Journal of Marine Research, 63, 187–201, 2005

On the world-wide circulation of the deep water from the North Atlantic Ocean

by Joseph L. Reid[1]

ABSTRACT

Above the deeper waters of the North Atlantic that have entered from the circumpolar flow, convection in the Labrador Sea and overflow from the Mediterranean, Norwegian, and Greenland seas combine at mid-depth and circulate in the subarctic cyclonic gyre, and flow southward along the western boundary into the South Atlantic. Because of the nature of these sources the mid-depth waters of the North Atlantic are the warmest, most saline, highest in oxygen and lowest in silica of any of the mid-depth waters of the World Ocean. They have been called the North Atlantic Deep Water.

In the Atlantic these characteristics have vertical extremes that separate the inflowing water from the far south into an upper and a lower layer (Reid *et al.,* 1977). These characteristics are so strong that their patterns trace much of the large-scale circulation. Lateral extremes in these tracers extend southward along the western boundary of the Atlantic Ocean. They turn offshore near 50S and eastward with the circumpolar flow. The tracers indicate that some of the eastward flow turns northward along the western boundaries in the Indian and Pacific oceans, but the lateral extreme remains strong enough to give a clear signal all the way to the Drake Passage.

1. Introduction

The mid-depth waters of the North Atlantic are the warmest, most saline, highest in oxygen and lowest in nutrients in that depth range (1500 to 3000 m) in the World Ocean. These characteristics provide signals that identify these North Atlantic waters along a very long flow path. Although the signals are weakened by mixing with adjacent waters along the flow, they are still strong enough to define a path all along the western boundary of the Atlantic and, with the circumpolar current (Gordon and Molinelli, 1982), into the Indian and Pacific oceans and through the Drake Passage into the Atlantic.

Two earlier studies (Reid and Lynn, 1971; Reid, 1981) dealt with the spread of the deep waters of the North Atlantic. The first followed the vertical salinity maximum to its intersection with the bottom in the equatorial Pacific. The second mapped the characteristics along a shallow isopycnal. (It was also 37.0 in σ_2, but in the older equation of state. In the current equation it would be 36.98 in σ_2. It lies from 400 to 600 m shallower than the σ_2 37.00 in the present work.)

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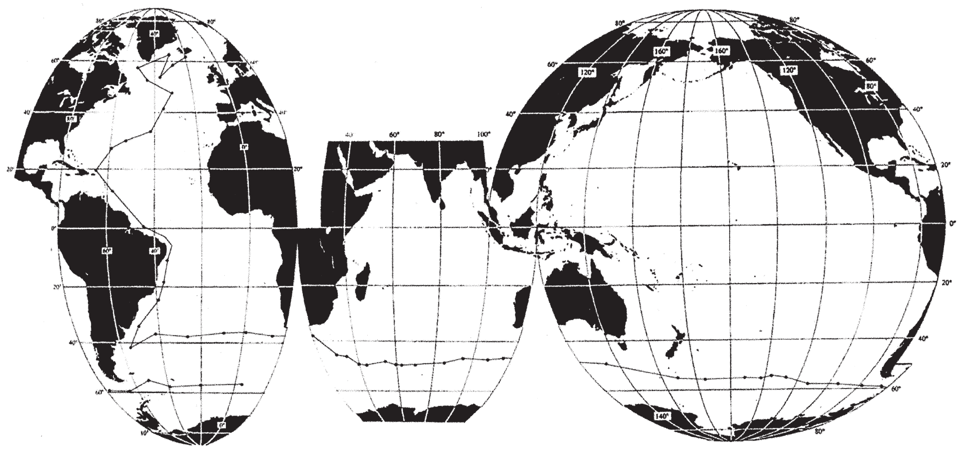


Figure 1. Path of the vertical section from the North Atlantic through the Indian and Pacific oceans and Drake Passage, returning to the Atlantic.

The present study deals with a layer (where σ_2 is 37.00) that lies between that of the two earlier studies. It corresponds more nearly to the vertical maximum in salinity along the path from the North Atlantic to the circumpolar flow and through the Drake Passage into the South Atlantic. It adds new data to show the patterns of oxygen and silica, which have lateral extremes along the flow, but vertical extremes only in the Atlantic. It also maps the geostrophic flow along the isopycnal (as in Reid, 1981, 1994 and 2003).

The isopycnal where σ_2 is 37.0 can represent the patterns of these signals, both lateral and vertical. A line of stations along the flow of the water where σ_2 is 37.00 is shown in Figure 1, beginning in the northwestern Atlantic. It extends southward through the Atlantic and eastward with the circumpolar flow through the Indian and Pacific oceans, returning to the Atlantic through the Drake Passage (Fig. 1 and Fig. 2). The depth, flow, and tracers are shown on the vertical section (Fig. 2) and on the isopycnal (Figs. 3, 4, and 5). Where the isopycnal rises above 1500 m south of about 50S, it is continued along values of σ_1 and σ_0, and where it lies deeper than 3000 m in the Pacific north of about 45S, it is continued along a value of σ_3. The pattern of flow along the isopycnal (Figs. 3b, 4b, and 5b) is derived from top-to-bottom fields of geostrophic flow in the Atlantic, Indian, and Pacific oceans (Reid, 1994, 1997, and 2003). As the stations are chosen along the path of flow instead of across, the depth of the isopycnal does not rise and fall sharply. North of 40S it is shallowest in the far north Atlantic (1000 to 2400 m), 2400–2800 m in the South Atlantic, 2600–2800 m in the Indian Ocean and deepest (about 3200 m) in the Pacific. In all three oceans it slopes upward from 40S nearly to the surface south of 60S. Where it lies north of the equator in the Indian and Pacific oceans, both the potential temperature and salinity extend monotonically downward, toward lower salinity in the Indian and higher salinity in the Pacific.

