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On the Circulation of the Intermediate Water in the Southwestern Atlantic Ocean¹

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ABSTRACT

In early studies of the Antarctic Intermediate Water in the South Atlantic it was assumed that the flow was mostly thermohaline and meridional. However, there is evidence that the wind-driven subtropical anticyclonic circulation in the South Atlantic Ocean extends to and includes the Intermediate Water, as in other oceans.

Introduction. Wüst (1935) has described the formation and flow of the Antarctic Intermediate Water, the North Atlantic Deep Water, and the Bottom Water in the Atlantic Ocean by means of the "core layer"; he defined the movement of these bodies of water as a thermohaline circulation with a strong meridional sense of movement, assuming that the wind-driven subtropical circulation extends only to a shallower depth. Since then, other investigators have suggested that, as in the other oceans, the anticyclonic gyre extends to greater depths, embracing the Intermediate Water. The purpose of the present work is to examine, with more data than Wüst had and by means of isopycnal analysis and relative geostrophy, the flow of the Intermediate Water in the southwestern Atlantic.

Method. The method chosen has been called isopycnal or isentropic analysis. Depth, salinity, potential temperature, and oxygen have been examined along surfaces (or strata) defined by a density parameter. The method was first used by Parr (1938) and subsequently by Montgomery (1938), Clowes (1950), Riley (1951), Taft (1963), Reid (1956), Lynn and Reid (1968), and Reid and Lynn (in press). The descriptions and limitations have been discussed by the above-mentioned authors, especially by Montgomery, Lynn and Reid, and Reid and Lynn.

1. Accepted for publication and submitted to press 28 May 1971.

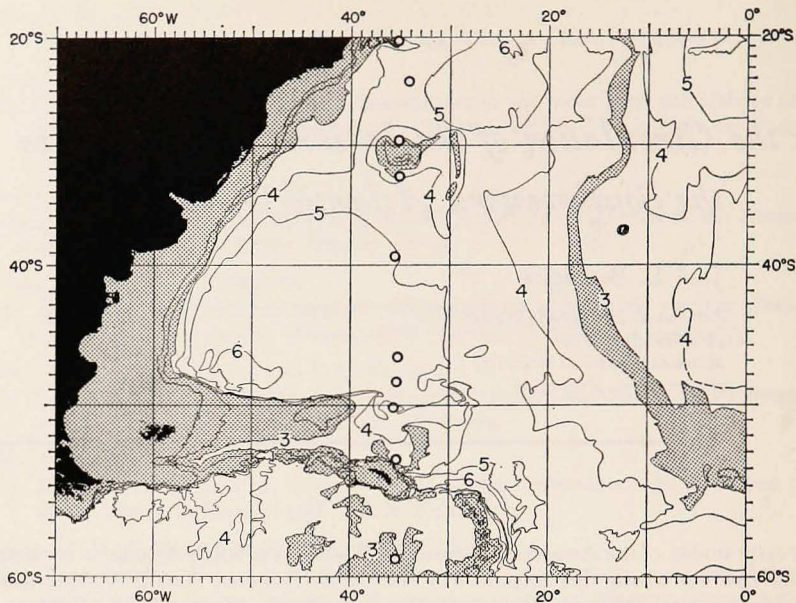


Figure 1. Depth (in km) in the southwestern Atlantic and positions of stations used in the vertical sections.

