Basin. From the 1990s, French (e.g., Lacarra et al., 2011; Martin et al., 2017), American (e.g., Sambrotto et al., 2003), Japanese (e.g., Aoki et al., 2017), and Australian (e.g., Rintoul, 2007; Williams et al., 2010; Snow et al., 2018) expeditions completed comprehensive sampling of the Adélie continental shelf, including a rare mid-winter expedition to the Mertz Polynya (Williams and Bindoff, 2003). The multidecadal record has provided evidence of changes in HSSW properties over time (Aoki et al., 2005; Rintoul, 2007; Jacobs and Giulivi, 2010; Aoki et al., 2013), most notably a sharp reduction in salinity following calving of the Mertz Glacier Tongue (Shadwick et al., 2013; Lacarra et al., 2014; Aoki et al., 2017; Snow et al., 2018) (Figure 5E).

### 2.1.3 "Deep" Southern Ocean

In this section, we focus on *in situ* hydrographic observations collected in the polar Southern Ocean (south of approximately 60° S) and within/north of the ACC. These observations of AABW have begun to reveal how it has changed over recent decades.

#### 2.1.3.1 Polar Southern Ocean

Over the polar Southern Ocean, multidecadal changes have been observed in the Weddell Sea, Ross Sea, and offshore East Antarctica thanks to a combination of early expeditions in the 1960s and 1970s and reoccupations of select hydrographic sections through the Global Ocean Ship-Based Hydrographic Investigation Program (GO-SHIP). Within the Weddell Basin, three hydrographic transects have been particularly frequently occupied over the past 30 years: A23 extends from the northern Weddell to South Georgia (Meredith et al., 2014), SR4 crosses the Weddell Sea from Cape Norvegia on the coast of Queen Maud Land to Joinville Island off the tip of Antarctic Peninsula (Fahrbach et al., 2004; Kerr et al., 2009; Kerr et al., 2018), and A12 sits along the Prime Meridian (Fahrbach et al., 2011). Outside of the Weddell Basin, two repeated transects capture long-term property changes in AABW sourced from the Weddell Sea: section SR1b spanning eastern Drake Passage south of Falkland Islands (Cunningham et al., 2003) and in the Vema Channel connecting the Argentine Basin and Brazil Basin (Campos et al., 2021). Abrahamsen et al. (2019) computed the AABW area along three hydrographic transects (A23, SR4, and SR1b) and identified a decadal decline of the dense water mass volume from the early 1990s to the mid-2010s, followed by a brief 4-year recovery until 2018. The most recent occupations at A23 and SR4 show that the decline of the AABW area has resumed (Zhou et al., 2023; Figure 6B). AABW warming has been detected in the Weddell Sea as well as freshening, even though the temperature signal is stronger in the densest waters (Figure 6A; Azaneu et al., 2013; Jullion et al., 2013; Zhou et al., 2023).

Directly downstream from the Ross Sea continental shelf, AABW has shown variability in volume, temperature, and salinity. A repeated hydrographic zonal section at 62°S (S4P) capturing the outflow from Cape Adare showed strong freshening between the 1990s and 2000s (Swift and Orsi, 2012). Subsequently, all repeated meridional GO-SHIP sections south of the Antarctic-Pacific ridge show the fresh anomaly being carried around the Ross Gyre and into the Bellingshausen Basin (Purkey and Johnson, 2013; Purkey et al., 2019). In addition, warming and a decrease in AABW volume were observed across the deep southern basin, possibly at an accelerated rate between the 2000s and 2010s (Purkey and Johnson, 2010; Desbruyères et al., 2016; Purkey et al., 2019). Recent observations at S4P show a recovery in AABW volume and salinity since 2018 near Cape Adare (Aoki et al., 2020b; Silvano et al., 2020; Gunn et al., 2023).

