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## BOTTOM WATER FORMATION

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### Introduction

Meridional sections of temperature and salinity through the Pacific and Atlantic Oceans (**Figure 1**) reveal that in the Pacific below 2000 m, more than half of the ocean depth, the water is colder than 2°C. The Atlantic is somewhat warmer, but there too the lower 1000 m of the ocean is well below 2°C. Only within the surface layer, generally less than the upper 500 m of the ocean is the water warmer than 10°C, amounting to only 10% of the total ocean volume. The coldness of the deep ocean is due to interaction of the ocean with the polar atmosphere. There, surface water reaches the freezing point of sea water. Streams of very cold water can be traced spreading primarily from the Antarctic along the sea floor, warming en route by mixing with overlying water, into the world's oceans (**Figure 2**).

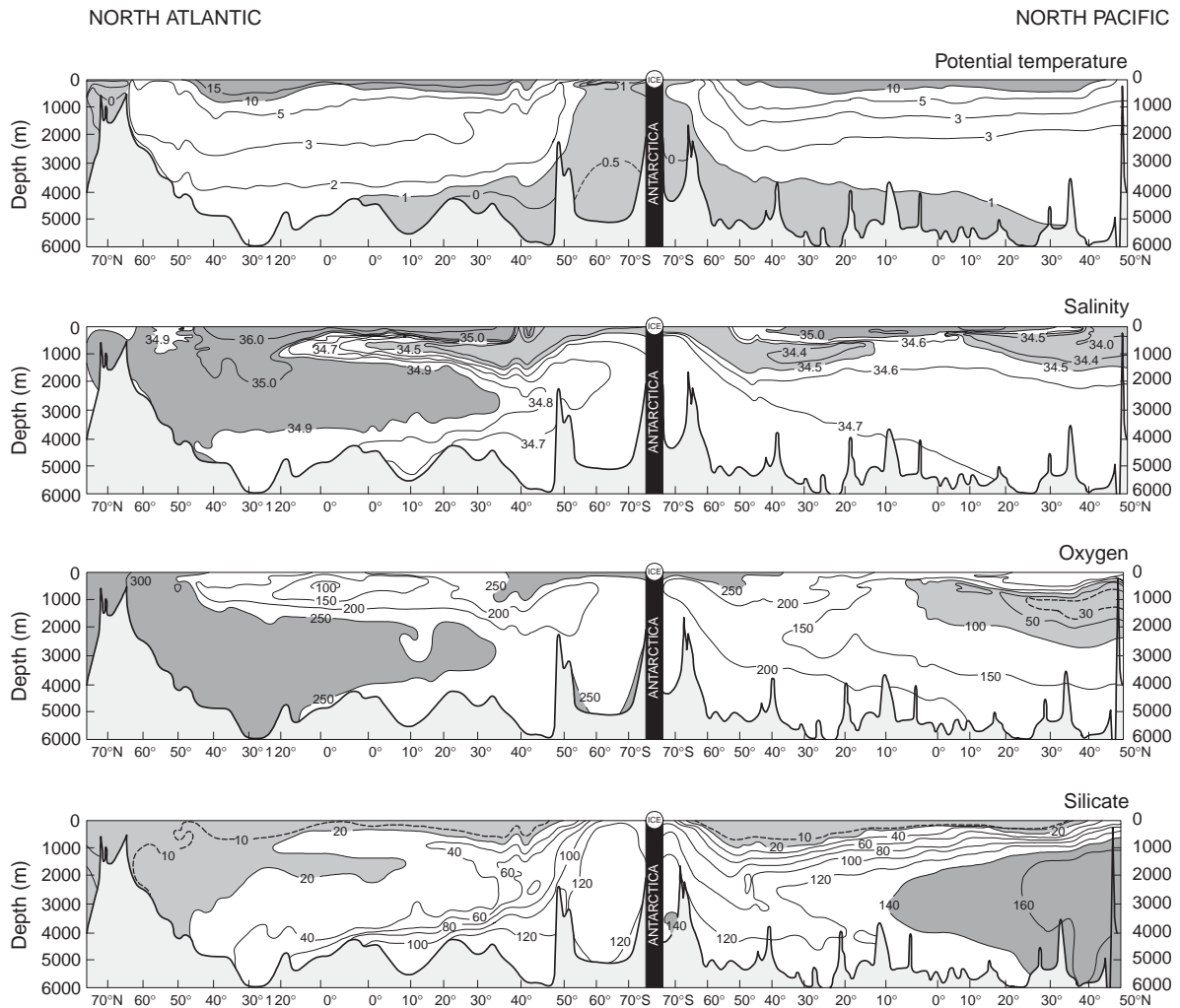
The coldest bottom water, Antarctic Bottom Water (AABW), is derived from the shores of Antarctica. There, freezing point, high oxygen concentration, water is produced during the winter over the continental shelf. At a few sites the shelf water salinity is sufficiently high, greater than 34.61‰, that, on cooling to the freezing point, the surface water density is sufficiently high to allow it to sink to great depths of the ocean. As the shelf water descends over the continental slope into the deep ocean it mixes with adjacent deep water, but this water is also quite cold so the final product arriving at the seafloor at the foot of Antarctica is about –1.0°C. Definitions used by different authors vary, but generally AABW is defined as having a potential temperature (the temperature corrected for adiabatic heating due to hydrostatic pressure) less than 0°C.