The patterns of characteristics and flow are shown along this isopycnal for all three oceans in Figures 3, 4, and 5. The patterns indicate that along the flow some of the Atlantic characteristics diminish. Both vertical and lateral mixing are seen to take place. Every-

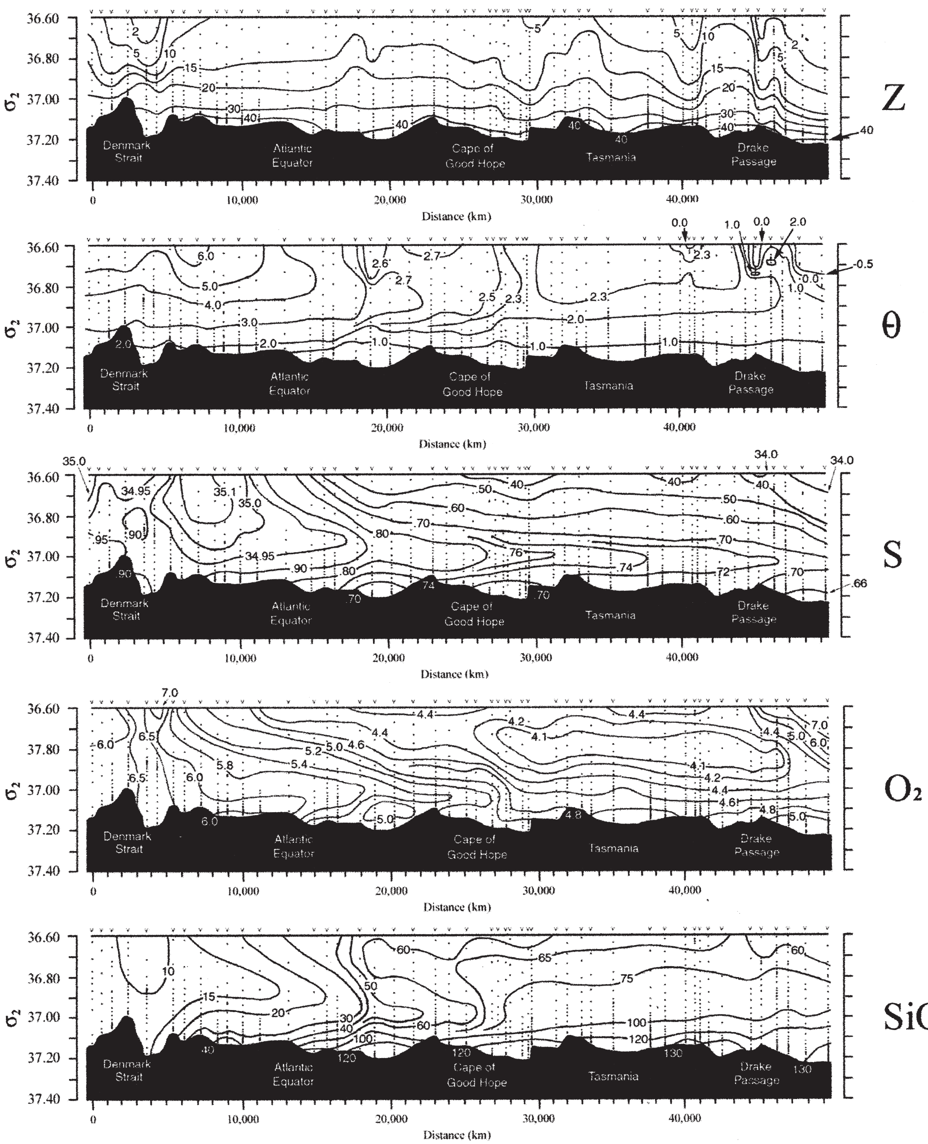


Figure 2. Depth (hm), potential temperature (°C), salinity, oxygen (ml/l^{-1}), and silica (μm kg^{-1}) along the line of stations shown in Figure 1. The ordinate is σ_2.

where south of about 25N in the Atlantic, about 10S in the Indian, and throughout the Pacific, the isopycnal lies beneath lower-salinity Intermediate Water. But the characteristics acquired in the northern North Atlantic are so extreme compared with other waters in their density range that they can be traced along a path from their sources in the Atlantic eastward around Antarctica and through the Drake Passage back into the Atlantic. The distance is greater than the circumference of the earth.