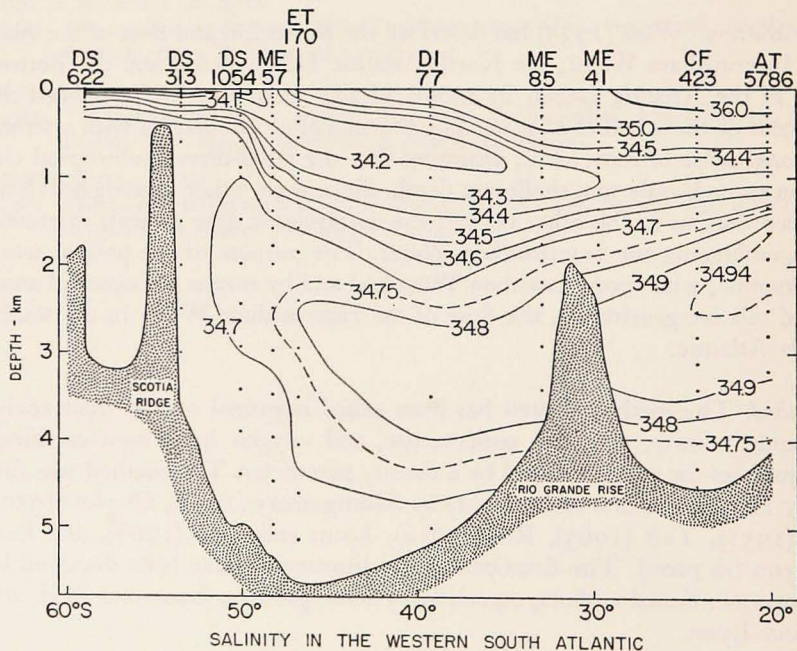


Figure 2. Vertical section of salinity (‰) along about 35°W.

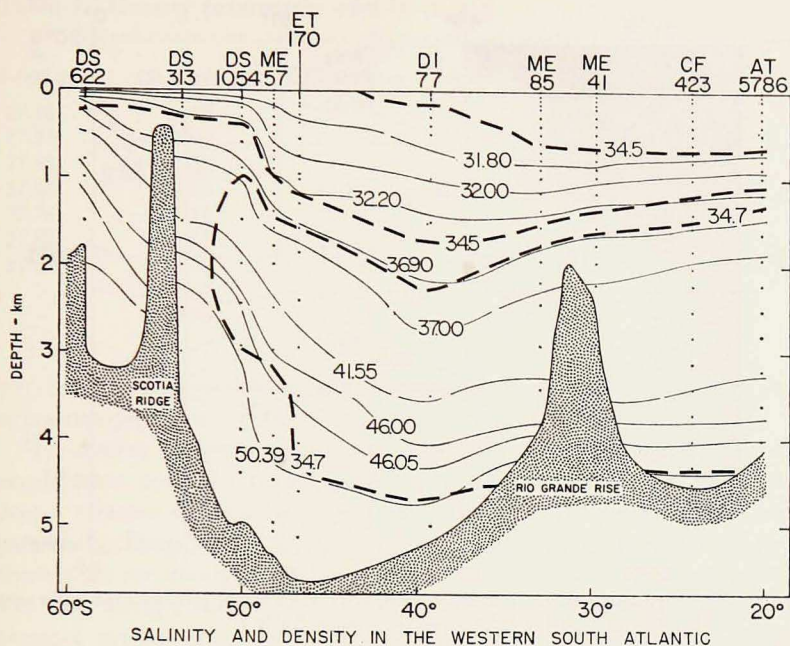


Figure 3. Vertical section of density parameters. Only one σ value is shown for each isopycnal; the corresponding values in the other depth ranges are given in Table I. The heavy dashed lines represent two of the isohalines from Fig. 2.

Lynn and Reid have suggested a method that may extend the use of density parameters to studies of water masses having a wide depth range. Since the present work deals with Intermediate Waters (which lie between 500 m and 1500 m over most of their extent), the density parameter used to define the strata is $\sigma_I = (\rho_I - 1) \times 10^3$, in which ρ_I represents the density² of a parcel of water if it were moved adiabatically to a pressure of 1000 db (Lynn and Reid 1968). Because in part of the region the depth of the strata studied is less than 500 m (Figs. 1-5), it has been necessary, in order to extend the studies above this depth, to shift from σ_I for depths below 500 m to σ_0 for depths above 500 m (σ_0 is the conventional potential density). In the three strata considered here, the shift can be made uniquely within the accuracy of the data, taking into account the differences in method and the period of observation.

For example, the stratum where $\sigma_I = 31.80$ is found at depths greater than 500 m over most of the area of this study. Along the line where it intersects the 500-m level, the values of σ_0 range from 27.174 to 27.185; a value of

2. In the equations used for the calculation, ρ actually represents specific gravity, not density. The density in grams per cubic centimeter is slightly greater than the specific gravity.

