Antarctic Intermediate Water in the South Atlantic

L.D. Talley

Scripps Institution of Oceanography
La Jolla, CA 92093-0230 USA

Abstract: Maps of the Antarctic Intermediate Water (AAIW) in the Atlantic, and on a global isopycnal which intersects the AAIW in the south, show the location and properties of the salinity and oxygen extrema associated with the AAIW, and the likely sources of AAIW. These are primarily the surface waters in the southeastern Pacific, which produce the South Pacific AAIW, and surface waters in northern Drake Passage and the Falkland Current loop, which produce the South Atlantic AAIW. This latter source is the primary one for AAIW of the Indian Ocean as well. Winter surface properties and annual-averaged Ekman pumping and Sverdrup transport for the southern hemisphere suggest that the formation density of the AAIW is the highest density which can be subducted in the South Pacific. The higher density of AAIW in the South Atlantic may result from more complex processes. The connection between the subtropical gyres of the Atlantic and Indian and between the Indian and Pacific Oceans contributes to modification of AAIW as it spreads tortuously northward around the subtropical gyres. Potential vorticity and AAIW salinity and oxygen illustrate the near barrier between the subtropical and tropical regimes, at about 20°to 25°north and south of the equator. Communication between the regimes is primarily through the western boundary currents.

Introduction

The intermediate layer originating from near the sea surface near the Antarctic Circumpolar Current (ACC) and extending northward through the Atlantic, Pacific and Indian Oceans has long been identified by the salinity minimum lying at about 800 to 1000 meters, and in more local regions by oxygen, silica and potential vorticity extrema. The earliest salinity minimum observations are from the Challenger expedition in the last century (Buchanan 1877). Merz and Wüst (1922) presented a more complete meridional section of salinity and summarized previous work and concluded that the low salinity layer contradicted hypotheses of upwelling from the deep ocean to the surface near the equator.

Wüst's (1935) meridional section of salinity and his core layer maps based on the *Meteor* data also clearly show the subtropical circulation of AAIW, intensification of flows along the western boundary, northward penetration of AAIW in the western boundary current in the tropics, and eastward penetration near the equator. Taft (1963) deduced from maps of salinity and oxygen for the globe on an isopycnal intersecting the AAIW that the southeast Pacific and South Atlantic are the sources of AAIW, with no source in the Indian Ocean. He showed that in the South Atlantic most of the AAIW from the southwestern corner spreads northward around the subtropical gyre rather than directly northward along the western boundary. He pointed out the important boundaries in AAIW properties near 20°S in all oceans.

In the Atlantic and Pacific, the intermediate and bottom layers, which are of Antarctic origin, flow northward on average while the deep water between them flows southward, as first suggested by Merz and Wüst (1922). AAIW is part of the return of upper layer water to the northern North Atlantic and

From WEFER G, BERGER WH, SIEDLER G, WEBB DJ (eds), 1996, *The South Atlantic: Present and Past Circulation*. Springer-Verlag Berlin Heidelberg, pp 219-238

is one of the sources of North Atlantic Deep Water (NADW). At 4°to 5°C, AAIW is too cold to furnish directly the warm portion of the observed northward heat transport in the central South Atlantic (Gordon 1986). However, Rintoul (1991) suggests that part of the AAIW originating in the southwest Atlantic upwells due to net surface heat gain in the southern Atlantic, and that thus the formation and circulation of this intermediate layer might be important for the NADW cell. AAIW is also the dense end-member of a shallow overturning circulation in which surface layers north of the ACC lose buoyancy and sink. A test of whether numerical models include the proper physics to reproduce the circulation is whether they successfully produce these large-scale layers. England et al. (1993) show the importance of surface salinity near Antarctica in enabling a numerical model to produce Antarctic Bottom Water and a reasonable AAIW layer.

The following is a summary of some results concerning AAIW with emphasis on the Atlantic, drawn from a larger work in preparation which treats the global distribution. AAIW should not be defined narrowly in terms of property extrema; rather it should be defined as a coherent layer which originates near the ACC. Based on all properties the complete AAIW layer, as distinguished from the overlying surface layer and the underlying NADW/Upper Circumpolar Water, could be taken as 27.0-27.4σ_θ (31.6-32.0σ_1) or possibly to about 0.1σ_θ denser. Nevertheless the primary emphasis here is on identification of the extrema which characterize AAIW because of what they reveal about its sources, and about properties on an isopycnal which intersects the AAIW at its sources near Drake Passage. A core layer approach is used, with full understanding that these are not surfaces of flow. (Neither are isopycnal/neutral surfaces, although locally they are more likely to be such.) A partial discussion of the formation of AAIW follows in the last section, including the relationship between winter surface properties in the southern hemisphere and the winds.

The principal South Atlantic fronts are major boundaries in AAIW properties. I follow Peterson and Stramma's (1991) and Tsuchiya et al.'s (1994) nomenclature. The most important are the Polar and Subantarctic Fronts, defining the ACC. The Polar Front (about 2°C at the surface) is the northern boundary of the near-surface temperature minimum, and the Subantarctic Front (about 4°C at the surface) is the southern boundary of the AAIW at most longitudes. A maximum horizontal density gradient is the best indicator of both. North of the Subantarctic Front lies the Subantarctic Zone, which is bounded to the north by the Subtropical Front. In the Subantarctic Zone is found Subantarctic Mode Water (SAMW) (McCartney 1977; 1982), a thick near-surface layer with temperature decreasing towards the east around the ACC. McCartney (1977) concluded that SAMW is the primary precursor of AAIW. North of the Subtropical Front is a lighter type of SAMW (Tsuchiya et al. 1994, for the southwestern Atlantic). This is bounded to the north by the Brazil Current Front in the west (Tsuchiya et al. 1994) and the Benguela Current Front in the east (Gordon et al. 1992). These might be considered to be a single front (BCF). North of the BCF is a front which marks the northern boundary of the subtropical circulation. Tsuchiya et al. (1994) call this the Subtropical-Subequatorial Front (STSEF) for want of a better term. It is the deep, poleward-shifted expression of the surface Angola-Benguela Front. Frontal structure which mirrors this pattern is found in the North Atlantic.

AAIW core layer and isopycnal properties

Data. The high quality discrete bottle dataset used in various studies by Reid (1986; 1989; 1994) plus other bottle and CTD data sets collected in the 1980's and 1990's in the Atlantic and Pacific were used for this study. Vertical extrema of salinity, oxygen, and silica were determined from the discrete bottle data. To map salinity and isopycnic potential vorticity, $Q = (f / \rho)\delta\rho / \delta z$ (where f is the Coriolis parameter and relative vorticity is ignored), the station data were interpolated to isopycnals using an Akima cubic spline which avoids introducing spurious vertical extrema. Densities were calculated relative to the sea surface (σ_θ) or 1000 dbar (σ_1). Vertical stability, using the pressure between isopycnals as a reference, was used to compute Q.

The isopycnal chosen for display is $31.7\sigma_1$, which corresponds closely with $27.1\sigma_\theta$. It characterizes the top of the AAIW layer in the Atlantic/ Indian and the middle of it in the Pacific. It was chosen for global mapping as it better illustrates AAIW formation than a slightly denser isopycnal which would better characterize the AAIW core layer at midlatitudes and in the tropics.

AAIW extrema (Figs. 1 and 2). The vertical section of salinity along about 25°W from South Georgia Island to Iceland (Fig. 1a) is the modern equivalent of one of Wüst's long meridional sections. Tsuchiya et al. (1992; 1994) describe the water masses on this section. The principal salinity layers identified by Merz and Wüst (1922) and Wüst (1935) are clearly recognized. The main AAIW salinity minimum at 25°W extends northward from the Subantarctic Front (SAF) at 45°S. AAIW of salinity less than 34.3 psu is found as far north as the Brazil Current Front, at 32°S where the low salinity core reaches its maximum depth The minimum can be traced across the equator, ending at about 21°N (here the section lies east of the Mid-Atlantic Ridge). Properties on a Greenwich meridian section (Fig. 13b in Reid 1989) are very similar (Whitworth and Nowlin 1987).

The AAIW is also a vertical oxygen maximum in the South Atlantic's subtropical gyre and in a small region of the tropics (see below) indicating relatively recent surface origin. Wüst (1935) showed an AAIW oxygen maximum reaching the equator along the western boundary, but only to about 20°S in the central and eastern Atlantic. Along 25°W (Fig. 1b) the AAIW oxygen maximum is found between the Subtropical Front and the STSEF at about 20°S (Tsuchiya et al. 1994). An AAIW oxygen maximum is absent south of the Subtropical Front due to the high oxygen of the overlying SAMW. Oxygen at the maximum between the Brazil Current Front and the STSEF is greatly reduced compared with south of the Brazil Current Front.