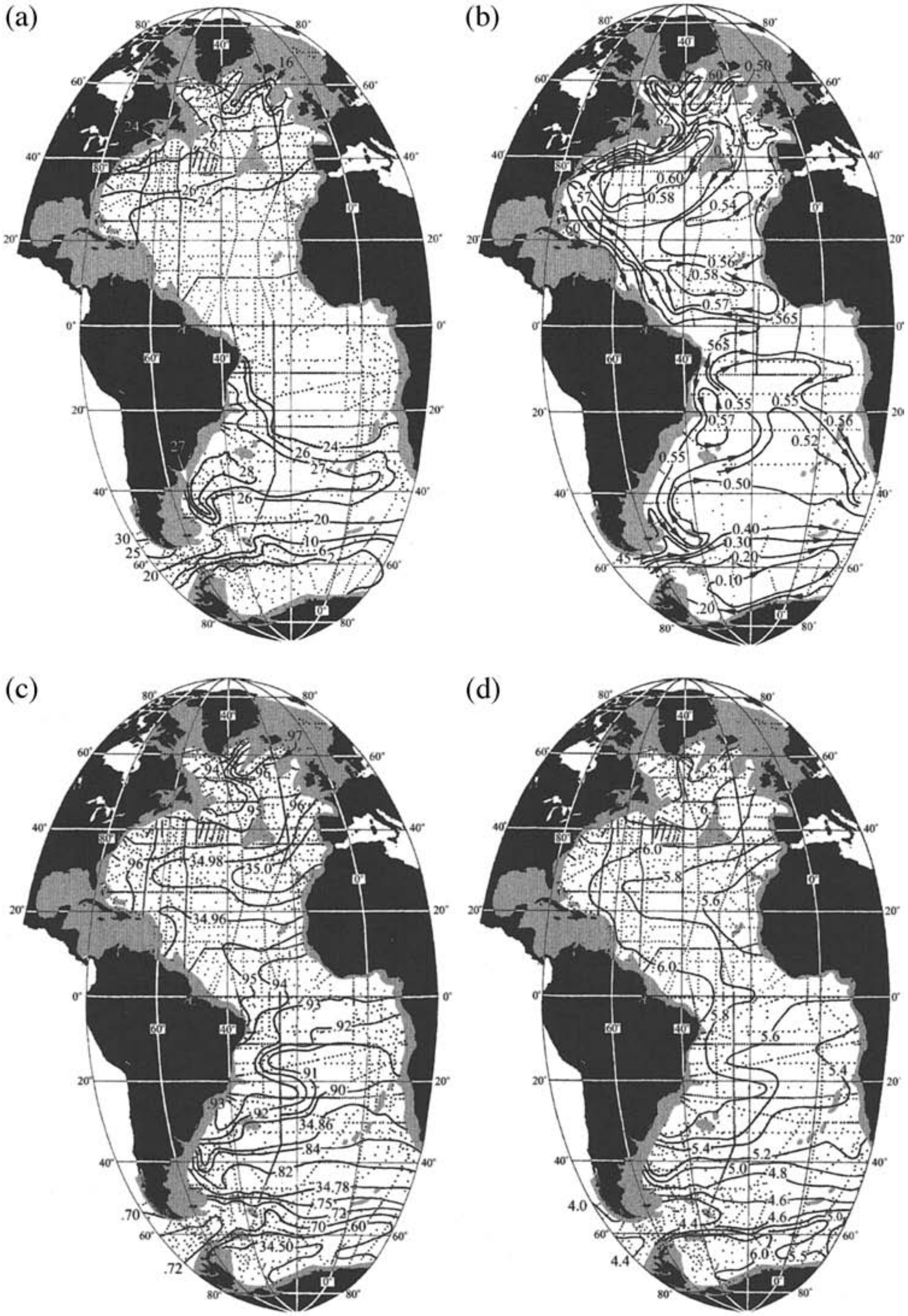


Figure 3. (a) Depth (hm) where σ_2 is 37.0; (b) Adjusted steric height along the isopycnal defined by 37.0 in σ_2; (c) Salinity along the 37.0 isopycnal; (d) Oxygen (ml/l^{-1}) along the 37.0 isopycnal and (e) Silica (μm kg^{-1}) along the 37.0 isopycnal.

(e)

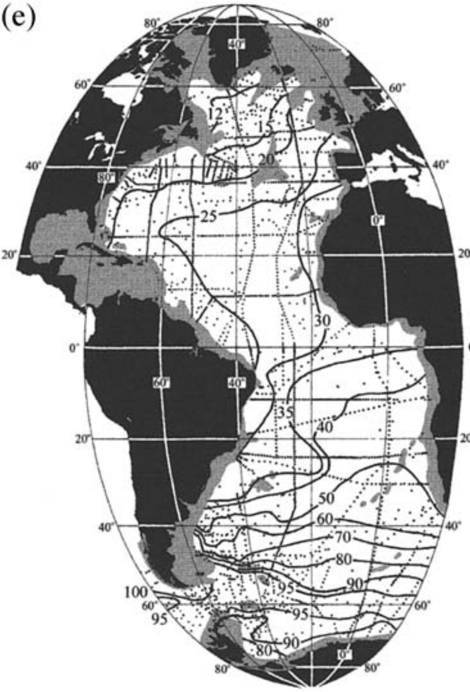


Figure 3. continued

2. The sources

The characteristics are derived from four sources. The shallowest is the warm and saline outflow from the Mediterranean Sea (Fig. 3), which extends both westward to North America and northward along the eastern boundary (Wüst, 1935; Worthington and Wright, 1970; Reid, 1978). South of about 20N, where it flows beneath the Intermediate Water from the south it appears as a vertical maximum (Fig. 2c).

The second source is the Labrador Sea (Talley and McCartney, 1982), which is less saline but colder and denser than the Mediterranean outflow. In its high latitudes the precipitation rate is high and the surface salinity is the lowest in the North Atlantic. However, warmer and more saline waters enter from the Norwegian and Greenland seas and the Mediterranean (Fig. 3c), and the salinity on this isopycnal ($\sigma_2 = 37.0$) is higher than any other waters of this density outside the Atlantic. Because of the deep winter overturn (to more than 1000 m), the oxygen in the Labrador and Norwegian-Greenland seas is higher than any other mid-depth water in the World Ocean Figs. 3d, 4d, and 5d).