Offshore East Antarctica, varieties of AABW originate from the Adélie Coast, off Cape Darnley/Prydz Bay, and, possibly and to a lesser extent, from Vincennes Bay (Kitade et al., 2014; see Figure 3 for location). Several transects of precise, top-to-bottom observations were obtained from the *Eltanin* and *Conrad* from the late 1960s to the 1970s. GO-SHIP sections I06, I08, I09, SR3, P15, and SR4, as well as projects such as BROKE/BROKE-West (Bindoff et al., 2000; Meijers et al., 2010), extended the time series from the 1990s. In the Australian Antarctic Basin, AABW freshened during the period 1970s–1990s, and the freshening accelerated from the 1990s to the 2000s (Shimada et al., 2012; van Wijk and Rintoul, 2014; Menezes et al., 2017). From the mid-2010s, the freshening changed to salinification due to changes in the bottom water formed upstream in the Ross Sea (Aoki et al., 2020b; Silvano et al., 2020; Figure 6D). Changes in AABW layer thickness have closely followed those in salinity, with contraction between the 1970s and the 2000s and a rebound in the 2010s (Figure 6E). AABW warming has been observed over recent decades (Couldrey et al., 2013; van Wijk and Rintoul, 2014; Katsumata et al., 2015), concurrent with full-depth warming due to a multidecadal poleward shift of the ACC's southern branch (Yamazaki et al., 2021). There is a gap between I06 (30°E) and I08 (~80°E), and observations are less systematic. However, the southern tip of I7 (~60°E) was occupied in 2013, and the full section was completed in 2019/20, revealing a weak freshening of AABW over the continental slope (Aoki et al., 2020c; Anilkumar et al., 2021; Yamazaki et al.[1]). The observed

1 Yamazaki, K., Katsumata, K., Hirano, D., Nomura, D., Sasaki, H., Murase, H., et al. Revisiting circulation and water masses over the East Antarctic margin (80-150°E). *Progr. Oceanogr.* (In review).