Scatter plots (Fig. 2) of all vertical salinity minima, oxygen maxima and silica maxima in the Atlantic are based on the broadly distributed bottle data set used in Figs. 3-7. The AAIW salinity minimum clusters around 31.8 to $31.9\sigma_1$ between 40°S and 20°N. South of about 40°S the salinity minima are more scattered - these are in the surface layer above the temperature minimum. North of about 15°N, the density increases from about 31.85 to $32.0\sigma_1$, and north of about 25°N the salinity minimum layer becomes indistinct. (The cluster in the north at about $32.4\sigma_1$ is the Labrador Sea Water.) The densest salinity minima are the Lower Circumpolar Water relative to the overlying saline NADW. The characteristic density for the Atlantic AAIW salinity minimum thus is approximately $31.8\sigma_1$ south of about 25°S. North of this it is denser, about 31.85 to $31.9\sigma_1$; this corresponds to about $27.3\sigma_\theta$, used in Suga and Talley (1994) to study the tropical circulation of AAIW. Reid (1989; 1994) selected $31.938\sigma_1$ which also is more typical of the tropics and North Atlantic. The main locus of the salinity minimum in the Indian Ocean is $31.8\sigma_1$; in the Pacific Ocean's subtropical gyre it is $31.7\sigma_1$ (not shown).

An AAIW oxygen maximum is apparent south of about 25°S, where the salinity minimum is less dense. The oxygen maximum is slightly less dense than the salinity minimum; this is much more apparent when actually mapping the two extrema. The arc of high oxygens north of 40°N is the Subpolar Mode Water there, and the layer at $32.4\sigma_1$ is the Labrador Sea Water. The densest high oxygens mark the North Atlantic Deep Water.

A silica maximum is evident at densities much higher than AAIW in the South Atlantic's subtropical gyre; this is actually the Upper Circumpolar Water and not the AAIW. This layer is truncated from below in the tropics by the North Atlantic Deep Water, and the silica maximum in the tropics is closely associated with AAIW. The clear silica maximum in this zonally-undifferentiated view ends at 25-30°N, although it can be traced on individual sections far to the north (Tsuchiya, 1989), unlike the salinity minimum. The densest silica maxima mark the Lower Circumpolar Water.

Salinity minimum (Fig. 3a and 4) and isopycnic salinity. The AAIW salinity minimum is bounded to the south by the Subantarctic Front, where isopycnals plunge steeply from 100-200m to greater than 1000 m in the western subtropical South Atlantic. The minimum terminates in the North Atlantic between 20-25°N, with a rather ill-defined

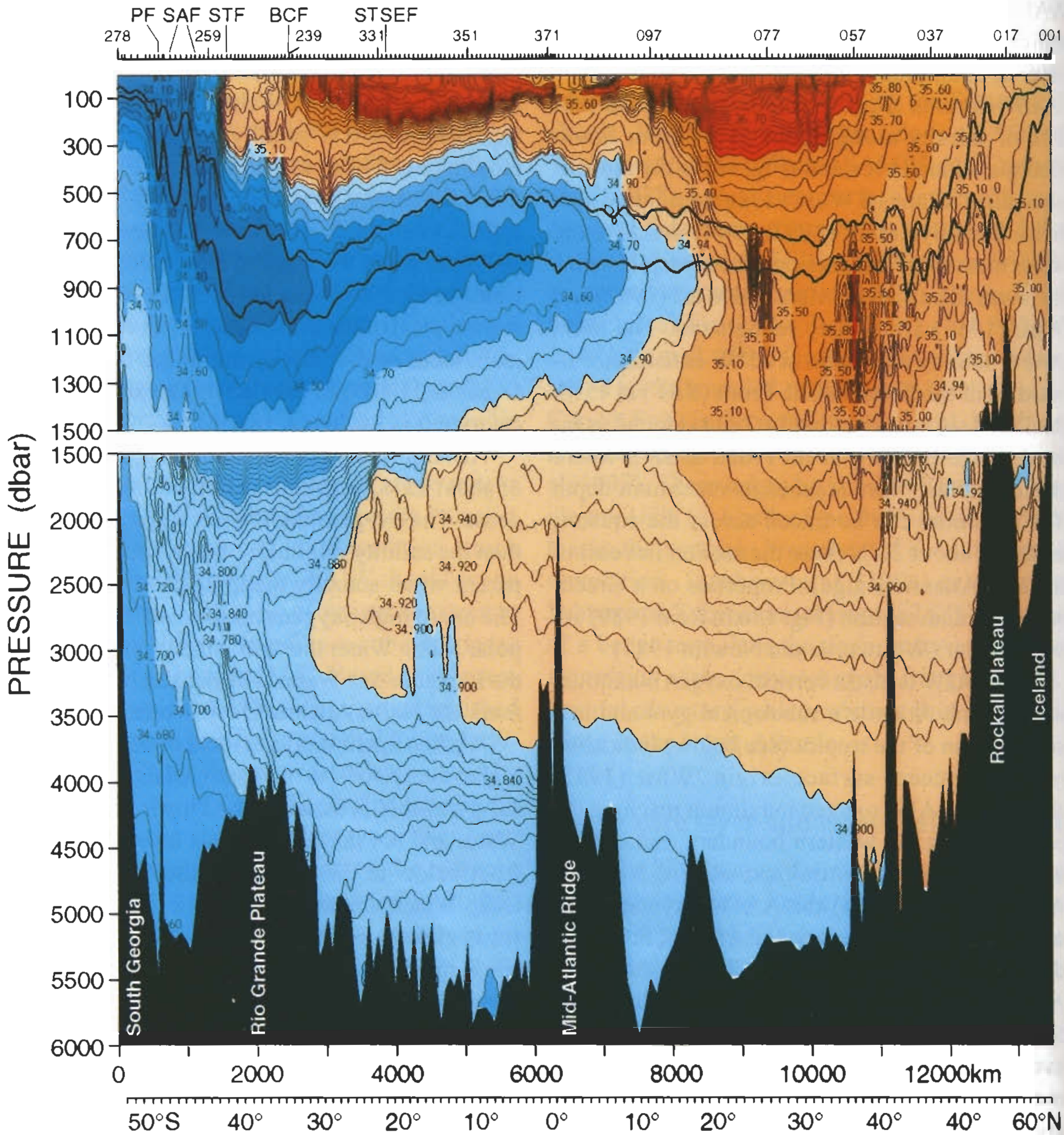

Figure 1. (a) Salinity and along approximately 25°W, from South Georgia Island to Iceland, from 1988-1989. The two curves which pass through the AAIW are the 31.7 and 31.9 σ_1 isopycnal contours. The North and South Atlantic portions were described in Tsuchiya et al. (1992, 1994) respectively. Annotations above the section indicate the Polar Front (PF), Subantarctic Front (SAF), Subtropical Front (STF), Brazil Current Front (BCF), Subtropical-Subequatorial Front (STSEF). CTD data were smoothed with a Gaussian with an 11 dbar half-width and then optimally mapped to a 20km x 40dbar grid for the deep sections and 20km x 10dbar for the shallow sections.