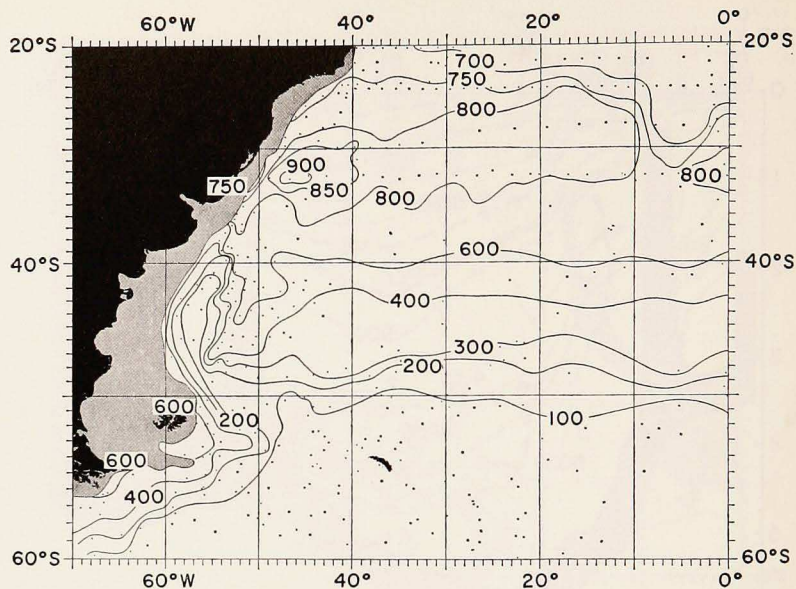


Figure 4. Depth (in meters) of the stratum where $\sigma_t = 31.80$ (between 500 and 1500 m). σ values for the other parts of the depth range are given in Table I.

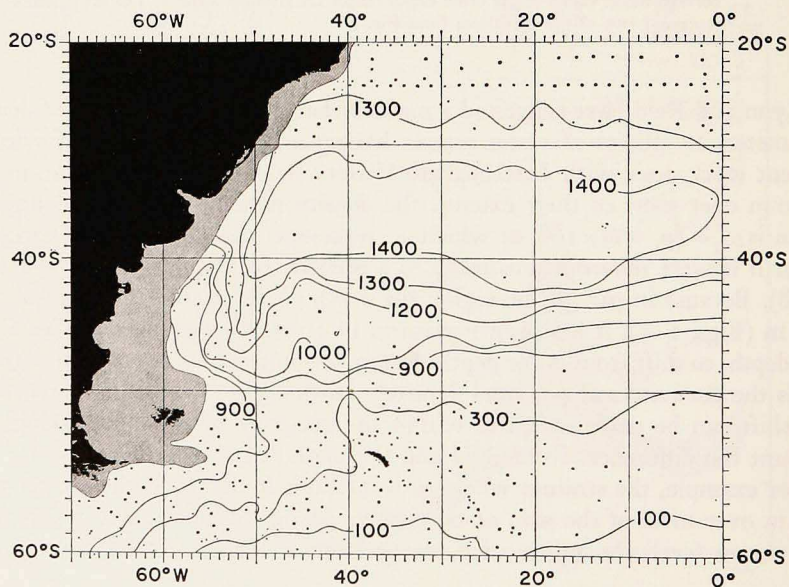


Figure 5. Depth (in meters) of the stratum where $\sigma_t = 32.20$ (between 500 and 1500 m). σ values for the other parts of the depth range are given in Table I.

Table I. Density parameters used in Fig. 3.

σ_0 0-500 m	σ_1 500-1500 m	σ_2 1500-2500 m	σ_3 2500-3500 m	σ_4 3500-4500 m	σ_5 > 4500 m
27.18	31.80				
27.34	32.00				
27.54	32.20				
27.68	32.35	36.90			
27.76	32.44	37.00			
27.82	32.515	37.09	41.55		
27.845	32.56	37.145	41.625	46.00	50.27
	32.58	37.18	41.67	46.05	50.325
	32.60	37.21	41.71	46.10	50.39

27.18 for σ_0 was used to extend this stratum into shallower depths. The three strata mapped here are the first three of those listed in Table I.

To observe the geostrophic flow along at least one stratum, I have used the acceleration potential from the stratum defined by $\sigma_1 = 32.00$ relative to a deeper stratum defined by $\sigma_2 = 36.90$; this density corresponds to the upper part of the Deep Water. It has not been possible to use a deeper stratum, since there were not enough data from deeper waters in the western part of the area. For flow along a surface of uniform specific-volume anomaly (δ_i) relative to a pressure surface (p_r), the acceleration potential (Montgomery 1937) can be written as follows:

$$A.P. \Big|_{p_r}^{\delta_i} = - \int_{p_r}^{p_i} \delta dp + \delta_i p_i,$$

where p_i is the pressure where δ_i occurs. In the present study, the flow is calculated relative to the flow along another δ surface (with corresponding potential specific-volume anomaly δ_2), and the function is

$$A.P. \Big|_{\delta_2}^{\delta_1} = - \int_{p_2}^{p_1} \delta dp + \delta_1 p_1 - \delta_2 p_2,$$

p_2 being the pressure where δ_2 occurs.