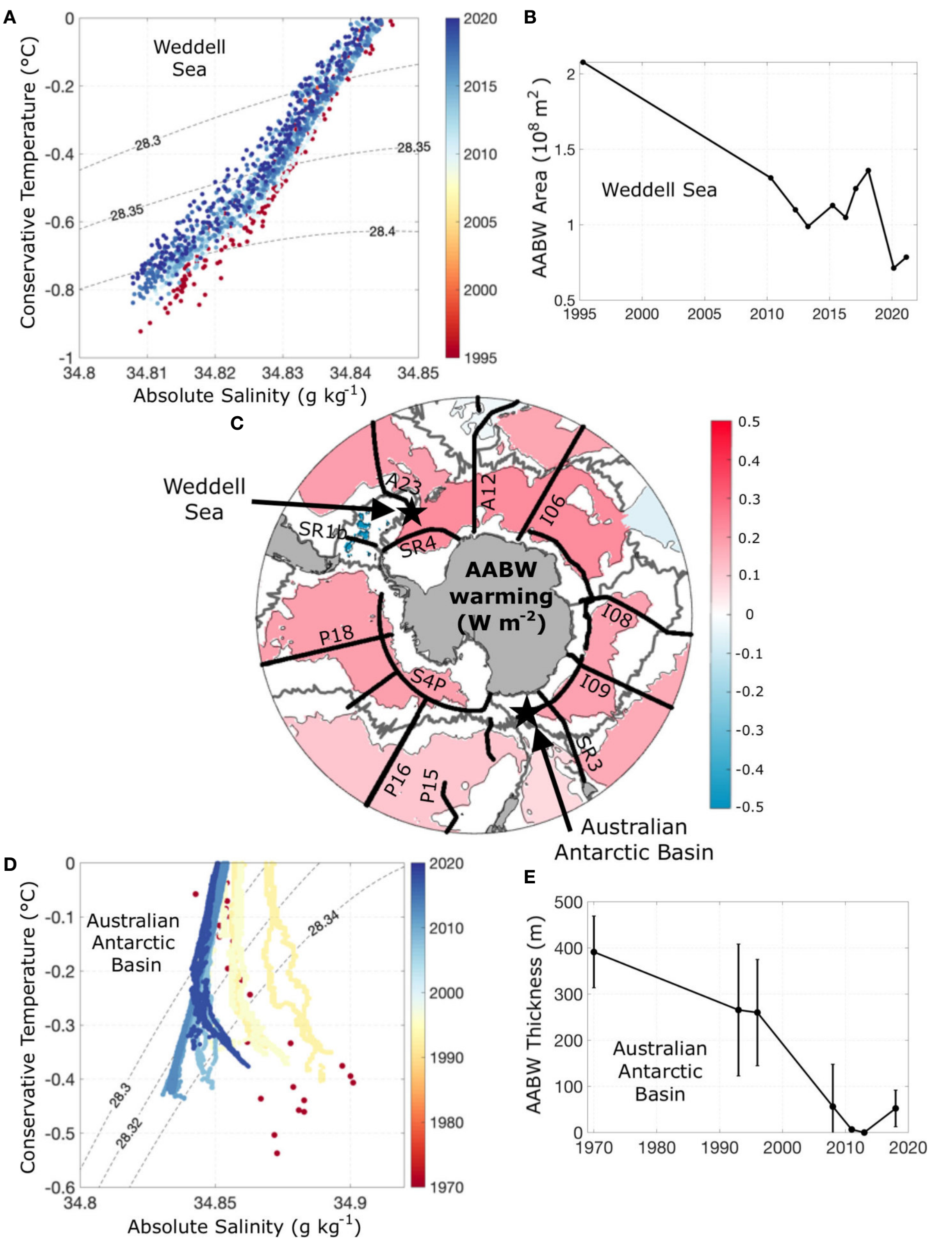


FIGURE 6
Decadal variability of Antarctic Bottom Water (AABW) properties from repeat hydrographic data. **(A)** Conservative temperature (°C) versus absolute salinity (g/kg) diagram in the Weddell Sea from measurements collected along the A23 line south of 60°S (see black star in panel C for location). **(B)** AABW area (m2) along the A23 line south of 60°S (Abrahamsen et al., 2019; Zhou et al., 2023; neutral density >28.4 kg/m$^3$). **(C)** AABW warming (W/m$^2$) between the 1990s and the 2010s (see Purkey and Johnson, 2010, for methodology; >4,000 m depth). **(D)** Conservative temperature versus absolute salinity plot in the Australian Antarctic Basin obtained by observations along the P11S line at 150°E (see black star in panel **C** for location). **(E)** AABW (neutral density >28.34 kg/m$^3$; Silvano et al., 2020) thickness (m) along 150°E. AABW density varies in different sectors and therefore AABW definitions change accordingly. GO-SHIP sections are depicted in black in **(C)**.

warming and freshening might be associated with the shoaling of the deep ventilation from East Antarctica (Shimada et al., 2022).

### 2.1.3.2 Antarctic Circumpolar Current and north

The hydrographic properties of AABW in the ACC region and to the north have been observed, mapped, and monitored from ship-based observations for decades. Reoccupations of GO-SHIP sections have revealed warming within AABW around the globe, accounting for ~10% of the total increase in ocean heat content (Purkey and Johnson, 2010; Desbruyères et al., 2016) plausibly owing to a decrease in AABW production rates (Masuda et al., 2010; Purkey and Johnson, 2012; Li et al., 2023). Within the Southern Ocean (Figure 6C), deep warming and declining AABW volume were noted as early as the 1980s in the western South Atlantic basin and continued through the 2020s (Coles et al., 1996; Johnson and Doney, 2006; Purkey and Johnson, 2010; Johnson et al., 2014; Desbruyères et al., 2016; Johnson, 2022). Similarly, deep warming over the past three decades has been observed in the Indian and