The third and fourth sources are the overflows from the Norwegian and Greenland seas (Lee and Ellett, 1967; Worthington and Wright, 1970; Swift, 1984; and Dickson and Brown, 1994). The waters flowing northward from the open Atlantic into the Norwegian-Greenland Sea are warm and very saline. Because of their high salinity they become very dense as they cool, and they sink to great depths. Beneath the inflow, these denser waters flow back into the Atlantic over sills east and west of Iceland. The overflow east of Iceland is evident from the top of the ridge down to more than 3000 m (Swift, 1984) and clearly supplies water of high salinity and oxygen and low silica to the northwestern Atlantic.

The overflow west of Iceland reaching the bottom through the Denmark Strait is the densest bottom water found in the northern North Atlantic (Mantyla and Reid, 1983). Though it contributes to the deep flow out of the Atlantic, it is colder and less saline than the waters which it meets south of the strait on this isopycnal. It is not a source of the highest salinity of the North Atlantic but it does provide high oxygen and low silica.

The vertical sections show the denser waters underlying these North Atlantic extremes. In the far north the bottom waters are from the Iceland-Faeroe and Denmark Strait overflows, but south of about 40N the underlying waters are from the far south. These denser waters are colder and less saline than the overlying waters along this section, and higher in silica.

3. Circulation

A general pattern of the geostrophic circulation along this isopycnal in the Atlantic, Indian, and Pacific oceans, derived from earlier studies (Reid, 1994, 1997 and 2003), is used herein. There are anticyclonic gyres in the subtropics, some eastward flow near the equator and cyclonic gyres in the far north and south (Figs. 3b, 4b, and 5b). The high-latitude cyclonic gyre in the Indian Ocean south of Australia is not seen where σ_2 is 37.0 (Fig. 4b), but only at 2500 m or greater depths. The North Atlantic differs from the other oceans in that there is a deep equatorward flow along the western boundary, crossing the equator and joining the poleward flow of the anticyclonic gyre in the South Atlantic.

The circumpolar current flows cyclonically around the Antarctic continent, but within each of the three deep Antarctic basins—Weddell Sea, the Australia-Antarctic Basin, and the Ross Sea—there is a separate deep cyclonic gyre partly separated from the north by the American Antarctic, the Southwest and Southeast Indian, and the Pacific Antarctic ridges. All three basins show evidence of bottom-water formation along the coast. In the Weddell and Ross seas these deep gyres extend upward from the bottom to the surface, but in the Australia-Antarctic Basin the flow is cyclonic only below about 2000 m (Reid, 2003). It does not extend up to the surface where σ_2 is 37.0, which lies well above the cyclonic flow.

In each of the three oceans, part of the eastward flow around Antarctica turns northward as a western boundary current along the southeastern edges of the continents, and then back southward and around the anticyclonic gyre (Figs. 3b, 4b, and 5b). Some of it continues northward around the gyre and some turns eastward and then southward along the eastern boundary. In the Atlantic and Pacific these southward flows turn eastward at the south ends of the continents, joining the circumpolar flow (Figs. 3b and 5b). But in the Indian Ocean the flow along the south coast of Australia turns westward, as part of the anticyclonic gyre, and the southward flow along the west coast of Australia turns westward and joins the gyre (Fig. 4b).

