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Cooling and Ventilating the Abyssal Ocean

Alejandro H. Orsi
Department of Oceanography, Texas A&M University, College Station, Texas

Stanley S. Jacobs, Arnold L. Gordon, and Martin Visbeck
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

Abstract. The abyssal ocean is filled with cold, dense waters that sink along the Antarctic continental slope and overflow sills that lie south of the Nordic Seas. Recent integrations of chlorofluorocarbon-11 (CFC) measurements are similar in Antarctic Bottom Water (AABW) and in lower North Atlantic Deep Water (NADW), but Antarctic inputs are $\approx$ 2°C colder than their northern counterparts. This indicates comparable ventilation rates from both polar regions, and accounts for the Southern Ocean dominance over abyssal cooling. The decadal CFC-based estimates of recent ventilation are consistent with other hydrographic observations and with longer-term radiocarbon data, but not with hypotheses of a 20th-century slowdown in the rate of AABW formation. Significant variability is not precluded by the available ocean measurements, however, and interannual to decadal changes are increasingly evident at high latitudes.

1. Introduction

It has long been known that the deepest waters of the abyssal ocean originate in the polar regions. The first deep ocean measurement, made in 1751 at 1630 m in the subtropical North Atlantic [*Ellis,* 1751], was explained as a manifestation of ocean convection, with cold polar surface waters sinking to the ocean floor and spreading equatorward, forcing warm surface waters poleward [*Rumford,* 1800]. Sparse temperature observations and the distribution of ocean basins and bathymetry led to the contention that the southern source of bottom currents was stronger and more influencial in spatial extent than the northern source [*Carpenter et al.,* 1869; *Buchan,* 1895]. Since that time, many thousands of measurements have produced a more complete picture of the deep ocean thermal structure [*Levitus and Boyer,* 1994] (Fig. 1). But does this figure indicate that southern inflows are colder, with readier access to the abyss [*Mantyla and Reid,* 1983] or that overturning is more rapid there? Can it be reconciled with the recent hypothesis that a 20th-century slowdown may have occurred in deep water production in the Southern Ocean [*Broecker et al,* 1999]? To address these questions we have analyzed complementary observations from well-sited long-term current meter arrays, and from the time-based tracers chlorofluorocarbon (CFC) and radiocarbon (^{14}C). These results provide estimates of the renewal rates for that 40% of the global ocean deeper than 2500 m, the average temperature of which is 1.36°C. This constitutes our 'abyssal ocean', defined to exclude the more variable and shallower Labrador Sea and Antarctic Intermediate Waters.

2. Hydrographic and Geochemical Observations

Estimation of the contribution of northern overflows to the abyssal ocean has been facilitated by a series of direct current measurements made between 1973 and 1993 [*Saunders,* 1990; *Ross,* 1984; *Meincke,* 1983]. The total transport from the Nordic Seas across 400-900 m sills in the Greenland-Scotland Ridge is 5.8 Sv (1 Sv = 10^6 m^3 s^{-1}) at $\theta \approx$ -0.5°C to +0.4°C. These overflows entrain warmer waters and enter the abyssal ocean at a combined rate of 8.6 Sv and with temperatures between +0.5°C and +1.0°C [*Dickson and Brown,* 1994]. Southern injections into the abyssal ocean have been more difficult to measure directly because the sites are remote, frequently covered by sea ice, and distributed along a Slope Front that extends more than 18,000 km around Antarctica [*Whitworth et al.,* 1998]. In addition, spatial variability of thermohaline properties and a variety of bottom water definitions have led to different ideas regarding the relative strengths of source regions [e.g., *Carmack,* 1977; *Rintoul,* 1998]. Most process and monitoring studies have been carried out in the Weddell Sea, where recent work has confirmed earlier calculations of 3-5 Sv of 'Weddell Sea Bottom Water' production [*Gordon,* 1998]. Hydrographic estimates for generation of the more inclusive AABW have typically ranged from 5-15 Sv [e.g., *Carmack,* 1977; *Jacobs et al.,* 1985], but are not well constrained.