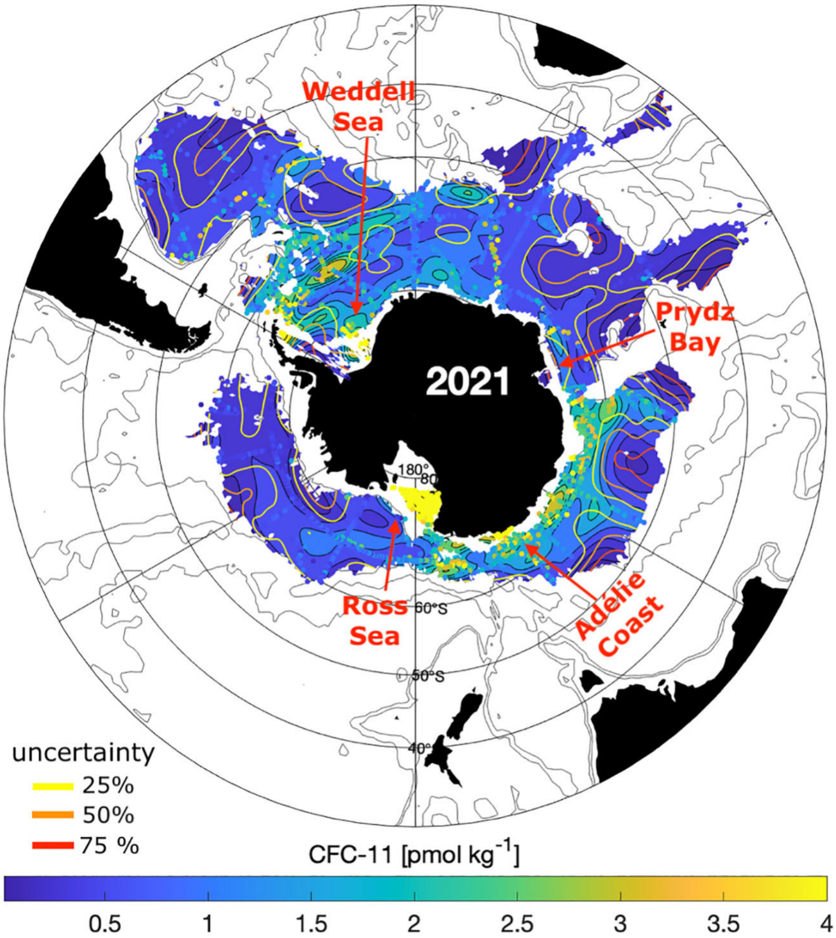


FIGURE 9
CFC-11 used as a tracer to map Antarctic Bottom Water (AABW). Reconstructed map of CFC-11 concentration in 2021 for water denser than 28.27 kg/m$^3$ (i.e., AABW). Objective mapping following Cimoli et al. (2023). Dots indicate available observations, whereas solid lines indicate uncertainty in the reconstruction (color-coded as shown in the legend). Note that in large areas of the Southern Ocean, the uncertainty is over 50%, as very few CFC data are available. Red arrows show the main areas of AABW formation.

dual locations of deep water production, with a larger production on the west side of the Ross Basin and a more moderate production from the Glomar Challenger Trough (Gordon et al., 2009) with a high-CFC signature seen in the plume of shelf water flowing into the deep currents along the continental slope (Purkey et al., 2018). CFC concentrations revealed a similar dual production of deep water along the Adélie–George V Coast, with high- and low-salinity abyssal waters being exported from the Adélie and Mertz Sills, respectively (Williams et al., 2010). In the Weddell Sea, CFC-based estimates suggest at least 3.5 Sv of AABW production (Mensch et al., 1996; Meredith et al., 2001a), with discrepancies in estimates of the contributions reaching the Atlantic and Indian Oceans. Haine et al. (1998) estimated 0.8 to 1.6 Sv of AABW transport into the South Indian Ocean, while Meredith et al. (2001a) estimated 3.2 Sv into the Indian Ocean and 0.9 Sv into the South Atlantic. Furthermore, repeated CFC observations have suggested a 15% to 21% decline in ventilation rates of bottom waters in the Weddell Gyre in the 27-year long period from 1984 to 2011 (Huhn et al., 2013). Finally, Meredith et al. (2013) used CFCs and SF6 to demonstrate the trapping and retention of AABW in deep trenches as it flows northward from source regions in the Weddell Sea, creating remarkably strong deep stratification due to temporal changes in the unimpeded waters flowing above. In general, comparison between different regional estimates of AABW formation rates is challenging, as AABW is defined in different ways in different studies, typically based on neutral density or temperature (e.g., neutral density >28.27 kg/m$^3$ in Orsi et al., 1999; potential temperature<0°C in Meredith et al., 2001a).

### 2.4.2 Other tracers

In addition to CFCs, other tracers can be used to investigate AABW in terms of both freshwater input (oxygen isotopes and noble gases) and abyssal ventilation (dissolved oxygen and radiocarbon).