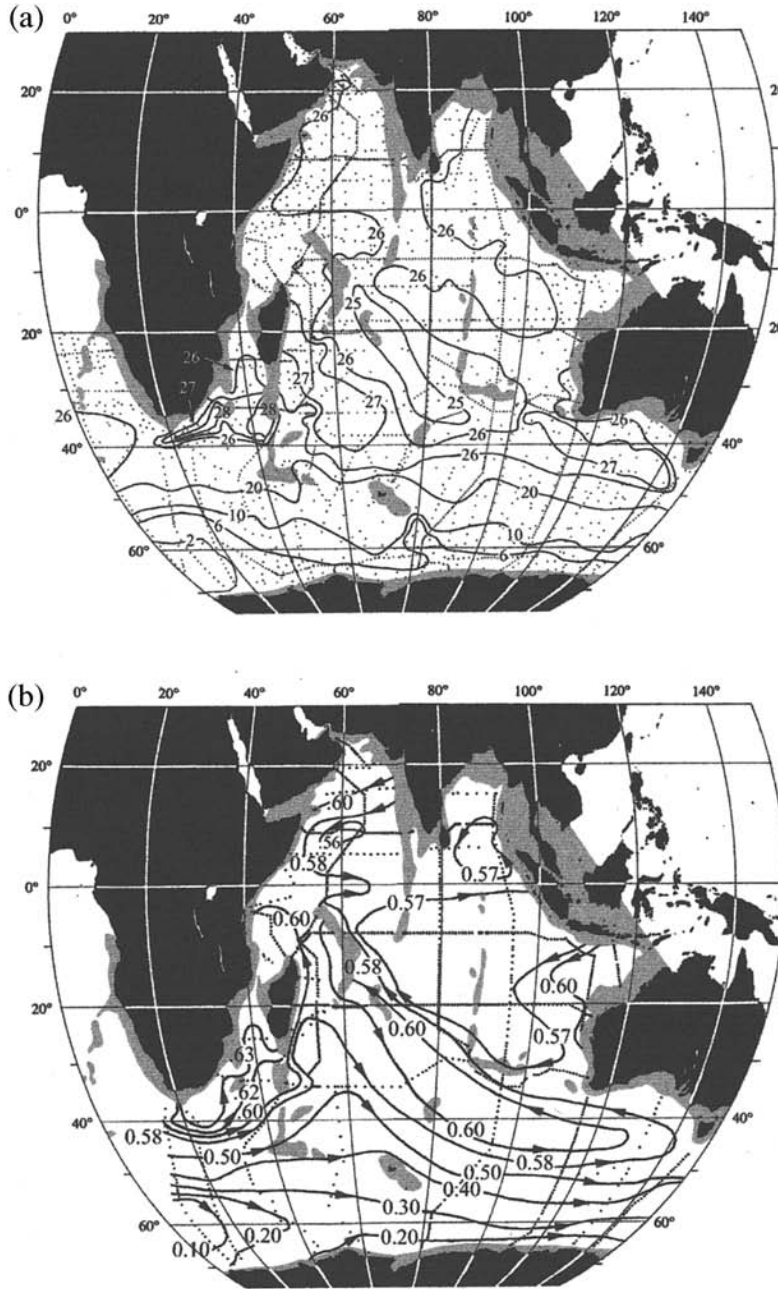
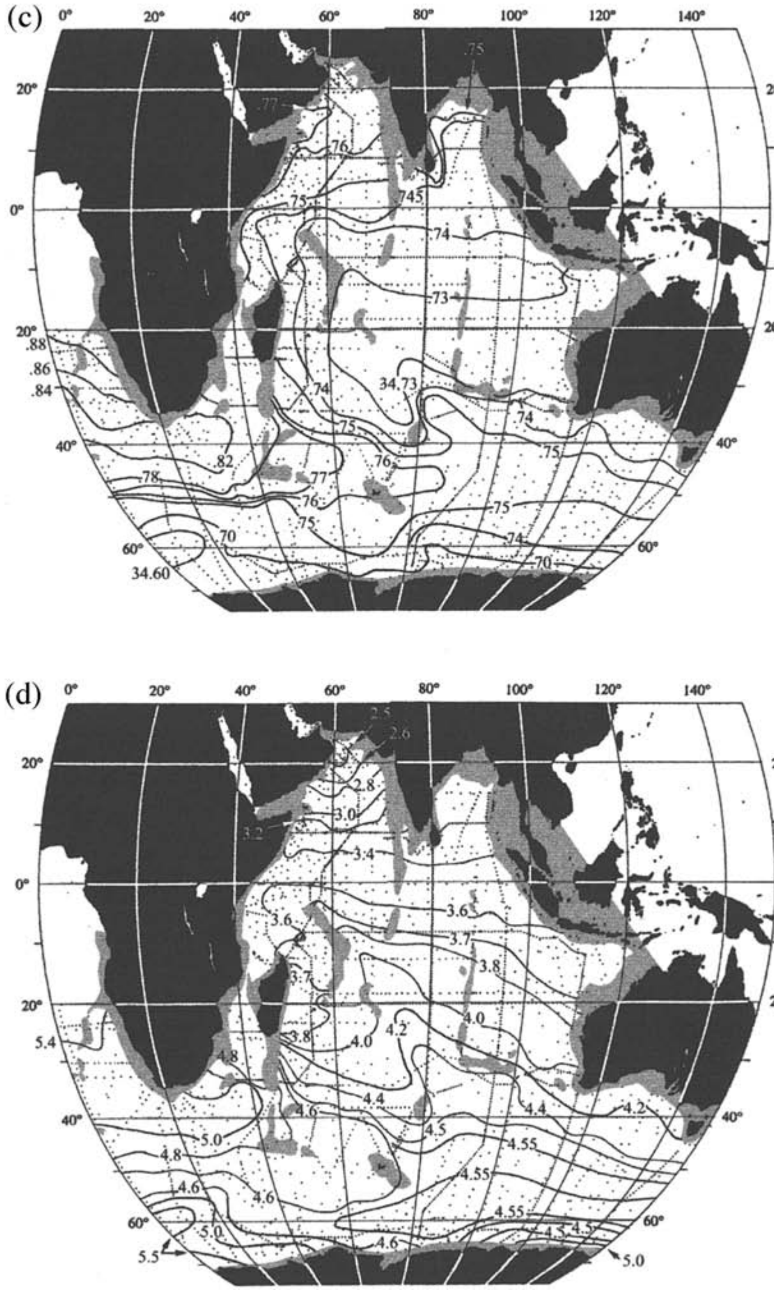


Figure 4. (a) Depth (hm) where σ_2 is 37.0; (b) Adjusted steric height along the isopycnal defined by 37.0 in σ_2; (c) Salinity along the 37.0 isopycnal; (d) Oxygen (ml/l^{-1}) along the 37.0 isopycnal and (e) Silica (μm kg^{-1}) along the 37.0 isopycnal.