AABW spreads into the lower 1000 m of the world ocean, where it cools and renews oxygen concentrations drawn down by oxidation of organic material within the deep ocean. AABW is said to ventilate the deep ocean.

In the Atlantic Ocean the 2°C isotherm marks the base of a wedge of relatively salty water, associated with high dissolved oxygen and low silicate concentrations (see **Figure 1**). This water mass is called North Atlantic Deep Water (NADW). The densest component of NADW is formed as cold surface waters during the winter in the Greenland and Norwegian Seas. This water sinks to fill the basin north of a ridge spanning the distance from Greenland to Scotland. Excess cold water overflows the ridge crest, mixing on descent with warmer more saline water, producing a bottom water product of about +1.0°C. The overflow water stays in contact with the sea floor to near 40°N in the Atlantic Ocean, where on spreading southward it is lifted over the remnants of denser AABW.

Export of Greenland and Norwegian Sea bottom water has been estimated from a series of current measurements. Transports of about  $2 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  of near 0.4°C water occur between the Faroe Bank and Scotland,  $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  of similar water passes through notches between Iceland and Faroe Bank, and  $3 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  of near 0°C is exported through the Denmark Strait, between Greenland and Iceland. The overflow plumes rapidly entrain warmer waters, producing bottom water of near +1.0°C. With entrainment of other deep water, a production rate of about  $8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  of overflow water is likely. Less dense components of NADW, that do not contact the seafloor are formed in the Labrador Sea and Mediterranean Sea. The total production of NADW is estimated as  $15 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ .

As the Antarctic is the primary source of the cold bottom waters of the world ocean, Antarctic Bottom Water is discussed in this article. See **North Atlantic Deep Water** for further information on that Northern Hemisphere deep water mass.