Geochemical measurements of transient tracers provide important temporal information from which ventilation rates can be derived. For the northern hemisphere, CFC-based analyses are broadly consistent with the physical measurements, showing an average overflow of 4.8 Sv from the Nordic Seas between 1970 and 1990, subsequently rising by entrainment to 7.6 Sv of lower NADW entering the abyssal North Atlantic [*Smethie and Fine,* 2001] (Fig. 2). In the south, integrated CFC measurements below the upper boundary (28.27 kg m^3) of AABW indicate 8.1 Sv sinking across the 2500-m isobath on the Antarctic continental rise [*Orsi et al.,* 1999]. About 60% of this volume enters the Atlantic sector of the Southern Ocean at $\theta \approx$ -1.2°C, and the remainder in the Indian and Pacific sectors at $\theta \approx$ -0.8°C.

The comparable volume and colder temperatures of the southern sources means that overturning in the Southern Ocean must dominate abyssal cooling (Fig. 1). To mantain the abyssal ocean at a temperature near 1.36°C, injection of cold deep and bottom waters constitutes an important

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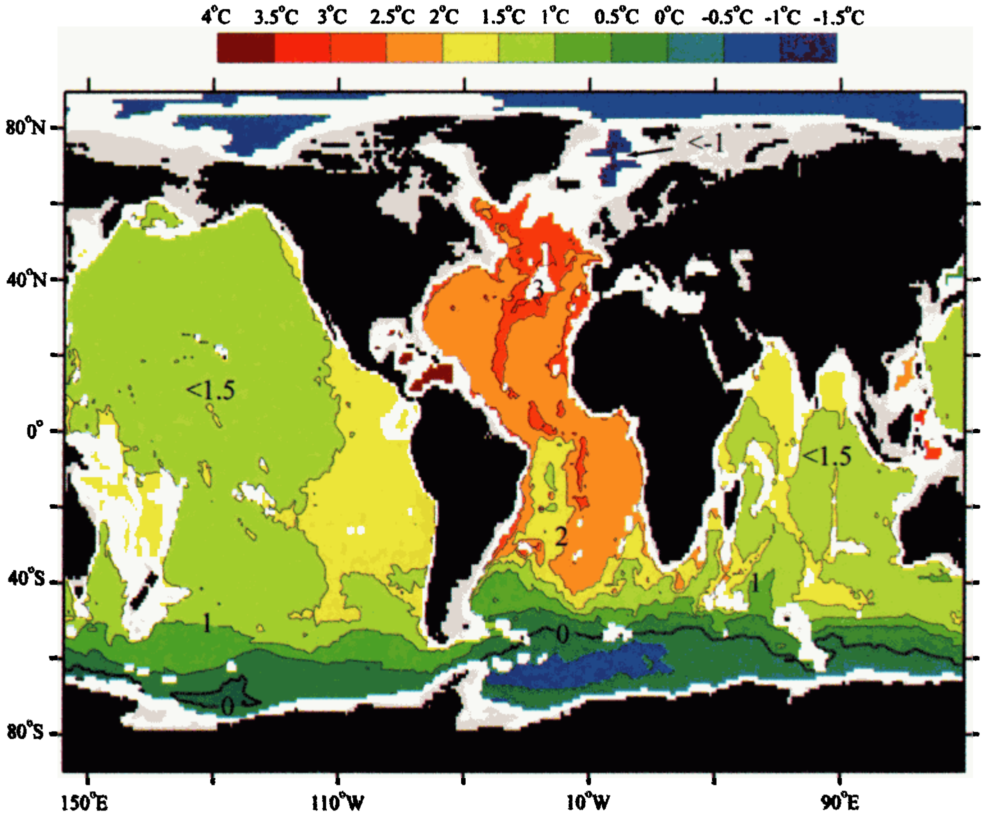

Figure 1. Spatial distribution of the depth-averaged potential temperature below 2500 m in the world ocean, from [*Levitus and Boyer*, 1994]. Stronger cooling occurs in the Southern Ocean, where very cold, dense waters generated over the Antarctic continental shelf can access the deep ocean along the lengthy continental slope. In the Arctic and Nordic (Norwegian, Greenland and Iceland) Seas, less cold and dense waters reach the abyssal ocean only across narrow sills in the ocean ridge between Greenland and Scotland. Depths shallower than 500 m are shaded in gray. The abyssal ocean's mean temperature of 1.36°C excludes the 0.5% volume trapped deep within the Arctic and Nordic Seas.