In a strict sense, an acceleration potential exists for a surface of uniform specific-volume anomaly only (Montgomery 1937). However, Reid (1965) and Tsuchiya (1968) have used uniform δ_T (δ minus the pressure terms), which, in their opinion, is not very different from δ in the upper 1200 m and is a good representation of an isentropic stratum. In the present study, the chosen strata ($\sigma_1 = 32.00$ and $\sigma_2 = 36.90$) are not uniform in δ and extend over a wider depth range; therefore, the difference from uniform δ strata is larger than that in the Reid or Tsuchiya studies. The validity of the field in Fig. 6 can be tested by making the calculation correctly through use of the δ

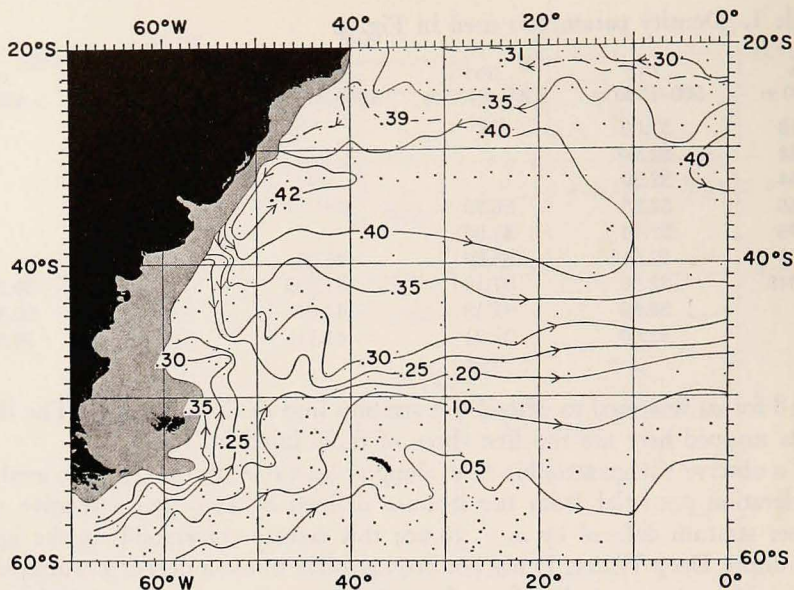


Figure 6. Acceleration potential along the stratum where $\sigma_1 = 32.00$ relative to the stratum where $\sigma_2 = 36.90$ (between 1500 and 2500 m). σ values for the other parts of the depth range are given in Table I. Unit is the dynamic meter (1 dyn m = 10 joules/kg).

corresponding to the shallowest position of the strata (in which case the calculated values of acceleration potential at the deeper positions are increased by a maximum of 0.06 dyn m within the anticyclone) or the δ corresponding to the deepest positions (in which case the values in the shallower areas near 60°S are decreased by a maximum of about 0.03 dyn m). In either case, the effect of the approximation used in Fig. 6 is to weaken rather than to intensify the gradients. The pattern of relative geostrophic flow is not substantially different from that indicated on a map of geopotential anomaly at 1000 db with respect to 2000 db, made for comparison.

Choice of the Strata. The three strata chosen lie within the salinity minimum (Figs. 2 and 3), which is observed at intermediate depths throughout the Atlantic in the region between the Antarctic Convergence and 25°N; the water in the salinity minimum is referred to as Antarctic Intermediate Water.

Since the patterns are similar in these three strata, not all the maps examined are shown. Instead, the depths of the upper and lower strata are shown in Figs. 4 and 5; the relative acceleration potential along the middle stratum is shown in Fig. 6; the potential temperature along the upper stratum and the salinity and oxygen along the middle stratum are shown in Figs. 7, 8, and 9.