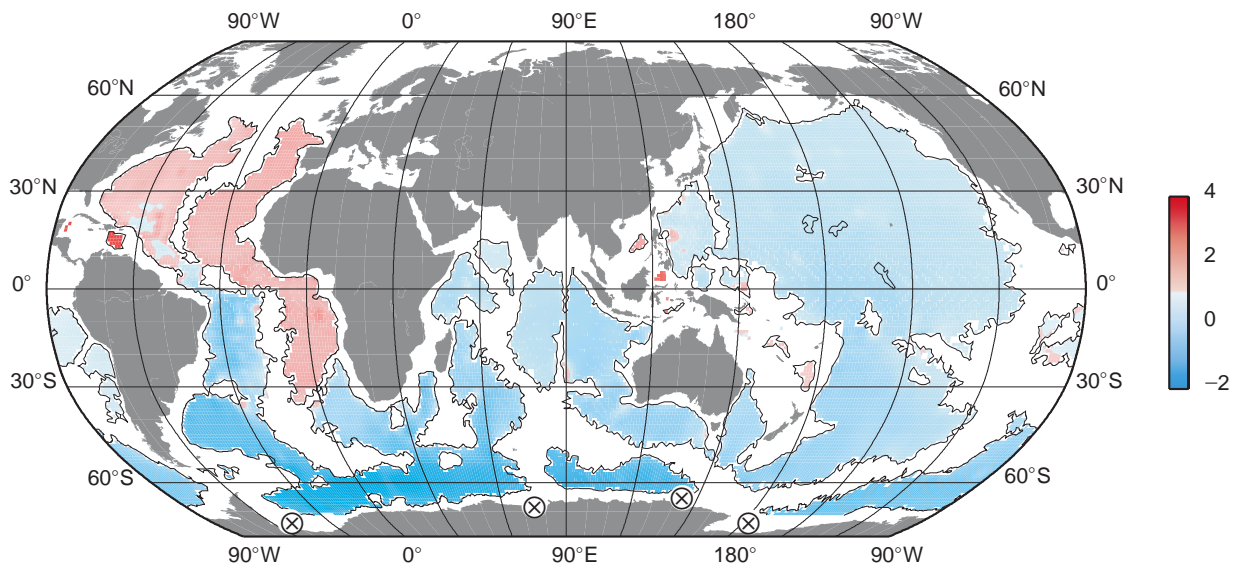
**Figure 1** Meridional sections of temperature and salinity through the Pacific and Atlantic Oceans. Antarctica is at the center of the figure.

### Formation of Antarctic Bottom Water

Antarctic Bottom Water is formed at a few sites along the continental margin of Antarctica during the winter months (Figure 2). The shelf dense water slips across the shelf break to descend to the deep ocean, perhaps within the confines of incised canyons on the continental slope. The shelf water is made dense (Figure 3) by the very cold winds from Antarctica, which spur the formation of sea ice. Normally sea ice acts to insulate the ocean from further heat loss and thus attenuates the continued formation of sea ice. But along the shores of Antarctica sea ice is blown northward by the strong winds descending over the cold glacial ice sheet of Antarctica. The removal of the sea ice exposes the ocean water to the full blast of the cold air, forming coastal polynyas (persistent bands of ice-free ocean

adjacent to Antarctica; Figure 4). Production and removal of yet more sea ice continues within the coastal polynyas, which act as ‘sea ice factories’. As sea ice has a lower salinity than the sea water from which it formed, approximately 5‰ versus 34.5‰ of the sea water, salt rejected during ice formation, concentrates in the remaining freezing point sea water making it saltier, and hence denser. The exposure of the ocean to the atmosphere also raises the dissolved oxygen concentration within the shelf water. As the ability of sea water to hold oxygen increases with lowering temperature, the oxygen concentration of the shelf water is very high, about 8 ml l<sup>-1</sup>.

The shelf water at some sites, such as the Weddell and Ross seas, is made even colder on contact with floating ice shelves that are composed of glacial (freshwater) ice. Ocean contact with glacial ice



**Figure 2** Bottom potential temperature along the seafloor, for oceanic areas deeper than 4000m. The four symbols along the coast of Antarctica mark the places where Antarctic Bottom water forms.

occurs not only at the northern face of the ice sheet, but also at hundreds of meters depth along the bases of floating ice shelves. As the freezing point of sea water is lowered with increasing pressure ( $-0.07^{\circ}\text{C}$  per 100 m of depth), the shelf water in contact with the base of the ice shelves often at a depth of many hundreds of meters, attains temperatures well below  $-2.0^{\circ}\text{C}$ . The cooling of shelf water in contact with the glacial ice is linked to melting of the glacial ice, hence this very cold water is slightly less saline than the remaining shelf water. Ocean–glacial ice interaction is believed to be a major factor in controlling Antarctica’s glacial ice mass balance and stability. The resultant water, called ice shelf water, can be identified as streams within the main mass of shelf water by its low potential temperatures. Ice shelf water with potential temperatures as low as  $-2.2^{\circ}\text{C}$  have been measured. This very cold water may act to encourage formation of AABW, as the seawater compressibility increases with lowered temperature. Thus as the shelf water begins its descent to the deep ocean, compressibility of the ice shelf water induces water of greater density, which accelerates the descent, limiting mixing with adjacent water.