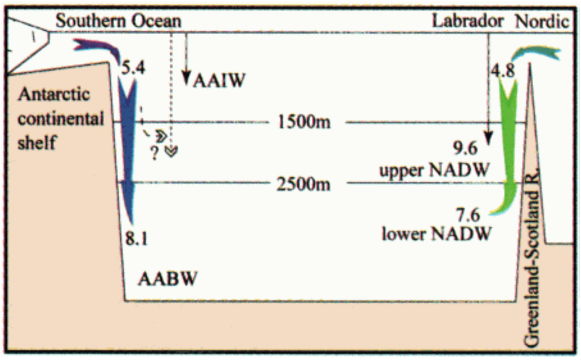

Figure 2. Schematic illustration of abyssal ocean inputs from high latitudes, based on analyses of CFC data. The layer deeper than 2500m receives 7.6 Sv (1 Sv = 10^6 m^3 s^{-1}) of lower NADW, of which 4.8 Sv has crossed sills in the Greenland-Scotland Ridge, and 8.1 Sv of AABW, of which ≈ 5.4 Sv is derived from the Antarctic continental shelf. Southern near-surface ('ventilated') components are ≈ 2°C colder than the Nordic overflows. Most Labrador Sea Water enters the upper NADW. Deep convection during polynya events (dotted arrow) and lateral intrusions along the Antarctic continental slope (dashed arrow) also ventilate the region deeper than 1500m. Most Antarctic Intermediate Water (AAIW) remains in the top 1500m.

cooling mechanism. The sinking of 8.1 Sv of new AABW with an average temperature of -1°C represents a heat loss for the abyssal ocean about three to four times larger than that resulting from the injection of 7.6 Sv to 8.6 Sv of new lower NADW at an average temperature of 0.7°C. Together these polar inflows cool the abyssal ocean at a rate of ≈ 0.1 x 10^{15}W, which in steady state and with negligible geothermal heating must be balanced by the downward diffusion of heat. The mean vertical temperature gradient (7 x 10^{-4} °K m^{-1}) across the 3 x 10^{14} m^2 area of the 2500 m interface yields a vertical diffusivity near 10^{-4} m^2 s^{-1}, consistent with global estimates [*Munk and Wunsch*, 1998].

Representative CFC saturation levels of the near-surface ingredients in AABW and lower NADW depend on atmospheric CFC concentration, surface conditions, water column stability and, near Antarctica, sea ice cover and residence time beneath ice shelves [*Schlosser et al.*, 1991]. Surface waters in the Southern Ocean can reach 90% saturation in summer, but most Antarctic deep and bottom waters are not formed from surface waters south of 40°S [*Broecker et al.*, 1998] but from denser shelf waters [*Whitworth et al.*, 1998] that are typically only 40-60% saturated. Available CFC and temperature measurements indicate that ≈ 5.4 Sv of near-freezing Antarctic shelf waters (at 50% CFC saturation) mixed with ≈ 5% CFC deep water provide the 'ventilated' component of new AABW (≈ 35% saturation) found on the continental rise [*Orsi et al.*, 1999; 2001]. The shelf water component in AABW must increase its original volume about 50% by entrainment during sinking, consistent with the entrainment rates estimated for Nordic overflows [*Dickson and Brown,* 1994; *Smethie and Fine,* 2001]. With date-normalized CFC inventories of 11 million moles in both AABW and lower NADW [*Orsi et al.*, 1999; *Smethie and Fine,* 2001], the latter requires a smaller surface component with mean saturations exceeding 50%, and/or entrainment of ambient waters with saturations above 5%.