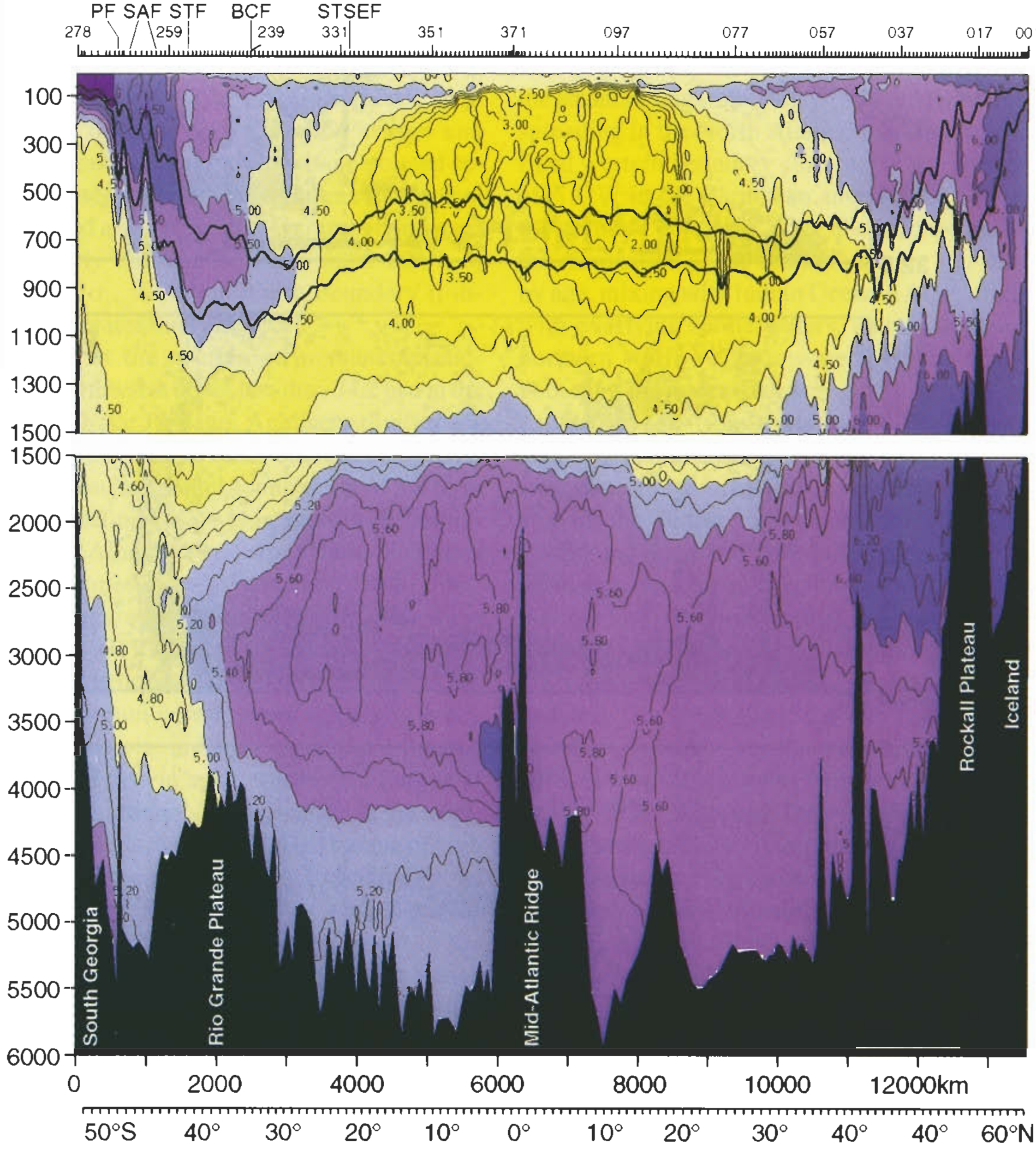

Figure 1. **(b)** oxygen (ml/l) along approximately 25°W, from South Georgia Island to Iceland, from 1988-1989. See fig. 1. (a) for details.

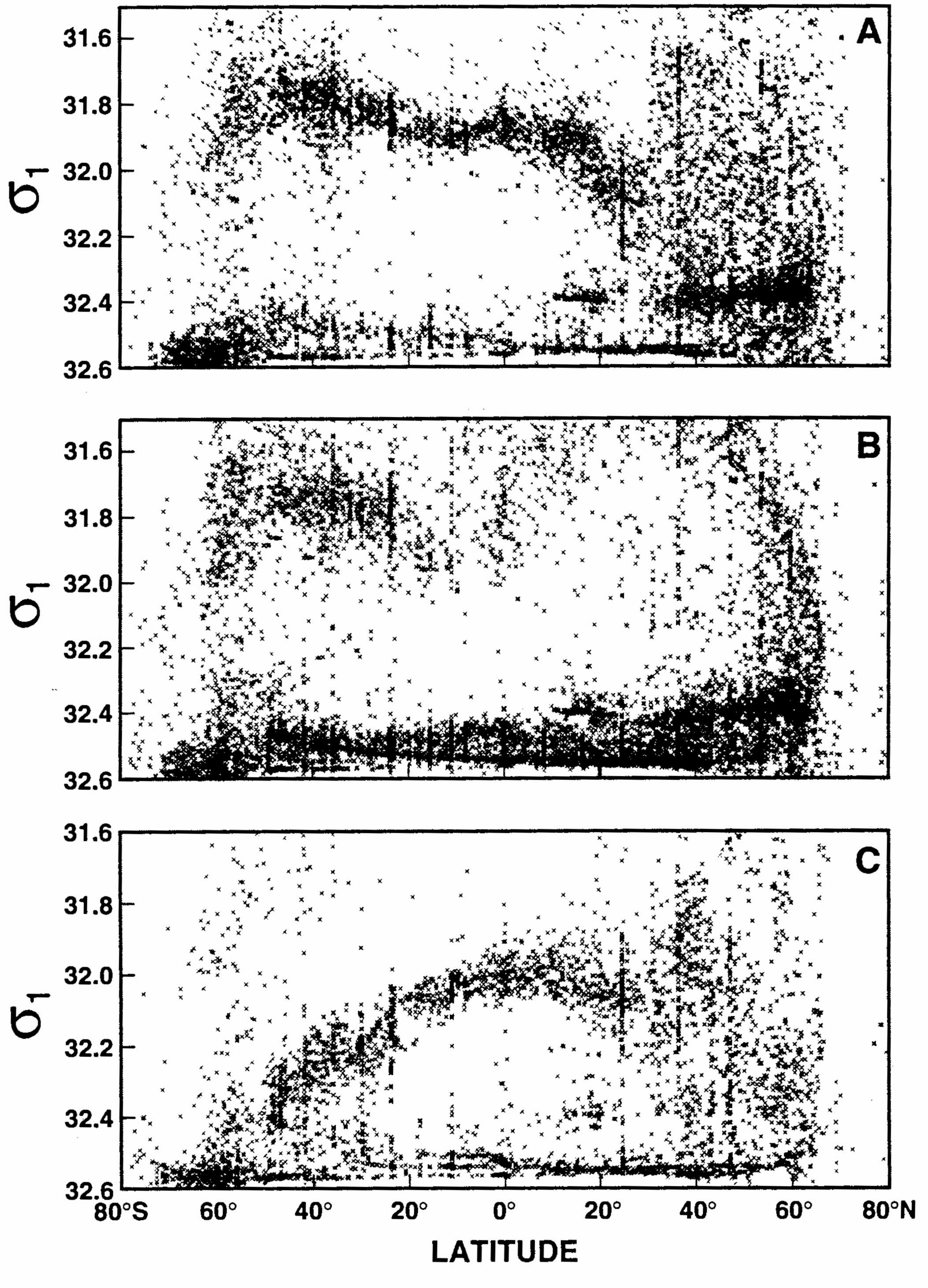

Figure 2. **(a)** All salinity minima in the potential density anomaly range 31.6 to 32.6 σ_1, referenced to 1000 dbar. **(b)** All oxygen ~~minima~~ maxima in the same potential density anomaly range. **(c)** All silica maxima in the same potential density range. Station distribution is evident from the maps of Figs. 2-6 . The data were not interpolated; all vertical extrema were selected.

boundary where it meets the Mediterranean Water in the eastern Atlantic. The depth distribution is similar to Wüst's (1935), with the modern data adding a shallow ridge in the Benguela Current and extending northwestward near 20°S. The minimum is remarkably flat in the tropics (750± 50m). North of 20°N the core deepens to 1000m as the Mediterranean Water chews into the top of the salinity minimum. AAIW density is less than $31.8\sigma_1$ in Drake Passage and around the subtropical gyre, with an isolated region of denser minima in the central subtropical gyre centered at 40°S. Density increases northward and is nearly uniform between 20°S-20°N, at $31.85\text{-}31.95\sigma_1$. At the northern boundary it increases to greater than 32.0 σ_1.

Salinity at the minimum increases monotonically northward, being less than 34.2 psu in the south and Drake Passage. Agulhas salinities are greater than 34.4 psu, with no obvious connection to the 34.4 psu minimum found north of 35°S. In the tropics, salinity is lower in the western boundary current. Along the equator, salinity increases eastward, connecting with saline water in the tropical cyclonic gyre (Gordon and Bosley 1991; Suga and Talley 1994). Salinity increases to more than 35.1 psu at the northern boundary. Oxygen at the salinity minimum core mirrors salinity in many important aspects, indicating ventilation in the south, an increase in age northward, a tongue of high oxygen at the western boundary in the tropical South Atlantic, and an eastward tongue of high oxygen along the equator. Low oxygen is found in the usual tropical locations at the eastern boundary. Oxygen increases towards the north in the North Atlantic, because the saline water which mixes with the southern hemisphere water outcrops in the northern North Atlantic (see Tsuchiya 1989; Reid 1994).