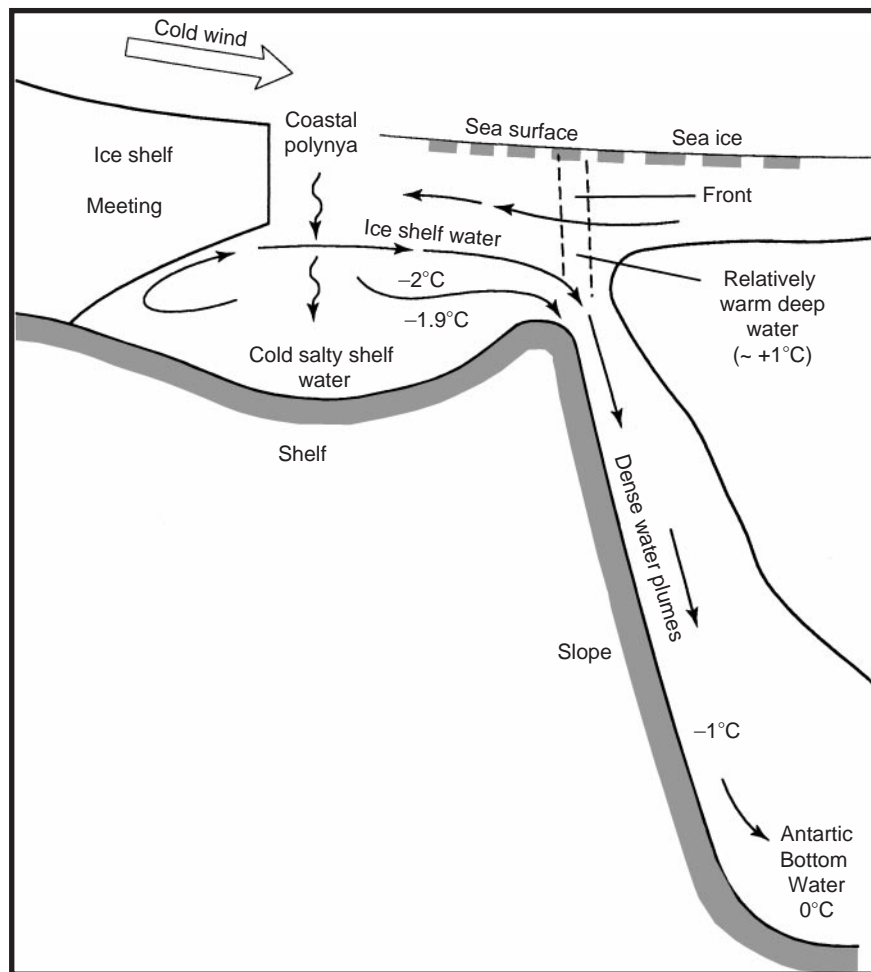
As shelf water escapes the shelf environs, offshore water must flow onto the shelf to compensate for the shelf water loss. The offshore water is warmer than the dense shelf water, with temperatures closer to  $+1.0^{\circ}\text{C}$ . Once on the shelf this water cools to renew the reservoir of freezing point shelf water. The onshore flow is drawn from deep water of the world ocean that slowly flows southward and up-

ward, crossing the Antarctic Circumpolar Current. It may be viewed as ‘old’ AABW returning from its northern sojourn. In this way the overturning thermohaline circulation cell forced by AABW formation is closed; the escape of very cold shelf water, spreading northward, mixing en route with warmer overlying water, eventually results in upwelling to return to the Antarctic. The whole process takes some hundreds of years. Only now can the chlorofluorocarbons (CFC) added to the ocean surface layer in the last 70 or so years, be detected reaching along the seafloor into the midlatitudes of the Southern Hemisphere.