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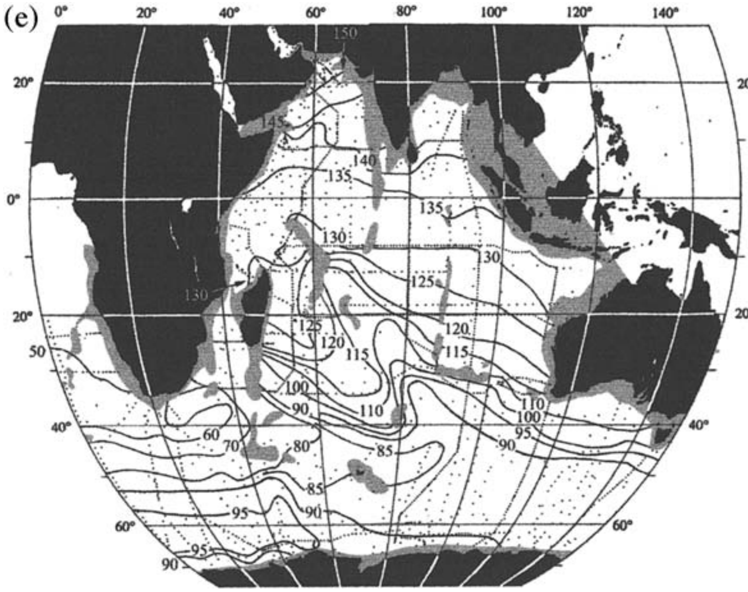


Figure 4. continued

4. The patterns along the isopycnal surface

High values of salinity and oxygen and low values of silica extend southward along the western boundary in the Atlantic and contrasting values from the circumpolar current extend northward in mid-ocean (Figs. 3c, 3d, and 3e). High salinity from the Mediterranean outflow extends westward as part of the anticyclonic gyre. Because the patterns of potential temperature along the isopycnal would be so nearly like those of salinity, such maps are not shown.

In the Indian Ocean (Fig. 4) all three of the tracers show extreme values extending southeastward with the subtropical anticyclonic gyre and contrasting extreme values flowing northwestward around the gyre (Mantyla and Reid, 1995). The same patterns are seen in the South Pacific Ocean (Fig. 5) and in the North Pacific also except for salinity, which decreases northward from the equator.

Both the South Indian and South Pacific oceans show a lateral minimum in salinity near 25S in this density range. This is roughly within the anticyclonic gyres. It is created by vertical exchange with the overlying less saline Intermediate Water. In the Indian Ocean it lies between the high salinity from the Red Sea (Beal *et al.,* 2000) and the high salinity from the Atlantic.

5. Salinity where σ_2 is 37.0

The vertical section (Fig. 1) begins from the overflow across the Iceland-Faeroe Ridge. This overflow water is very high in salinity (Figs. 2c and 3c). It extends around the

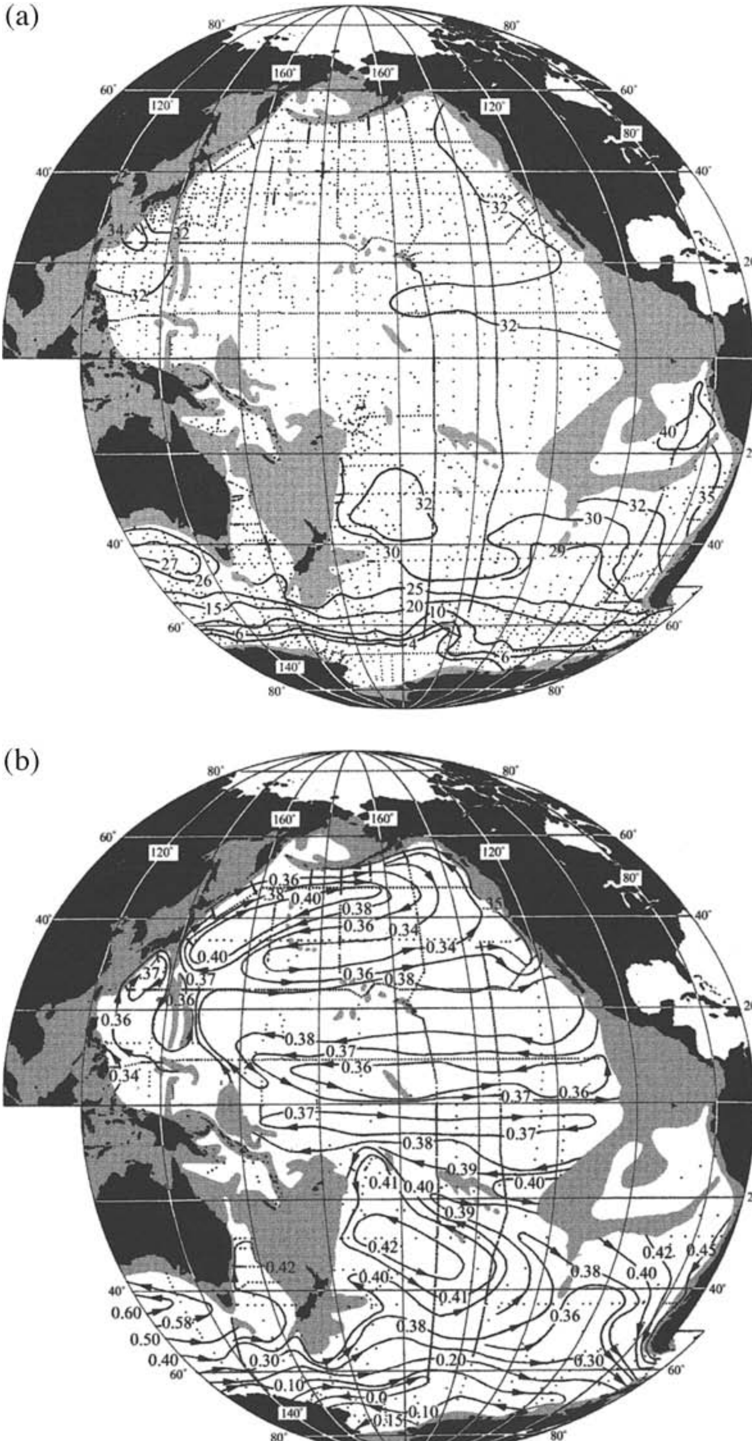
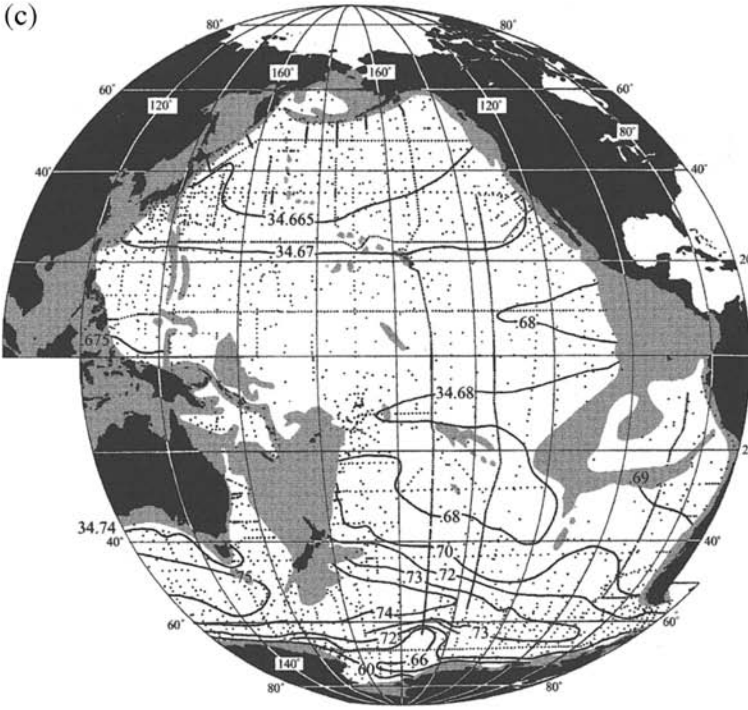