The motivation to use stable oxygen isotopes of seawater ($\delta^{18}O$, the ratio between $H_2{}^{18}O$ and $H_2{}^{16}O$) along with hydrographic parameters arises from the need to disentangle freshwater sources that ultimately control abyssal water properties. Continental ice is very isotopically light (depleted in the $H_2{}^{18}O$ molecule and thus with low $\delta^{18}O$ values), and this signal is transferred into shelf waters through glacial melt input during processes at the ice shelf/iceberg–ocean boundary (Weiss et al., 1979; Schlosser et al., 1991; Weppernig et al., 1996; Akhoudas et al., 2020). Oceanic measurements of $\delta^{18}O$ can thus reveal in striking detail how abyssal water masses form by using simple mass balance calculations in which water mass concentrations including glacial melt can be computed (Meredith et al., 2001b; Meredith et al., 2008). In "cold" regime areas of Antarctica such as the Weddell and Ross Seas, where HSSW flows into ice shelf cavities and gains glacial meltwater, the resulting ISW that is exported northward is easily discernable by its depleted isotopic signature and is composed of up to 8% of glacial melt (Schlosser et al., 1990; Loose et al., 2009; Akhoudas et al., 2020). Compiling $\delta^{18}O$ observations from 1973 to 2017 in the Weddell Gyre, Figure 10A shows the isotopic signature of the bottom water layer and clearly highlights the newly ventilated dense waters from the shelf becoming isotopically enriched (i.e., higher $\delta^{18}O$ values) as they entrain the old CDW along the continental slope; this process is critical to the production of AABW and feeds the along-slope current. The distribution of meltwater links the rate of ice melting to the bottom water formation with an AABW production of ~8 Sv in the Weddell Sea, including 55% of newly ventilated HSSW and ISW (Akhoudas et al., 2021). Noble gases such as helium and neon can also be used to trace glacial meltwater in Antarctica (e.g., Huhn et al., 2018). Noble gases are typically present in low concentrations in oceanic waters, and a high excess of helium and neon can be used to estimate fractions of glacial meltwater in polar oceans. While glacial meltwater only represents a small proportion of waters sourced in the southern high latitudes, increasing glacial melt content in shelf waters has the potential to decrease their salinity, slowing their formation with consequences on the AABW export (Silvano et al., 2018).

Other dissolved gases can also act as dye tracers that help to define and identify water masses (Talley et al., 2011; Rae and Broecker, 2018; Liu and Tanhua, 2021). Once waters descend below the ocean surface, they carry a signature of gases taken up by surface waters when in contact with the atmosphere. In the cold Antarctic seas, the capability for water to absorb atmospheric gases is relatively high, although the sea ice cover can partially impede air–sea exchanges (Watts et al., 2022). Spatial variations in the efficiency of air–sea gas exchange and ocean circulation patterns confer AABW with a clear signature in several gases, including dissolved oxygen and radiocarbon. The global spatial distribution of dissolved gases has played an important role in identifying the sources and pathways of AABW in the modern ocean (e.g., Sverdrup et al., 1942; GO-SHIP; de Lavergne et al., 2017; Purkey