3. Discussion and Conclusions

Inflows to the abyssal ocean derived from decadal-scale CFC data, within their estimated 30% error limits [*Smethie and Fine,* 2001], agree with ventilation rates obtained from multi-century scale ^{14}C observations. The combined AABW and lower NADW flow of 15.7 Sv (Fig. 2) into the abyssal ocean volume (53,660 x 10^4 km^3) south of 65°N corresponds to a renewal time of 1085 yrs. To compare that value with a ^{14}C-based 30 Sv renewal rate [*Broecker et al.*, 1998], which applies to the larger ocean volume below ≈ 1500m, shallower inputs such as the 9.6 Sv of upper NADW from the Labrador Sea [*Smethie and Fine,* 2001] and the more sparsely-sampled southern components must be added. The latter would include shelf water mixtures off the Wilkes Land Coast and in the NW Weddell Sea [*Carmack and Killworth,* 1978; *Rintoul,* 1998; *Whitworth et al,* 1994], and deep convection within sporadic offshore polynyas [*Gordon,* 1978]. In combination, these sources account for the additional 4.7 - 6.9 Sv that would be required for a steady-state 30/15 Sv global/Southern Ocean [*Broecker et al.*, 1998; *Orsi et al.*, 2001].

This physical and chemical evidence offers little support for hypotheses of a possible 20$^{\text{th}}$ -century slowdown or near-zero production of deep and bottom water in the Southern Ocean [*Broecker et al.*, 1999; *Worthington,* 1977]. The CFC-based abyssal ocean renewal rates over recent decades are compatible with hydrographic [*Ganachaud and Wunsch,* 2000] and longer-term ^{14}C measurements, and are similar in magnitude in the southern and northern hemispheres. The observations do not reveal whether AABW production might have been stronger during the Little Ice Age. For example, if the AABW formation rate during that 500 yr period [*Broecker et al.*, 1998] were 16.2 Sv (twice the value in Fig. 2), with other parameters unchanged, then overturning for the abyssal ocean would drop from 1085 to 862 years (885 to 780 yrs for 38.1 Sv into the larger reservoir deeper than 1500m). The difference between these estimates is well within the combined error bars of the geochemical analyses.

A decline in the rate of deep water formation in the Southern Ocean cannot be inferred by comparing the volume of NADW that emerges from the South Atlantic with the amount of AABW produced in the Weddell Sea [*Broecker et al.*, 1998]. But one can easily be misled by reports that most bottom water is generated in the Weddell Sea, and that its volume is relatively small [*Orsi et al.*, 1999; *Fahrbach et al.*, 2001]. 'Weddell Sea Bottom Water' is a cold and fresh variant, however, that would be trapped in the Weddell-Enderby Basin if it did not upwell and mix into the more widespread AABW class. In addition, the concept of surface water simply overturning to become deep water, as in the Labrador Sea, has rarely been documented in the Southern Ocean. It occurred in the Weddell Polynya of the early 1970s, but that feature existed for only 1/9 of the satellite-era sea ice record, during which it generated only 1.6-3.2 Sv of deep water [*Gordon,* 1978]. Nevertheless, that is the primary mode of deep convection in the Southern ocean in most general circulation models [*Goodman,* 1998], which as yet have insufficient resolution to accommodate the Antarctic continental shelf and slope regimes. Even if brine drainage and freshwater inputs are accurately parameterized, caution must be exercised in interpreting AABW variability resulting from modeled processes that are uncommon in the modern ocean [*Kim and Stössel,* 2001].

While the temperature, CFC and ^{14}C measurements appear consistent with a relatively steady-state overturning rate in the Southern Ocean over recent centuries, future changes may well be in the cards. General circulation models commonly depict a reduced deep ocean ventilation rate in a warmer and wetter climate, now widely anticipated, and regional models are becoming increasingly realistic. At the same time, the observational evidence is growing for significant temporal variability in AABW and its precursors [*Fahrbach et al.*, 1995; *Jacobs and Giulivi,* 1998].

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A. H. Orsi, Department of Oceanography, Texas A&M University, College Station, TX 77843, (e-mail: aorsi@tamu.edu)

S. S. Jacobs, A. L. Gordon, and M. Visbeck, Lamont-Doherty Earth Observatory, Columbia University, RT 9W, Palisades, NY 10964, (e-mail: agordon@ldeo.columbia.edu, sjacobs@ldeo .columbia.edu, visbeck@ldeo.columbia.edu)

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