Figure 5. (a) Depth (hm) where σ_2 is 37.0; (b) Adjusted steric height along the isopycnal defined by 37.0 in σ_2; (c) Salinity along the 37.0 isopycnal; (d) Oxygen (ml/l^{-1}) along the 37.0 isopycnal and (e) Silica (μm kg^{-1}) along the 37.0 isopycnal.

(c)



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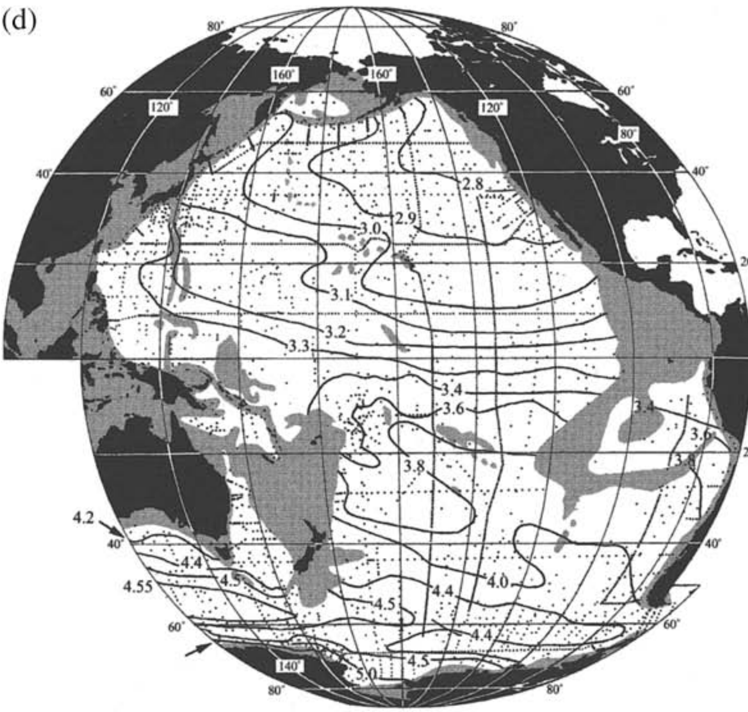

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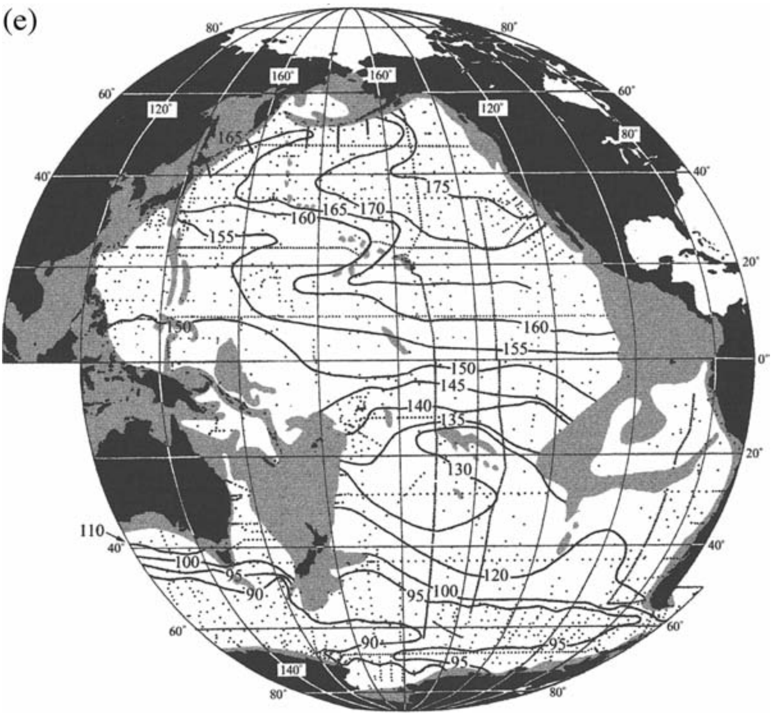