The major features of the salinity and oxygen distribution at the AAIW salinity minimum were already quite clear in Wüst's (1935) presentation. However, it is useful to see that our modern and much larger data set does not contradict these features, and provides sharpened focus for important features. These include: (1) a southern boundary which is essentially the Subantarctic Front, (2) continuity of the southernmost AAIW salinity minimum with that in Drake Passage or with the thick surface layer north of the Subantarctic Front in Drake Passage, (3) possible continuity of mid-latitude AAIW with that of the Agulhas retroflection, (4) the narrow, northward western boundary current in the tropics, eastward flow in the equatorial zone (although possibly not right on the equator - Suga and Talley 1994), (5) northward spreading in the North Atlantic in a less well-defined western boundary current, (6) the presence of AAIW in the Caribbean and Gulf of Mexico, the northern boundary along about 25°N, and (7) the elimination of the southern source signatures by age, mixing with Indian Ocean AAIW, mixing with overlying saline waters, and mixture with northern North Atlantic waters which increase both the salinity and oxygen.

Salinity on isopycnals which characterize AAIW (Fig. 4) has a similar pattern to that in the various core layers (salinity, oxygen extrema) and also on the denser isopycnals mapped in Reid (1989) and Suga and Talley (1994), so only global features and Atlantic features which differ from the core layer description (Fig. 3a) are mentioned here. In the Atlantic equatorial region, relatively low salinity spreads eastward at about 5°S, as also seen at $27.3\sigma_\theta$ ($31.9\sigma_1$) in Suga and Talley (1994). The high salinity near the eastern boundary at 10°S, in the cyclonic gyre (Taft 1963; Gordon and Bosley 1991; Suga and Talley 1994) is isolated, unlike at the salinity minimum (Fig. 3a) or on the $31.938\sigma_1$ surface shown by Reid (1994). The isolated high salinity indicates the presence of vertical mixing, as noted in Gordon and Bosley (1991) and Suga and Talley (1994). In the North Atlantic, the saline Mediterranean and fresh Labrador and GIN Sea influences are notable. A large meridional gradient occurs between 10° and 20°N, separating the AAIW and Mediterranean Water.

In the Indian Ocean, the overall salinity is higher than in either the Atlantic or Pacific Oceans. The salinity of the Agulhas is higher (> 34.5 psu) than in the western subtropical gyres of either the South Atlantic or South Pacific. The high salinity apparently comes from the tropics. The dominant salinity in the subtropical region is between 34.4

Figure 3. (a) Salinity at the AAIW salinity minimum. The southern boundary is taken to be the 200 m depth contour for the salinity minimum, and coincides well with the Subantarctic Front. The northern boundary is the edge of the uniform occurrence of the salinity minimum; to the north, minima in the desired density range occur at some stations. The northern boundary coincides roughly with the change from tropical to subtropical regimes evident in the potential vorticity distribution (Fig. 5).

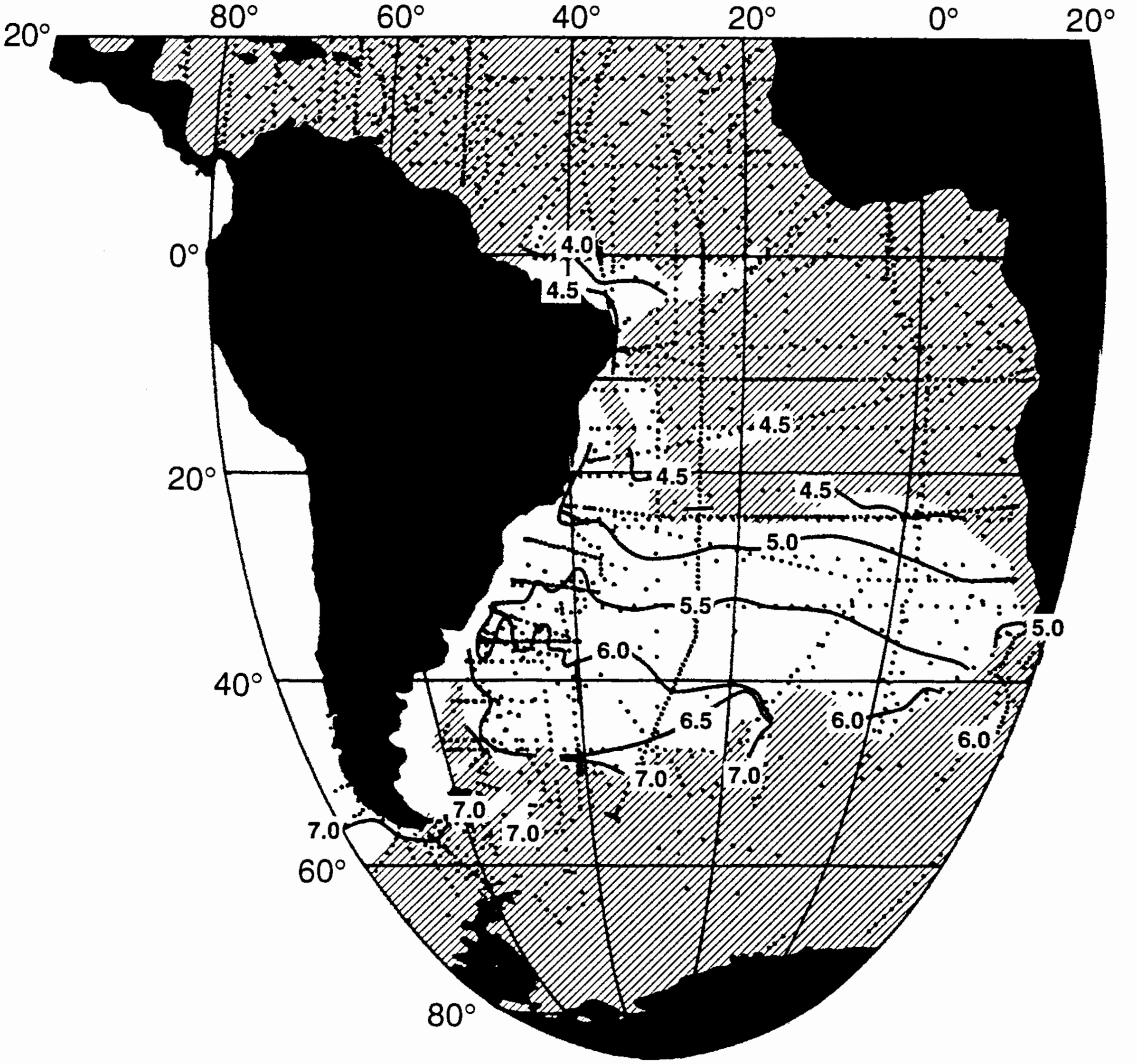

Figure 3. (b) Oxygen (ml/l) at the AAIW oxygen maximum. The southern boundary is somewhat aligned with the Subtropical Front. The northern boundary across most of the South Atlantic is the Subtropical-Subequatorial Front, which corresponds with the change from tropical to subtropical regimes in the potential vorticity distribution (Fig. 5).