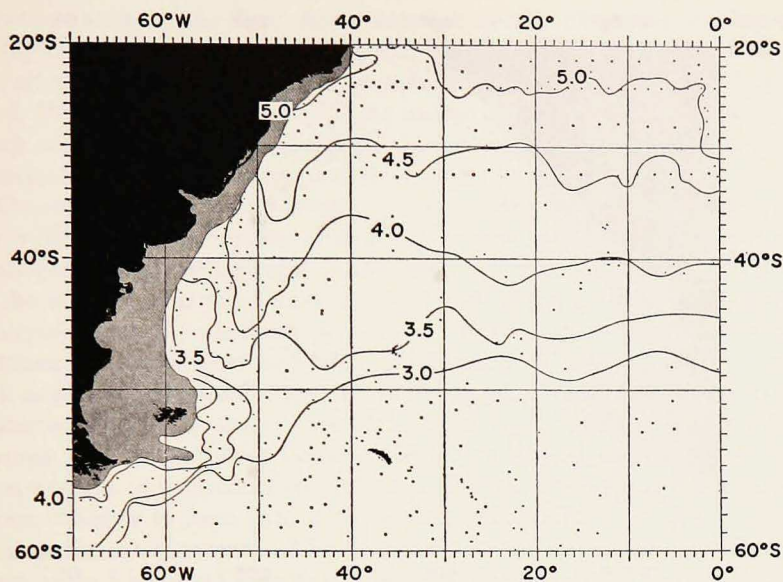


Figure 7. Potential temperature ($^{\circ}\text{C}$) along the stratum where $\sigma_t = 31.80$ (between 500 and 1500m). σ values for the other parts of the depth range are given in Table I.

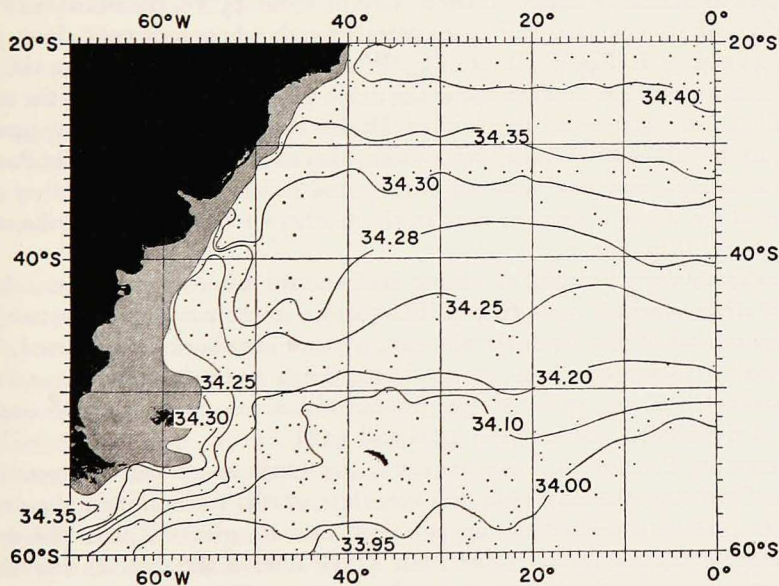


Figure 8. Salinity (‰) along the stratum where $\sigma_t = 32.00$ (between 500 and 1500 m). σ values for the other parts of the depth range are given in Table I.

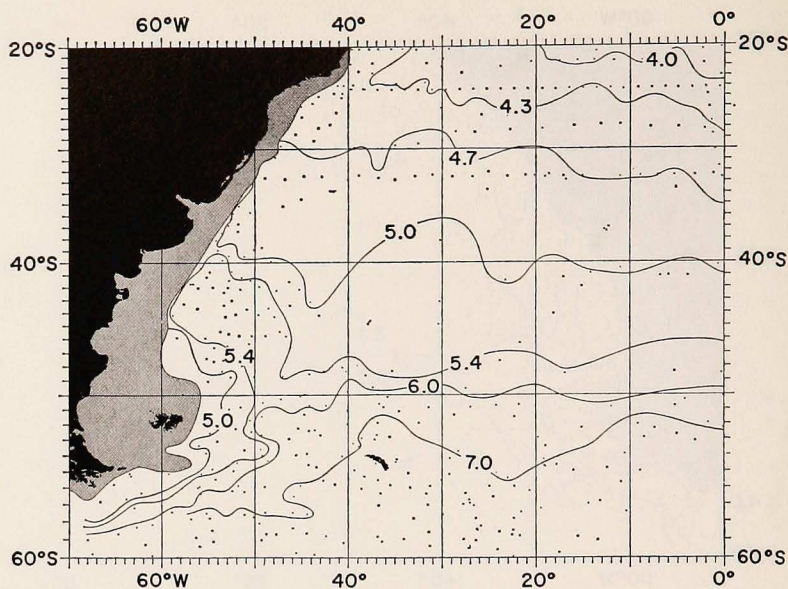


Figure 9. Dissolved oxygen (ml/L) along the stratum where $\sigma_1 = 32.00$ (between 500 and 1500 m). σ values for the other parts of the depth range are given in Table I.