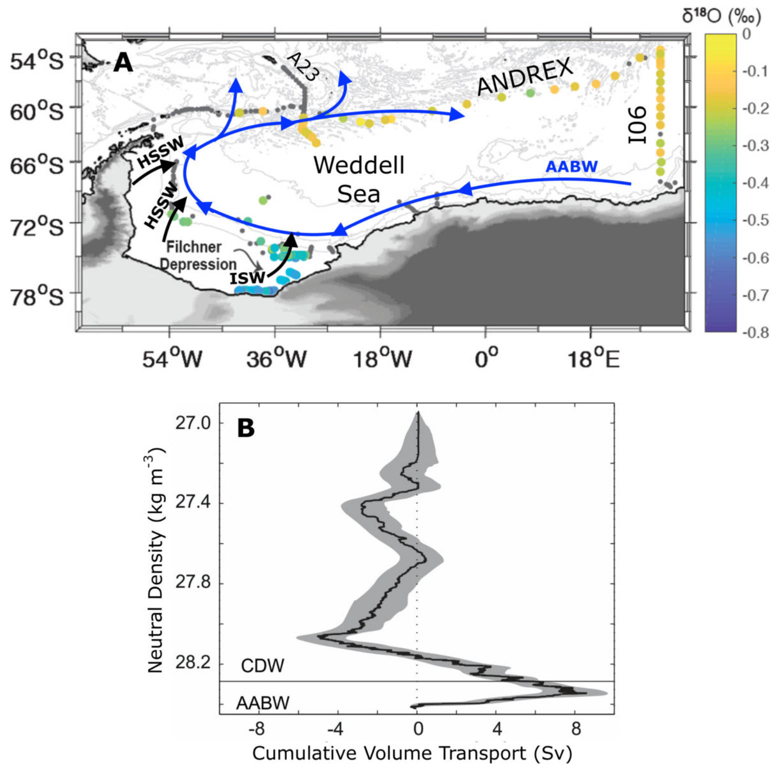


FIGURE 10
$\delta^{18}O$ and inverse modeling to quantify Antarctic Bottom Water (AABW) formation processes. **(A)** Spatial map of observed AABW $\delta^{18}O$ in the Weddell Sea. $\delta^{18}O$ is shown on the 28.37 kg/m$^3$ neutral density surface to capture the densest AABW variety that originates on the continental shelf of the south-western Weddell Sea. Gray dots represent profiles where density near the bottom is less dense than 28.37 kg/m$^3$. AABW circulation is shown by blue arrows, while areas of high-salinity shelf water (HSSW) and Ice Shelf Water (ISW) export are in black. Repeated GO-SHIP sections I06, A23, and ANDREX (Jullion et al., 2014) are highlighted. **(B)** Accumulated volume transport across the combined ANDREX–I06 section (positive is transport directed out of the Weddell Sea; see **(A)** for location; Naveira Garabato et al., 2016). Uncertainty is shown in gray. Related calculations indicate 13.3 $\pm$ 3.2 Sv of Circumpolar Deep Water (CDW) and AABW less dense than 28.345 $\pm$ 0.008 kg/m$^3$ are transformed into both denser AABW by downslope convection around the gyre's south-western rim (8.4 $\pm$ 2.0 Sv) and upper ocean waters less dense than 28.061 $\pm$ 0.011 kg/m$^3$ by upwelling within the Weddell Gyre (4.9 $\pm$ 2.0 Sv). The value 28.27 kg/m$^3$ is included for reference (horizontal black line).

et al., 2018; Rae and Broecker, 2018) and in the "paleo ocean" (e.g., Williams et al., 2019; Glasscock et al., 2020; Rafter et al., 2022). Such tracers have also begun to provide information about the causes of AABW variability, including its production rate, and how it ventilates the deep ocean (van Wijk and Rintoul, 2014; Katsumata et al., 2015; Gunn et al., 2023). With continuing data collection and increased availability, improved techniques (e.g., Cimoli et al., 2023), and combination with synthetic tracers from models (e.g., Solodoch et al., 2022), dissolved gases can provide further insight into the variability of AABW over the past century.

# 3 New observing systems

## 3.1 Profiling floats

Profiling floats are part of the Argo program and have revolutionized the field of oceanography and the ability to monitor the ocean since the 2000s (Riser et al., 2016). Such floats were designed to autonomously measure ocean properties (temperature, salinity, and pressure) between the surface and 2,000 m depth, usually every 10 days, and in areas not covered by sea ice. This design precluded monitoring of AABW and its source waters on the Antarctic continental shelf. However, over the last decade, new technological developments have enabled profiling floats to sample under sea ice (Klatt et al., 2007; Riser et al., 2016) on the Antarctica continental shelf and below 2,000 m depth ("Deep Argo" floats).