### **Formation Rate of Antarctic Bottom Water**

Measurement of the formation and escape of Antarctic shelf water and the subsequent formation of Antarctic Bottom Water is difficult because the formation regions are geographically remote, covered by sea ice year-round, and distributed along a shelf break frontal region that extends more than 18 000 km around Antarctica. In addition, the thermohaline properties of source waters vary spatially, which can lead to quite different ideas regarding the mixing ‘recipes’ and specific processes leading to the ultimate cold products. It can be argued that for every  $1 \times 10^6 \text{ m}^3$  of shelf water escaping  $2 \times 10^6 \text{ m}^3$  of AABW is formed.

The best observed bottom water formation is in the Weddell Sea (the extreme southern Atlantic



**Figure 3** Schematic of circulation and water masses in the Antarctic continental shelf.

Ocean). There, deep-reaching convective plumes of very cold surface water descend over the continental slope into the deep ocean (Figure 5), producing Weddell Sea Bottom Water. This is a particularly cold form of AABW, having initial potential temperatures at the seafloor of  $-1.5^{\circ}\text{C}$ . The transport of bottom water of less than  $-0.7^{\circ}\text{C}$  emanating from the Weddell Sea is estimated to be  $2\text{--}5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ , presumably drawing from a shelf water flux of  $1\text{--}3 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ . Because of its coldness Weddell Bottom Water has a major effect on the bottom water properties of the World Ocean, particularly within the Atlantic Ocean which has the coldest bottom water.

Circumpolar estimates for the formation rate of AABW, generally defined as having a potential temperature of less than  $0^{\circ}\text{C}$ , are in the range of  $10\text{--}15 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ , but such values are not well constrained by the sparse observations. Based on CFC measurements a firm estimate of  $9.4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  has been made for the circumpolar production of AABW colder than  $-1.0^{\circ}\text{C}$

descending to depths greater than 2500 m. This value is similar to estimates of descending NADW from the Greenland and Norwegian Seas overflow.

It is not clear what controls the rate of shelf water export from the continental shelf. At the edge of the shelf is a strong ocean front (Figure 5). Movement of this front may be associated with escape of dense shelf water. The presence of canyons incised into the continental slope may also act as paths for descent to the deep ocean.

### Deep Convection Within the Southern Ocean

In addition to descending dense water plumes over the continental slope of Antarctica, deep reaching convection over the deep ocean may occur. In winter, a thin veneer of sea ice stretches from Antarctica northward, reaching half the distance to the Antarctic Circumpolar Current. A delicate balance is achieved between the cold atmosphere and upward



**Figure 4** Satellite image of a coastal polynya shown as the dark region extending from the ice-covered shore and sea ice on the left. (See also **Polynyas**.)

flux of oceanic heat into the atmosphere, resulting in the formation of approximately 0.6 m of sea ice. In this balance cold, low-salinity water sits stably over a warmer, more saline deep water layer.

During the austral winters of 1974 to 1976, near the Greenwich Meridian and 66°S in the vicinity of a seamount called Maud Rise, the ice displayed strange behavior, which has not been repeated since. A large region normally covered by sea ice in winter remained ice free throughout the winter, though it was surrounded by sea ice. This remarkable anomaly, is referred to as the Weddell Polynya. Though a full Weddell Polynya has not been observed since the mid-1970s, short lived polynyas (lasting roughly one week) are frequently observed by satellite imaging in the Maud Rise region. During the Weddell Polynya episode the normal stratification was disturbed as cold surface water convected to depths of 3000 m. It is estimated that during the three winters of the persistent Weddell Polynya,  $1\text{--}3 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  of surface water entered the deep ocean, as a form of AABW. The Weddell Polynya convection may represent another mode of operation of Southern Ocean processes, one in which surface water sinks into the deep ocean at sites away from the continental margins, in what oceanographers refer to as open ocean convection,