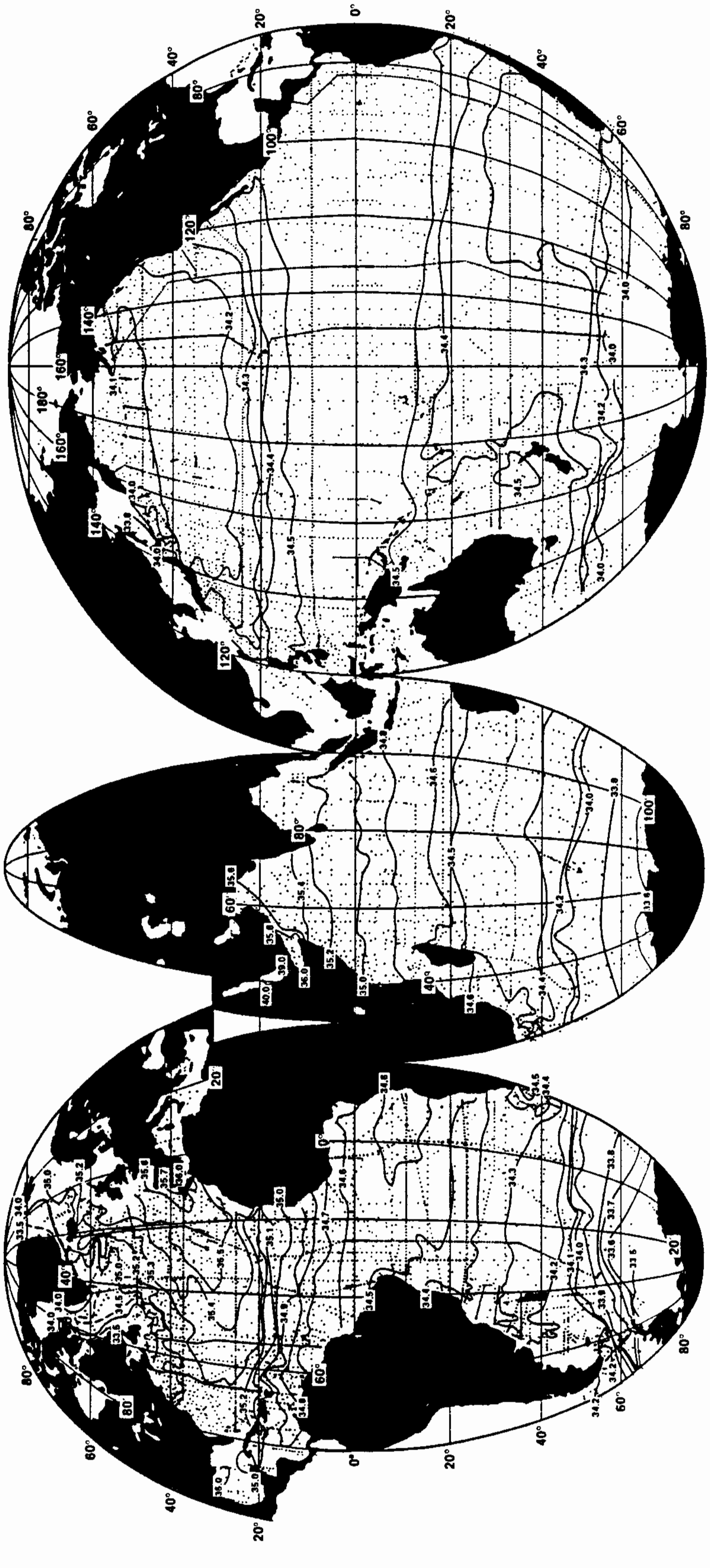

Figure 4. Salinity at $31.7\sigma_1$ for the globe, based on discrete bottle data inter-polated to the isopycnal using an Akima cubic spline.

and 34.5 psu, and is continuous with the region south of Australia and the Tasman Sea. The Red Sea and Arabian Sea are the most saline regions. The AAIW salinity minimum lies below $31.7\sigma_1$ throughout the Indian Ocean.

In the South Pacific, salinity at $31.7\sigma_1$ shows the clear signs of subduction in the eastern subtropical gyre: the low salinity tongue penetrates northward and counterclockwise around the gyre. In the follow-on study of the global AAIW, it will be shown that the $31.7\sigma_1$ isopycnal outcrops just south of the Subantarctic Front in the southeastern Pacific, and that this is located north of the climatological zero of wind stress curl, and hence in the subtropical gyre. Salinity on this isopycnal in the Pacific increases towards the equator, where it is highest, and then decreases to the north, due to the influence of the fresh water of the northern North Pacific and especially the Okhotsk Sea.

Oxygen maximum and isopycnic oxygen (Fig. 3b and Fig. 5). In the South Atlantic the oxygen maximum associated with AAIW is found in the subtropical gyre and extending northward along the western boundary and eastward along the equator. As shown above for 25°W (Fig. 1a), its area is much more restricted than the salinity minimum. Its northern boundary is the STSEF at about 20°S and it penetrates into the tropics only along the western boundary. It is found penetrating weakly into the Indian Ocean between 35°S and the SAF, with oxygen values decreasing monotonically eastward from the southwestern South Atlantic. The Agulhas does not contain an AAIW oxygen maximum. This suggests that the Indian Ocean maximum is advected from the South Atlantic rather than being local (Taft 1963).

The oxygen maximum is about 100 meters shallower than the salinity minimum in the subtropical gyre. Its density is thus lower than the salinity minimum density, being less than $31.7\sigma_1$ in the southeastern Pacific, Drake Passage, and along the western boundary to 38°S. In most of the subtropical gyre it is between 31.7 and $31.8\sigma_1$, and increases to greater than $31.8\sigma_1$ in the tropical western boundary region.

Oxygen at $31.7\sigma_1$ is displayed for the Atlantic Ocean only (Fig. 5). Very high oxygen (> 7.5 ml/l) occurs where the isopycnal lies close to the surface south of the Polar Front, with a reduction to about 6 ml/l through the Falkland loop, and high meridional gradients across the Polar Frontal Zone east of 40°W. Oxygen decreases towards the north. A split of the westward flow between 20° and 30°S occurs at the western boundary, and a tongue of high oxygen extends northward along the western boundary and then eastward near the equator. This eastward tongue appears to be more centered on the equator than at slightly higher density, such as the $27.3\sigma_\theta$ in Suga and Talley (1994). The eastern tropical minima are obvious both north and south of the equator.

Warner and Weiss (1992) showed no measurable chlorofluoromethanes in the eastern tropical regions, coincident with the very low oxygen regions. Thus low oxygen in the tropics is due to long residence time rather than especially high consumption. They also showed high oxygen along the western boundary and eastward along the equator, with the latter slightly displaced to the south.

In the northern hemisphere, the highest oxygen values are at the western boundary and decrease northward, reaching a minimum at 10°N and through the Caribbean. Oxygen is high in the subpolar North Atlantic because this isopycnal outcrops; the high values enter the subtropical gyre in the east, and increase the western boundary oxygen somewhat. The Gulf Stream is an axis of low oxygen, although at 3.5 ml/l, it is higher than where the water from the South Atlantic crosses the equator. Relatively high silica (Tsuchiya, 1989) in the Gulf Stream is due to South Atlantic influence, suggesting that at part of the reason for low Gulf Stream oxygen is South Atlantic water, although tropical North Atlantic water also has low oxygen.

Silica maximum. In the North Atlantic, far from the Antarctic source and beyond the boundary of the recognizable salinity minimum, AAIW can be tagged by a silica maximum (Tsuchiya 1989). In the South Atlantic subtropical gyre the silica maximum is identified with Upper Circumpolar Water which lies below the AAIW; its silica is enriched over that of the North Atlantic Deep Water by admixture of silica-rich Pacific

Figure 5. Oxygen (ml/l) at $31.7\sigma_1$ for the Atlantic Ocean, as in Fig. 3.

and Antarctic waters. Its silica is higher than that of AAIW since the latter originates from silica-poor surface waters. In Tsuchiya et al. (1994), it was shown that the Upper Circumpolar Water is truncated from below by NADW north of the STSEF at about 20°S; to the north the density of the silica maximum is only slightly higher than that of the salinity minimum (Fig. 2). It appears on virtually every station in the tropics and sporadically on stations at higher northern latitudes, being apparent even on the zonal section at 48°N. Tsuchiya (1989) mapped the silica as a lateral maximum (on an isopycnal) far northward, showing the southern influence on the intermediate waters in the North Atlantic's subpolar gyre.

Potential vorticity (Q) minimum and isopycnic Q (Fig. 6). The AAIW core can be identified as a weak stability/potential vorticity minimum in the southwestern South Atlantic (Tsuchiya et al. 1994), where isopycnic potential vorticity is $f/\rho\ \delta\rho/\delta z$, and ρ is the locally-referenced potential density. A more persistent AAIW-related potential vorticity signature in the South Atlantic is its position at the top of the low potential vorticity of the deep ocean. Thus it marks the base of the main pycnocline. The strongest AAIW Q minimum is just on the northern side of the SAF in the western region; it underlies a stronger near-surface Q minimum associated with SAMW (McCartney 1977; 1982). In the Polar Frontal Zone, between the Subantarctic and Polar Fronts, the AAIW density is that of the surface outcrop in winter, marked by the potential vorticity minimum which is closest to the sea surface. Extremely low potential vorticity at AAIW densities is found in northern Drake Passage and along the western boundary, suggesting convective overturn (McCartney 1982) enhanced by the baroclinicity of these strong currents. The AAIW Q minimum even in these regions is however much weaker than in the southeastern Pacific, where AAIW is associated with a strong and spatially-persistent potential vorticity minimum (McCartney and Baringer 1993; Talley, in preparation).