Profiling floats have been deployed on the Antarctic continental shelf since the 2010s (see Figure 11A). These floats are designed not to surface when a specified threshold is reached (for example, when the ocean temperature falls below a certain value) in order to avoid sea ice encounters. This threshold can be chosen depending on the environmental setting and experimental design. As the position of the floats is unknown when sea ice is present, different interpolation schemes and acoustic tracking methods have been employed to reconstruct the under-sea ice trajectories. These include simple linear interpolation between known positions or more sophisticated

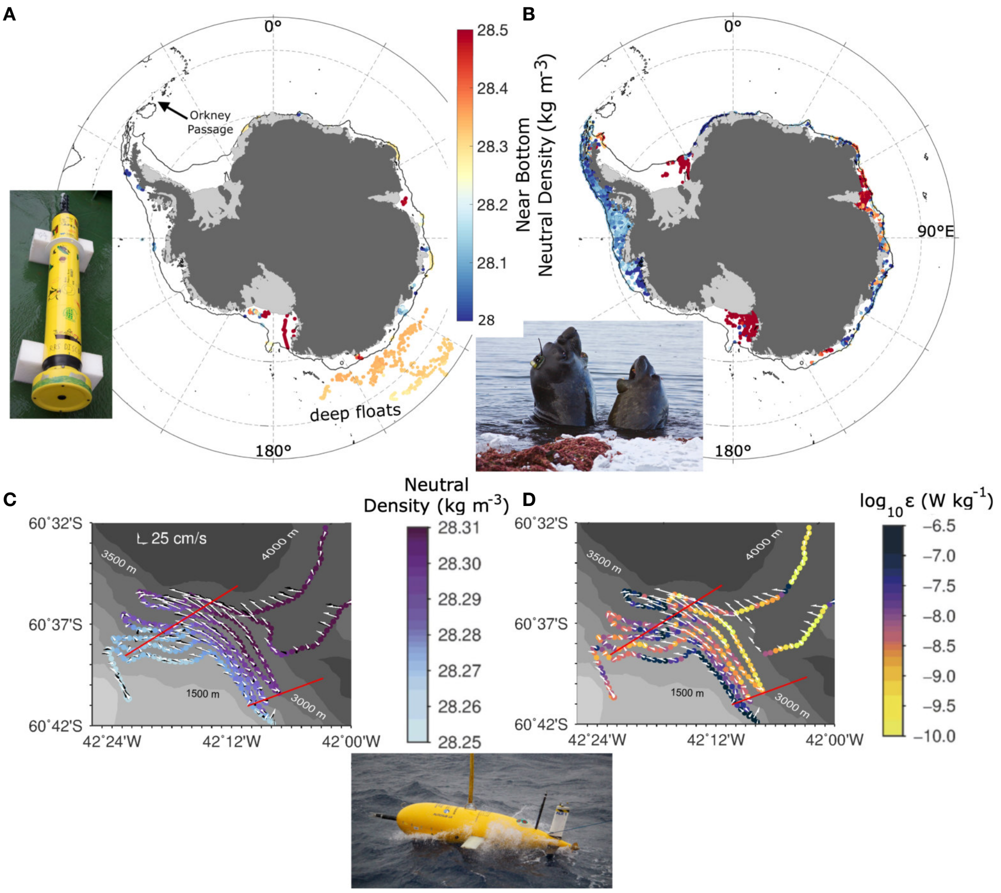


FIGURE 11
**(A)** Examples of new observing systems that can map Antarctic Bottom Water (AABW). Near-bottom neutral density (kg/m$^3$) obtained by profiling floats (on the continental shelf) and by deep floats (off the continental shelf). **(B)** Neutral density extracted by conductivity–temperature–depth (CTD)-instrumented seals at the deepest level reached at each location. The black line in panels **A** and **B** indicates the 1,000-m isobath, delimiting the continental shelf. Maps of **(C)** neutral density and **(D)** the rate of turbulent kinetic energy dissipation (W/kg), which quantifies mixing, measured by Autosub Long Range at ~90 m above the sea floor in the Orkney Passage (color). See **(A)** for location of Orkney Passage. Horizontal velocity averaged over 50–75 m (black vectors) and 125–150 m (white vectors) above the sea floor, bathymetry (gray shading), and two high-resolution CTD sections (red lines labeled B3 and B4), are shown in both **(C, D)** Adapted from Naveira Garabato et al. (2019). Images of a profiling float (P. Abrahamsen), CTD-instrumented seal (C. R. McMahon, IMOS Animal Tagging), and Autosub Long Range (A. Naveira Garabato) are shown in **(A-D)**, respectively.