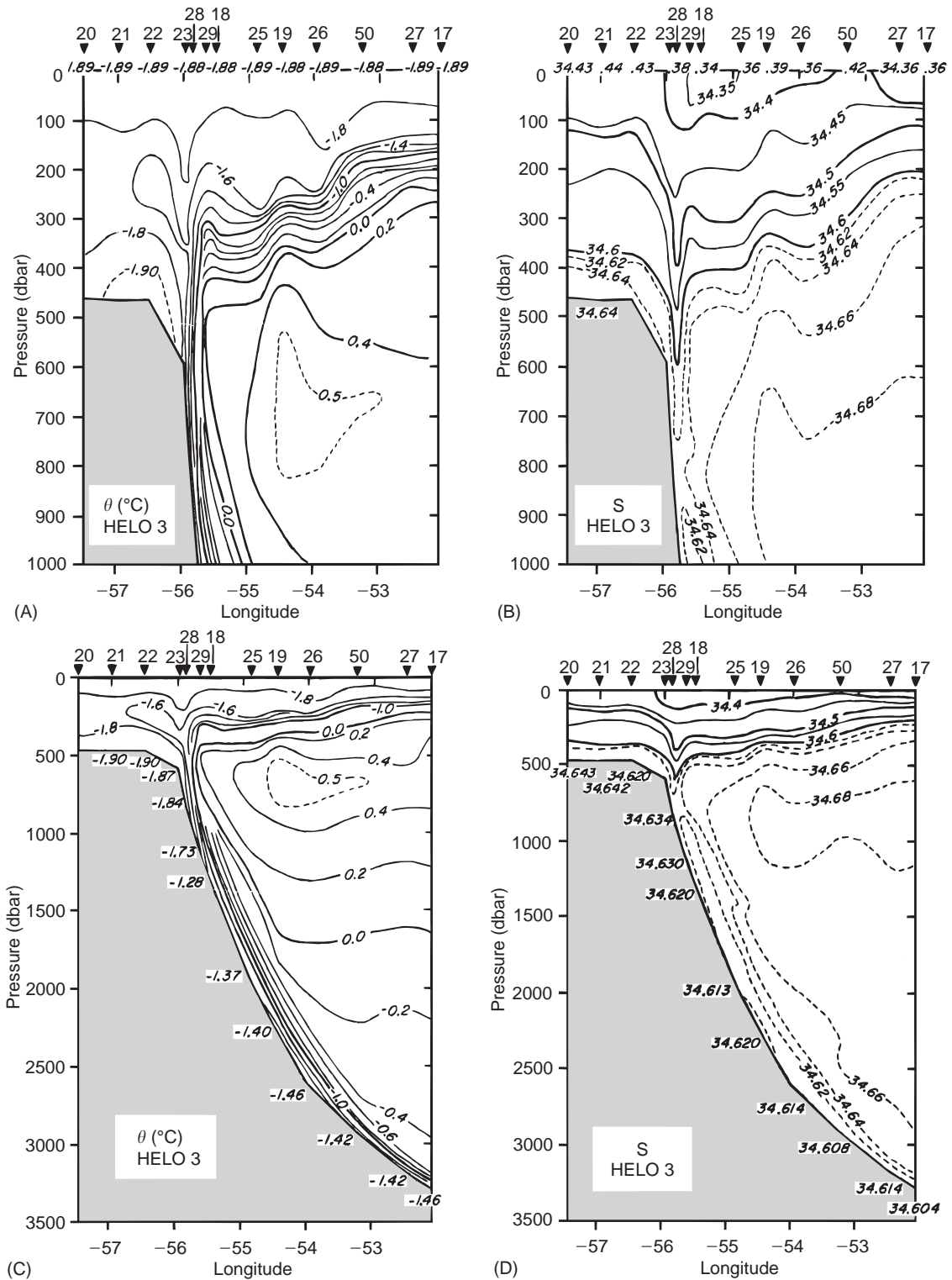
in contrast to the continental slope plume convection discussed above.