Patterns Shown by Maps. DEPTH. East of about 45°W , the isobaths extend zonally and are characterized by a central trough whose axis runs along 32°S (Fig. 4) and 37°S (Fig. 5). West of 45°W and in the southern region, the pattern is more complex and the slopes are much greater. The depths of the strata considered are greater in the area of Drake Passage, with a strong upward slope to the southeast; some of the contours that extend from the Drake Passage have a strong meridional sense until they reach about 40°S , where they turn eastward and adopt a zonal course. In the southern area the depth of the strata rises to less than 100 m.

ACCELERATION POTENTIAL (along the stratum where $\sigma_1 = 32.00$ relative to the stratum where $\sigma_2 = 36.90$). The pattern of the acceleration potential is similar to that of the depth. In the east, a zonal distribution is observed. The high value corresponds to the trough in the depth representation; the axis runs approximately along 37°S . A clear intensification can be seen in the western part of the section and between 45°S and 52°S .

SALINITY, POTENTIAL TEMPERATURE, AND OXYGEN. These characteristics generally change monotonically from south to north; the salinity and potential temperature increase and the oxygen decreases. As observed with the depth, the sense of the isolines is zonal from 45°W toward the east. In the Drake Passage, warmer and saltier water is observed near the coast, with a low concentration of oxygen.

Interpretation of the flow. ANTICYCLONIC GYRE. From the distribution of depth, acceleration potential, and zonal distribution of properties, it appears that all of the flow south of 37°S is eastward and all of it north of 32°S is westward. Wüst (1935) did not accept the existence of an anticyclonic gyre at the depth of these strata (Figs. 4 and 5), though other investigators (Riley 1951, Martineau 1953, Taft 1963, and Reid 1965) have accepted it.

CIRCULATION IN THE WESTERN AREA. The circulation appears to be much like that of the surface wind-driven current system. The presence of the Malvinas Current³ is apparent in the depth distribution (the meridional sense of the isobaths near the Drake Passage) and in the gradient of acceleration potential. From the northern part of the Drake Passage this Current carries northward some warmer and more saline water of lower oxygen content as well as some colder Antarctic water of lower salinity and oxygen content; the colder water near the coast, between 40° and 50°S , contrasts sharply with the warmer water from lower latitudes. This Current, at the depths considered here, extends to approximately 40°S and then turns southward and eastward, where it begins to form part of the subtropical anticyclone.

THE BRAZIL CURRENT. This Current is in the western part of the section north of the Malvinas Current; it is also east of the Malvinas Current according to the distributions of depth and acceleration potential, and the tongues of high temperature, high salinity, and low oxygen. At these depths the Brazil Current appears to extend along the coast to at least 38°S .

These extensions of the Malvinas and Brazil currents have been suggested before by Martineau (1953) and Reid (1965).

DRAKE PASSAGE. An eastward transport of water with relatively high salinity and temperature and with relatively low oxygen is present in the Drake Passage; this water, which evidently comes from the Pacific, is part of the Circumpolar Current. The maps by Taft (1963) and Reid (1965) suggest that this water might be influenced by a poleward flow of lower-latitude water along the coast of Chile.

Discussion. Using the "core-layer" method, Wüst (1935) described the origin and flux of the Antarctic Intermediate Water. He concluded that the major northward flux and spreading occurs along the coast of South America, well beyond the Malvinas and Brazil currents, as a principally thermohaline transport rather than as a wind-driven transport.

Defant (1941) and Sverdrup et al. (1942) accepted the conclusions of Wüst and assumed that the anticyclonic gyre in the South Atlantic is limited to a shallower layer (above the Intermediate Water). This concept has been accepted by most oceanographers, but not by all. It is noteworthy that the anticyclone is clearly shown in Defant's maps of the absolute topography for the 500, 800, and 1400 db levels.