East of the mid-Atlantic Ridge, the northern boundary of the Q minimum is the Benguela/Brazil Current Front (BCF), which supports the suggestion that Indian Ocean AAIW is entering the northern subtropical gyre and moving westward (Taft 1963; Gordon et al. 1992). At the western boundary, the BCF is about 5° south of the northern limit of the potential vorticity minimum. North of 20°S, weak potential vorticity minima reappear, but identification as AAIW is not clear.

The global map of potential vorticity at $31.7\sigma_1$ (Fig. 6) is based on individual station data rather than a smoothed average, and thus reveals more features and more detail than Keffer's (1985) map for the layer $27.0\text{-}27.3\sigma_\theta$ (roughly $31.6\text{-}31.9\sigma_1$), based on Levitus (1982) data. Keffer showed the dominance of the β-effect in the tropics, where $\beta = \delta f / \delta y = 2\Omega\cos\theta / R$ where θ is latitude and R is the earth's radius. Keffer showed homogenization of potential vorticity in the North Pacific, and also the South Pacific and Indian Oceans. He drew attention to the signature of ventilation in the North and South Atlantic subtropical gyres. Fig. 6 shows the same strong contrast between the β-dominated tropics and the subtropics. On the other hand, *only* the North Pacific has homogenized Q. Water of this density subducts from the sea surface in the subtropical regions of the other oceans; potential vorticity variations along the isopycnal's surface outcrop lead to subsurface variations and hence no overall homogenization.

The lowest Q outside the tropics is on either side of South America, around Drake Passage. The lowest is over Burdwood Bank ($< 2\times10^{14}$ $cm^{-1}sec^{-1}$), with the South Atlantic tongue extending northward in the Falkland loop and to the east between 40° and 45°S just north of the SAF. High potential vorticity appears to stream westward in the northern part of the gyre, originating from the Agulhas retroflection at the tip of Africa, and suggesting that there is indeed at least some Indian Ocean influence in the South Atlantic. The high Q tongue is separated from the β-dominated tropics by high meridional gradients.

West of Drake Passage is the other region of relatively low Q. The $31.6\sigma_1$ outcrops here and has very low potential vorticity, creating the South Pacific SAMW. The $31.7\sigma_1$ might not outcrop as vigorously. Nevertheless it has low potential vorticity ($< 6\times10^{14} cm^{-1}sec^{-1}$) in the southeast which

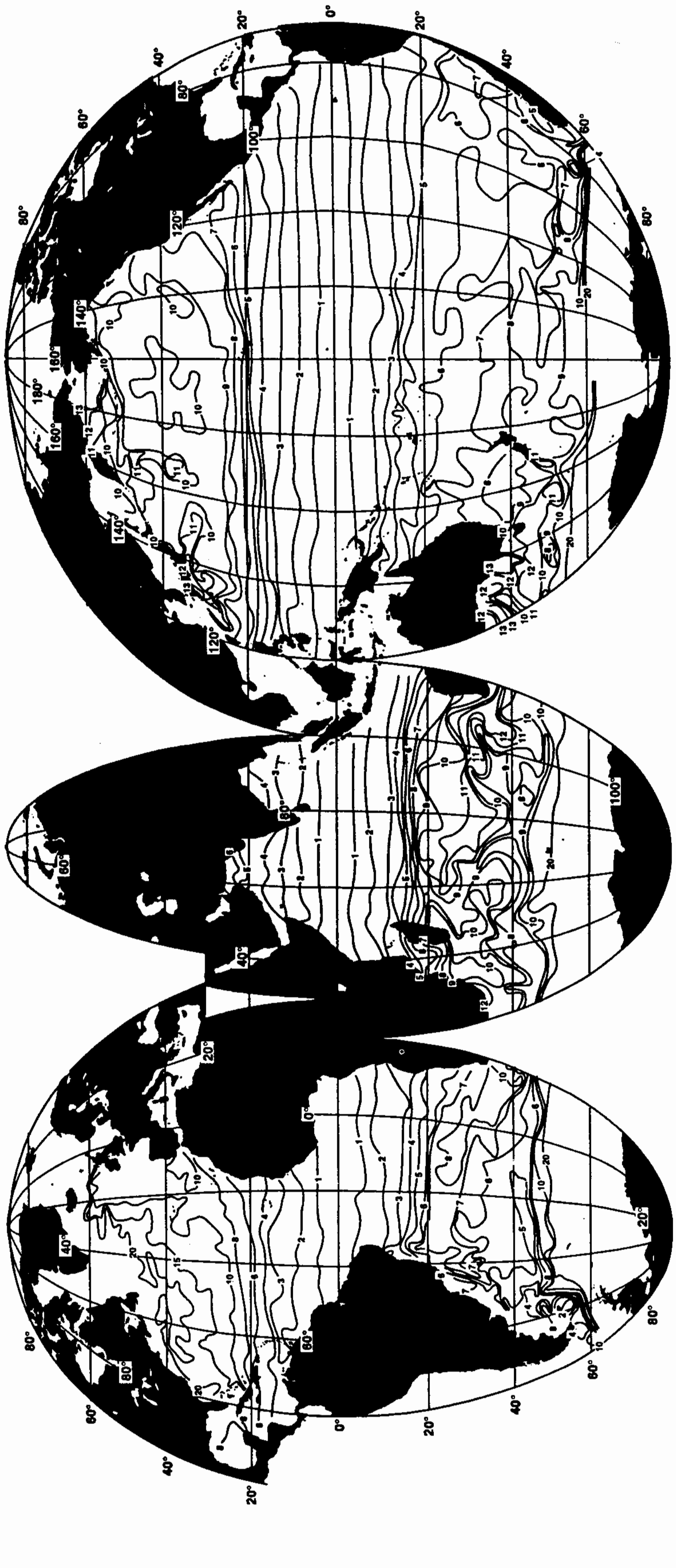

Figure 6. Isopycnic potential vorticity ($10^{14}cm^{-1}sec^{-1}$), ignoring relative vorticity, at $31.7\sigma_1$ for the globe. The absolute value is shown. (It is negative in the northern hemisphere.)

sweeps around the outer side of the subtropical gyre, and is separated from the β-dominated tropics by a high meridional gradient at about 20°S. The low potential vorticity is thus a signature of subduction of maximum density surface waters near the SAF. High potential vorticity enters from south of Tasmania and affects the southern and western parts of the subtropical gyre. A patch of high Q occurs at the eastern boundary at 30°S; this could be the eastern shadow zone of the subtropical gyre at this density.

Potential vorticity in the Indian Ocean subtropical gyre is overall higher but of a nearly identical pattern to the South Atlantic. Relatively low potential vorticity enters from the South Atlantic just north of the ACC. It branches into a core which enters the tight western part of the subtropical gyre near 70°E, where it corresponds to a high freon patch in the AAIW (Fine 1993), and an eastward core north of the SAF. Another tongue of relatively low potential vorticity extends northward into the subtropical gyre at 90° to 100°E. Along the northern side of the Indian Ocean's subtropical gyre, high potential vorticity streams westward from the southern side of Australia. This creates a higher meridional Q gradient bordering the tropics than in the other oceans. The highest potential vorticity in the southern hemisphere north of the ACC is in the South Australia Basin along the southern side of Australia. A constriction in the pattern south of Tasmania and New Zealand suggests that only the southern eastward limb of the anticyclonic flow can pass through.

Circulation

The geostrophic circulation in the South Atlantic at $31.7\sigma_1$ relative to 3000 dbar is represented by the pressure anomaly streamfunction (PAS) (Fig. 7) (Zhang and Hogg 1993), which is slightly more accurate than the acceleration potential. This reference pressure is deep enough to permit fairly accurate depiction of the flows, which have much in common with Suga and Talley's (1994) for the $27.3\sigma_\theta(\sim 31.9\sigma_1)$, and Reid's (1989; 1994) for the $31.938\sigma_1$. Figure 6 lies in complexity between those two, being entirely a matter of taste in hand contouring. The most vigorous flows are the ACC in Drake Passage, the Brazil and Falkland Currents at 35° to 50°S, the Agulhas retroflection, and the Gulf Stream. Between 25°S and 25°N, there is virtually no relief to the surface: all values lie between 1.2 and 1.3 dyn m. (This is not to say that the circulation is much weaker, since the vertical shear is 1/f times the lateral PAS gradient where f is the Coriolis parameter.)