It is not clear what triggered the Weddell Polynya of the mid-1970s. It is clear that if enough deep water can be brought to the sea surface to melt all of the ice cover, then further upwelled deep water, not to be diluted by ice melt, would produce cold saline water that can then sink back into the deep ocean. What would cause enhanced upwelling of deep water? This is not clear, though interaction of ocean circulation with the Maud rise is suspected to play a key role.

## Conclusion

Bottom water of the western Weddell Sea in the early 1990s is colder and fresher than observed in previous decades. The same is true for the Southern Ocean south of Australia. These observations suggest an increased role of the low salinity, ice shelf water in recent decades. However, the period over which observations have been taken within the hostile Southern Ocean, is not long enough to place much importance on this trend.

The presence of sea ice and the rather small spatial and temporal scales associated with the convective plumes, makes AABW formation processes very



**Figure 5** Potential temperature (A,C) and salinity (B,D) along a section at 67°40'S in the western Weddell Sea, showing the varied stratification over the continental shelf and slope. The sea floor is stippled. The values inserted along the seafloor are the bottom temperature and salinity within the descending plume of dense water. The sharp change in water properties on the upper 500 m at 56°W marks the shelf/slope front. (Reproduced from Gordon AL (1998) Western Weddell Sea thermohaline stratification. In: Jacobs SS and Weiss R (eds) *Ocean, Ice and Atmosphere*, Antarctic Research Series, vol. 75, pp. 215–240. Washington, DC: American Geophysical Union.)

difficult to observe and model. Advancement of AABW research represents a significant technological challenge to field and computer oceanographers.

## Summary

The ocean is cold. Its average temperature of 3.5°C is far colder than the warm veneer capping much of the ocean. Waters warmer than 10°C amount to only 10% of the total ocean volume; about 75% of the ocean is colder than 4°C. Along the seafloor the ocean temperature is near 0°C. The cold bottom water is derived from Southern Ocean, the ocean belt surrounding Antarctica. Sea water at its freezing point of -1.9°C is formed in winter over the continental shelf of Antarctica. Where the salt content of shelf water is high enough, roughly 34.61‰ (parts per thousand) the water is sufficiently dense to descend as convective plumes over the continental slope into the adjacent deep ocean. In so doing Antarctic Bottom Water is formed. It is estimated that on average between 10 and  $15 \times 10^6 \text{ m}^3$  of Antarctic bottom water forms every second! Antarctic Bottom Water spreads away from Antarctica into the world oceans, chilling the deep ocean to temperatures near 0°C. Bottom water warms en route on mixing with warmer overlying waters. Cold winter water also forms in the Greenland and Norwegian Seas of the northern North Atlantic. This water ponds up behind a submarine ridge spanning the distance from Greenland to Scotland. This water overflows the ridge crest into the ocean to the south. As the overflow water mixes with warmer saltier water during descent into the deep ocean, it results in a warmer, more saline water mass than Antarctic Bottom water. The Greenland and Norwegian Sea overflow water forms the densest component of the water mass called North Atlantic Deep Water and is estimated to form at a rate of around  $8 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ . The

overflow water stays in contact with the seafloor until the northern fringes of Antarctic Bottom Water encountered in the North Atlantic near 40°N, lifts it to shallower levels.

## See also

**Antarctic Circumpolar Current. Polynyas. Rotating Gravity Currents. Sub Ice-shelf Circulation and Processes. Weddell Sea Circulation.**

## Further Reading

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# BRAZIL AND FALKLANDS (MALVINAS) CURRENTS

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## Introduction

The zonal component of the mean prevailing winds, low latitude easterlies and mid-latitude westerlies induce anticyclonic<sup>1</sup> upper ocean circulation pat-

<sup>1</sup> Clockwise in the northern hemisphere and counter-clockwise in the southern hemisphere.