Figure 5. continued

Irminger Basin and through the Labrador Sea where it lies beneath less saline water and its salinity decreases to a value as low as those at the equator.

South of 50N it passes beneath the core of Mediterranean outflow and becomes warmer and more saline. The highest values in the mid-latitudes are directly from the Mediterranean outflow, part of which flows westward across the Atlantic. It joins the southward flow along the western boundary and passes beneath the Intermediate Water from the south (Tsuchiya, 1989). Vertical mixing with both this overlying low-salinity water and the underlying lower salinity from the far south reduces the salinity but leaves a vertical maximum a little less dense than 37.0 in σ_2, extending southward through the Atlantic. South of about 20S the salinity maximum lies near 37.0 in σ_2 along the section and remains so through the Drake Passage.

There is a vertical maximum in potential temperature in the South Atlantic that extends from about 20N to 42S (Fig. 2b). South of about 60S in the circumpolar flow, winter cooling of the surface water creates another vertical maximum south of the section which continues through the Drake Passage (Sievers and Nowlin, 1984). At the southernmost extension the maximum lies shallower and is eroded at the top by mixing with the colder low-salinity surface water, and the maximum is found at higher densities.

6. Oxygen where σ_2 is 37.0

At this density oxygen is highest in the far North Atlantic, from the deep overturns that take place in the Norwegian, Greenland, and Labrador seas (Figs. 2d and 3d). Like the salinity, it extends southward along the western boundary as a vertical maximum. The vertical maximum in oxygen is seen along the section only a short distance past Africa, but the lateral maximum continues to the Drake Passage (Figs. 2d, 3d, 4d, and 5d).

7. Silica where σ_2 is 37.0

The silica pattern (Figs. 2e, 3e, 4e, and 5e) is much like that of the oxygen, though reversed. It is low in the far North Atlantic, and a lateral minimum extends southward west of the anticyclonic gyres and then eastward with the circumpolar flow through the Indian and Pacific oceans to the Drake Passage. There are high values in the northern Indian and Pacific oceans extending southward with the southern anticyclonic gyre with low values looping northward in the east. Like the oxygen maximum the silica shows a vertical minimum in the Atlantic and part way into the Indian Ocean.

8. Discussion

Water overturned in the Norwegian, Greenland, Labrador, and Mediterranean seas pours into the North Atlantic Ocean at mid-depths and provides a deep layer with distinct characteristics. This layer is warmer, higher in salinity and oxygen and lower in nutrients than any other mid-depth waters of the World Ocean.

It flows southward along the western boundary of the Atlantic and most of it joins the circumpolar flow, extends around Antarctica and returns to the Atlantic through the Drake Passage. In the long path across the Indian and Pacific oceans its characteristics are diminished. Where it extends southward across the circumpolar flow to shallow depths near the boundary it becomes cooler and less saline, but can still bring salt near enough to the surface so that cooling can raise its density to cause overturn. In particular, more-saline water at this density is carried far southward with the cyclonic gyres of the Weddell and Ross seas, and can contribute to the abyssal waters formed there.

Water at this density enters the Atlantic Ocean through the Drake Passage and can still be recognized as a vertical and lateral maximum in salinity to about 50W. It is joined by and mixes with the much warmer and more saline water from the southward flow along the western boundary. Most of the mixture continues eastward with the circumpolar flow, but some part loops northward and joins the anticyclonic gyre, whose eastern limb flows northward east of the southward flow along the western boundary. Some part extends across the equator and can be seen in the tracers as far as 30N. Wüst (1935) showed this feature in a map of Middle North Atlantic Deep Water salinity but did not refer to it as indicating northward flow.

Thus, some circumpolar water of the same density as the southward flow along the western boundary extends into the North Atlantic. In its northward flow it becomes warmer and more saline by mixing with the adjacent southward flow, which therefore becomes successively cooler and less saline in the south.

Of course the northward flow of circumpolar water to the North Atlantic at densities near 37.00 in σ_2 is not large. The greater part of the northward flow that balances the southward flow of deep water is either from the Intermediate Water at shallower depths, or from much deeper.

Deep waters from the North Atlantic flow southward and then eastward through the Indian and Pacific oceans, but at least some of the deep waters for this density return to the North Atlantic, having made a complete circuit.

Acknowledgments. The work reported here represents one of the results of research supported by the National Science Foundation and the Integrative Oceanography Division of the Scripps Institution of Oceanography. I wish to acknowledge the assistance given by Arnold Mantyla in selecting the data and by David Newton for writing the various programs. I wish to acknowledge especially Sarilee Anderson for the great skill in handling the various data formats, in arranging the data and calculating and plotting the data points along the isopycnals and on the fields of steric height and for her patience in the long succession of adjustments.

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Received: *22 June, 2004;* revised: *13 October, 2004.*