The subtropical gyres of both hemispheres are clearly delineated. In the South Atlantic the southward overshoot of the Brazil Current at the western boundary is clearly apparent with the looped Falkland Current lying offshore. The PAS contrast across the Brazil Current is strongest south of 35°S, as shown by Zemba (1991); this major strengthening of the Brazil Current towards the south is likely related to the Sverdrup transport (Godfrey 1989) which is strongly affected by the southernmost location of Africa. The Agulhas retroflection is almost as strong as the Brazil Current, with a contrast of 0.3 dyn m compared with 0.5 dyn m. The double cyclonic gyre in the tropics (Suga and Talley 1994) is a splitting of the cyclonic gyre described by Gordon and Bosley (1991). Westward flow right along the equator and eastward flow to the south are suggested. However, floats released at the equator in the AAIW layer appear to have gone eastward (Richardson and Schmitz 1993), matching the tracer patterns better than would a westward flow.

The North Atlantic subtropical gyre is longitudinally less extensive than the South Atlantic's. A narrow cyclonic recirculation appears on its southeastern flank which is not apparent in Reid's (1994) adjusted circulation at 1000 dbar or Lozier et al.'s (1994) streamlines at $31.85\sigma_1$ which were based on averaged data. The circulation around the outer perimeter of the saline Mediterranean tongue appears weakly cyclonic, as seen more robustly in Lozier et al. (1994), and also as an offshore feature in Reid (1994). The tropical circulation in the North Atlantic is confusing since the total variation in PAS is so small between about 20°N and 20°S, but appears to contain a cyclonic gyre centered at 15°N; this is opposite to Reid's (1994) adjusted circulation.

Figure 7. Pressure anomaly streamfunction (dyn m) at 31.7σ_1 relative to 3000 dbar. A mean pressure of 750 dbar was subtracted prior to calculation. (Following Zhang and Hogg 1992).

Formation of AAIW

The following questions arise:
1) Where and how is AAIW principally injected from the surface? (**2**) What sets its density? (**3**) What are the significant modification processes both near its formation region and downstream?

1) *AAIW injection.* All recent work, dating from Taft (1963), asserts the importance of the region around Drake Passage for injection of AAIW (McCartney 1977; 1982; Gordon et al. 1977; Georgi 1979; Molinelli 1981; Sievers and Nowlin 1984; Peterson and Stramma 1991; Piola and Gordon 1989). McCartney (1977; 1982) showed the linkage of new AAIW with the surface pycnostad (SAMW) in the southeastern Pacific; a portion becomes the Pacific AAIW and the part which flows through Drake Passage is further modified and becomes the Atlantic and Indian Ocean AAIW. These concepts replace the earlier one of continuous injection all around Antarctica (Merz and Wüst 1922; Wüst 1935). The current debate is centered on the relative importance of cross-SAF exchange through and east of Drake Passage compared with air-sea interaction in modifying the properties of waters which become Atlantic AAIW.

There are two distinct types of AAIW: that produced west of Drake Passage and entering the South Pacific subtropical gyre through subduction (Luyten et al. 1983) and that produced east of Drake Passage in the confluence of the Falkland and Brazil Currents. All other variations in properties are due to mixing and differential advection (and biological processes for oxygen). The southeast Pacific process creates a subsurface pycnostad which can be identified as SAMW separately from AAIW but which I think should be very closely identified with AAIW. This process is identical to Subpolar Mode Water subduction, injecting thick pycnostads into the eastern North Atlantic subtropical gyre and SAMW subduction in the eastern South Indian subtropical gyre (both due to McCartney 1982), and a much less pronounced pycnostad subduction in the eastern North Pacific (Suga et al. 1996; Nakamura 1996). AAIW salinity minimum formation in the southeast Pacific is analogous to shallow salinity minimum formation through subduction in the eastern North Pacific (Yuan and Talley 1992) and to formation of the short-lived salinity minimum at the subarctic front in the North Atlantic (Subarctic Intermediate Water) (Arhan 1990).

The southwest Atlantic process creates the Atlantic and Indian Ocean AAIW; their subtropical gyres are connected in their eastward flowing branches (but more broken in their westward flow due to Africa). The thick winter surface layer south of the SAF (Falkland Current) and inshore of the Falkland Current is injected into the subtropical gyre through ring formation and mixing at the Brazil/Falkland confluence. This process is like that of North Pacific Intermediate Water (NPIW) formation where the Kuroshio and Oyashio waters meet (Talley 1993; Talley et al. 1995). It is marked by enhanced fine structure, as documented by Georgi (1981). An hypothesis is that because mixing is more central to this process than to the gentle subduction of the eastern South Pacific, the potential vorticity minimum associated with the original surface pycnostad is much less persistent in the South Atlantic than in the South Pacific.

(**2**) *AAIW density.* The debate here centers on why the Atlantic AAIW salinity minimum is denser than the southeastern Pacific AAIW minimum: 31.8 vs. 31.7σ_1 (27.1 vs. 27.0σ_θ). This increase could be due to air-sea exchange and mixing across the Polar Front in Drake Passage as the surface water makes its way through Drake Passage and around the Falkland Current loop (Georgi 1979). The contrast between Falkland Current and Brazil Current waters could also account for some increase in density of the AAIW through cabbeling (Martineau 1953) as the cold, fresh southern waters mix with the warmer, saltier subtropical waters; this process is important in NPIW formation in the North Pacific (Yun and Talley 1996).

The larger question is what sets the overall density of AAIW. We have two processes to consider: subduction (eastern Pacific) and mixing of the dominant near-surface mode from the Falkland Current. Maps of winter surface density and wind parameters will be presented in the more complete work. Based on the Hellerman and Rosenstein (1983) annual averaged winds and the winter surface density based on all individual winter stations, the only places where the surface isopycnals 27.0-27.1σ_θ (31.6-31.7σ_1) lie north of the zero wind-stress curl, so could be subducted, are in the southeastern Pacific and southwestern Atlantic. The densest, mass-important subduction in a subtropical gyre is of water in its poleward-eastern corner if isopycnal outcrops are relatively zonal. There are only two such southeastern corners in the Southern Ocean: the southeastern Pacific and the southeastern Indian Ocean, since the eastward flow from the South Atlantic continues unobstructed into the Indian Ocean. The subducted water in the southeastern Pacific is the AAIW which is equivalent to the SAMW there. The densest subduction for the Indian Ocean would then be the 26.8-26.9σ_θ SAMW outcropping near the zero wind-stress curl south of Australia.

If the Falkland/Brazil Current AAIW formation is analogous to NPIW formation, then subduction is not the central issue, but rather the density of the winter surface water in and inshore of the Falkland loop. This water is then mixed into the subtropical gyre at the confluence. The thick winter surface layer west of and in the Falkland loop is of density 27.1σ_θ (31.7σ_1).

(3) *Modification processes.* Is there exchange across the SAF which modifies AAIW around Antarctica? Molinelli (1981) looks at changes in AAIW salinity and transport around the ACC, showing that there might be an additional injection of some low salinity at Kerguelen Plateau, but he retains the central importance of Drake Passage for AAIW formation. Laterally minimum potential vorticity for the Atlantic/Indian AAIW is found north of the SAF; its downstream increase could be due to mixing with higher potential vorticity waters to either the north or south.

On the largest scale, AAIW is obviously modified and diluted considerably moving away from its two sources; this is in fact how the two sources are identified. It is not possible at this point in the study to assess the relative importance of isopycnal and diapycnal mixing. There is strong evidence for locally vigorous mixing in the AAIW within a few degrees of the equator in the Atlantic (Suga and Talley 1994), but this is a very small part of the overall modification process. Diapycnal mixing is the only possible process which can create the lateral salinity maximum in the AAIW layer in the tropical Pacific since there are no surface sources of high salinity water at this density.

Discussion

This extended abstract concerning AAIW in the Atlantic is part of work in progress, to describe the global distribution of AAIW, with the ultimate aim of further clarifying its formation, modification, and overall transports as related to deep water formation in the North Atlantic (by overturn) and North Pacific (by diffusion). A clear differentiation was made between the Pacific type of AAIW, formed through subduction in the southeastern corner, and the Atlantic/Indian type of AAIW, formed through injection of Falkland Current surface waters into the subtropical gyre at the Falkland/Brazil Current confluence. The Atlantic and Indian subtropical gyres function as one nearly continuous gyre in the poleward/eastward flow, with important mixing and injection of lower latitude waters occurring in the westward branch at the Agulhas. Westward flow past Africa and southern Australia creates large plumes of high potential vorticity which dye the northern side of the Atlantic and Indian subtropical gyres.

The strong barrier in potential vorticity between the subtropical and tropical regions in each of the oceans is accompanied by a jump in AAIW properties across the barrier. Circulation in the tropics does not cease, but is largely zonal rather than gyral (Richardson and Schmitz 1993; Suga and Talley 1994). Communication between the subtropics and tropics occurs in the western boundary current in both the Atlantic and Pacific; the property variation across the potential vorticity barrier is enhanced in the eastern parts of the oceans. It cannot be a coincidence that this barrier coincides with the cessation of the AAIW oxygen maximum in the South Atlantic and the cessation of the AAIW salinity minimum in the North Atlantic, (South) Indian, and North Pacific. The important dynamical barrier to meridional flow of AAIW density water in all oceans is not the equator but the tropical/subtropical boundary, where potential vorticity patterns change from fairly well mixed (subtropical) to β-dominated (tropics).

Acknowledgments

This work was supported by the National Science Foundation's Ocean Sciences Division, Grants OCE86-14486 and OCE92-01315, and by NOAA/OGP through the JIMO Consortium (NA47GP0188). Unpublished data from 1980 were made available by M. McCartney, who also made available an unpublished account of formation of AAIW in and east of Drake Passage. Discussions with J. Reid and R. Peterson were valuable. The invitation and support to present this work at the South Atlantic symposium in Bremen is gratefully acknowledged.

References

Arhan M (1990) The North Atlantic current and subarctic intermediate water. J Mar Res 48: 109-144

Buchanan JY (1877) On the distribution of salt in the ocean, as indicated by the specific gravity of its waters. J Roy Geogr Soc 47: 72-86

England M, Godfrey J.S., Hirst A.C., Tomczak M. (1993) The mechanism for Antarctic Intermediate Water renewal in a world ocean model. J Phys Oceanogr 23:1553-1560

Fine RA (1993) Circulation of Antarctic Intermediate Water in the South Indian Ocean. Deep-Sea Res 40: 2021-2042

Georgi DT (1979) Modal properties of Antarctic Intermediate Water in the southeast Pacific and the South Atlantic. J Phys Oceanogr 9:456-468

Georgi DT (1981) On the relationship between the large-scale property variations and fine structure in the Circumpolar Deep Water. J Geophys Res 86: 6556-6566

Godfrey JS (1989) A Sverdrup model of the depth-integrated flow for the world ocean allowing for island recirculations. Geophys. Astrophys. Fluid Dynamics 45:89-112

Gordon AL, Georgi DT, Taylor HW (1977) Antarctic polar front zone in the western Scotia Sea - summer 1975. J Phys Oceanogr 7:309-328

Gordon, A L (1986) Interocean exchange of thermocline water. J Geophys Res 91:5037-5046

Gordon AL, Bosley KT (1991) Cyclonic gyre in the tropical South Atlantic. Deep-Sea Res 38 (Suppl): 323-343

Gordon AL, Weiss RF, Smethie WM, Warner MJ (1992) Thermocline and intermediate water communication between the South Atlantic and Indian Oceans. J Geophys Res 95:7223-7240

Hellerman S, Rosenstein M (1983) Normal monthly wind stress over the world ocean with error estimates. J Phys Oceanogr 90:7087-7097

Keffer T (1985) The ventilation of the world's oceans: maps of the potential vorticity fields. J Phys Oceanogr 15:509-523

Levitus S (1982) Climatological Atlas of the World Ocean. NOAA Professional paper 13, U.S. Government Printing Office, Washington, DC 173 pp

Lozier MS, Owens WB, Curry RG (1994) The climatology of the North Atlantic. Progr in Oceanogr submitted

Luyten JR, Pedlosky J, Stommel H (1983) The ventilated thermocline. J Phys Oceanogr 13:292-309

McCartney MS (1977) Subantarctic mode water. In: Angel M (ed) A voyage of discovery: George Deacon 70th anniv. Vol., Deep-Sea Res (Suppl), pp 103-119

McCartney MS (1982) The subtropical recirculation of mode waters. J Mar Res 40 (Suppl.):427-464

McCartney MS, Baringer MO (1993) Notes on the S. Pacific hydrographic section near 32°S - WHP P6. WOCE Notes, 5

Merz A, Wüst G (1922) Die Atlantische Vertikalzirkulation. Zeit. Gesell. d. Erdkunde zu Berlin, 1. Vorträge und Abhandlungen, pp 1-34

Molinelli EJ (1981) The Antarctic influence on Antarctic Intermediate Water. J Mar Res 39:267-293

Nakamura H (1996) A pycnostad on the bottom of the ventilated portion in the central subtropical North Pacific: its distribution and formation. J Oceanogr in press

Peterson RG, Stramma L (1991) Upper-level circulation in the South Atlantic Ocean. Prog Oceanogr 26:1-72

Piola AR, Gordon AL (1989) Intermediate water in the southwest South Atlantic. Deep-Sea Res 36:1-16

Reid JL (1986) On the total geostrophic circulation of the South Pacific Ocean: flow patterns, tracers, and transports. Prog Oceanogr 16:1-61

Reid J.L. (1989) On the total geostrophic circulation of the South Atlantic Ocean: flow patterns, tracers, and transports. Prog Oceanogr 23:149-244

Reid J.L. (1994) On the total geostrophic circulation of the North Atlantic Ocean: flow patterns, tracers, and transports. Prog Oceanogr 33:1-92

Richardson PL, Schmitz WJ (1993) Deep cross-equatorial flow in the Atlantic measured with SOFAR floats. J Geophys Res 98:8371-8387

Rintoul SR (1991) South Atlantic interbasin exchange. J Geophys Res 96:2675-2692

Sievers HA, Nowlin WD Jr. (1984) The stratification and water masses at Drake Passage. J Geophys Res 89:10489-10514

Suga T, Talley LD (1994) Antarctic Intermediate Water circulation in the tropical and subtropical South Atlantic. J Geophys Res 100:13411-13453

Suga T ,Takei Y, Hanawa K (1996) Thermostad distribution in the North Pacific subtropical gyre: the central mode water and the subtropical mode water. J Phys Oceanogr, submitted

Taft BA (1963) Distribution of salinity and dissolved oxygen on surfaces of uniform potential specific volume in the South Atlantic, South Pacific, and Indian Ocean. J Mar Res 21:129-146

Talley LD (1985) Ventilation of the subtropcal North Pacific: the shallow salinity minimum. J Phys Oceanogr 15:633-649

Talley LD (1993) Distribution and formation of North Pacific Intermediate Water. J Phys Oceanogr 23: 517-537

Talley LD, Nagata Y, Fujimura M, Iwao T, Kono T, Inagake D, Hirai M, Okuda K(1994) North Pacific intermediate water in the Kuroshio/Oyashio mixed water region in spring, 1989. J Phys Oceanogr (in press)

Tsuchiya M (1989) Circulation of the Antarctic Intermediate Water in the North Atlantic Ocean. J Mar Res 47:747-755

Tsuchiya M, Talley LD, McCartney MS (1992) An eastern Atlantic section from Iceland southward across the equator. Deep-Sea Res 39:1885-1917

Tsuchiya M, Talley LD, McCartney MS (1994) A western Atlantic section from South Georgia Island (54°S) northward across the equator. J Mar Res 52:55-81

Warner MJ, Weiss RF (1992) Chlorofluoromethanes in South Atlantic Antarctic Intermediate Water. Deep-Sea Res 39:2053-2075

Whitworth T, Nowlin WD (1987) Water masses and currents of the southern ocean at the Greenwich meridian. J Geophys Res 92:6462-6476

Wüst G (1935) Die Stratosphäre. Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Vermessungs- und Forschungsschiff „Meteor“ 1925-1927, 6:109-288

Yun J-Y, Talley LD (1996) Cabbeling and the density of North Pacific Intermediate Water. In preparation

Zemba JC (1991) The structure and transport of the Brazil Current between 27° and 36° south. Ph.D. thesis, Woods Hole Oceanographic Institution/Massachusetts Institute of Technology, 160 pp

Zhang H-M, Hogg NG (1992) Circulation and water mass balance in the Brazil Basin. J Mar Res 50: 385-420