3. Also called the Falkland Current.

In later studies, many authors have concluded that the equatorward transport of the Intermediate Water in the South Atlantic cannot be identified as a western-boundary current that extends to the equator and is completely separated from the overlying current system: Clowes (1950) in his analysis of the stratum where $\sigma_t = 27.25$; Riley (1951) in his study of the transport and distribution of salinity, oxygen, phosphate, and nitrate along σ_t strata; Martineau (1953) in his work on the influence of the current system and of lateral mixing upon Antarctic Intermediate Water in the South Atlantic; Garner et al. (1962) in their computations of the volume transport of the wind-driven circulation over the Atlantic Ocean; Taft (1963) in his study of the distribution of depth, salinity, and oxygen along surfaces of constant potential steric anomaly ($\delta\theta$); and Reid (1965, part 8) in his comparison of the movement of the Intermediate Waters in the Pacific and Atlantic. I agree with these investigators and conclude that:

(i) The major wind-driven currents in the western part of the South Atlantic (in particular, the subtropical anticyclonic gyre and the Brazil Current) extend to depths of more than 1000 m, a viewpoint that is confirmed in the density distributions shown in the METEOR Atlas (Wüst and Defant 1936).

(ii) The Intermediate Waters lie within the density range of water that flows in an anticyclone.

(iii) A transport of Intermediate Water northward along the coast of South America, as was suggested by Wüst (1935), extends only as far as the Malvinas Current and has not been observed from 60°S to 20°S.

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APPENDIX

All of the available data from the desired depths in the area considered have been used; as the maps indicate, the coverage has not been uniform: in some areas there are ample data, in others not. The data, from 730 stations, were collected by the following ships: ALMIRANTE SALDANHA, ATLANTIS, CAPITAN CANEPA, CRAWFORD, DISCOVERY, METEOR, UMITAKA MARU, and VEMA.

REFERENCES

- CLOWES, A. J.
1950. An introduction to the hydrology of South African waters. Invest. Rep. Div. Fish. S. Afr., 12; 42 pp.
- DEFANT, ALBERT
1941. Quantitative Untersuchungen zur Statik und Dynamik des Atlantischen Ozeans. Wiss. Ergbn. dtsch. atlant. Exped. "Meteor", 6(2): 191-260.

GARNER, D. M., GERHARD NEUMANN, and W. J. PIERSON, JR.

1962. The average horizontal wind driven mass transport of the Atlantic for February as obtained by numerical methods. Proc. Sym. Math.-Hydrodynam. Meth. Phys. Oceanogr., Sept. 1961, Inst. Meeresk., Hamburg, 297-319, 8 figs.

LYNN, R. J., and J. L. REID

1968. Characteristics and circulation of deep and abyssal waters. Deep-sea Res., 15(5): 577-598.

MARTINEAU, D. P.

1953. The influence of the current systems and lateral mixing upon Antarctic Intermediate Water in the South Atlantic. W.H.O.I., Ref. No. 53-72; 12 pp. (unpublished).

MONTGOMERY, R. B.

1937. A suggested method for representing gradient flow in isentropic surfaces. Bull. Amer. met. Soc., 18: 210-212.

1938. Circulation in the upper layers of southern North Atlantic deduced with use of isentropic analysis. Pap. phys. Oceanogr., 6(2): 55 pp.

PARR, A. E.

1938. Isopycnic analysis of current flow by means of identifying properties. J. mar. Res., 1(2): 133-154.

REID, J. L., JR.

1965. Intermediate waters of the Pacific Ocean. Johns Hopkins oceanogr. Stud., 2; 85 pp.

REID, J. L., and R. J. LYNN

- In press. On the influence of the Norwegian-Greenland and Weddell seas upon the bottom waters of the Indian and Pacific oceans. Deep-sea Res.

RILEY, G. A.

1951. Oxygen, phosphate and nitrate in the Atlantic Ocean. Bull. Bingham oceanogr. Coll., 13(1): 1-126.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING

1942. The oceans; their physics, chemistry, and general biology. Prentice-Hall, Inc., Englewood Cliffs, N.J. 1087 pp.

TAFT, B. A.

1963. Distribution of salinity and dissolved oxygen on surfaces of uniform potential specific volume in the South Atlantic, South Pacific, and Indian oceans. J. mar. Res., 21(2): 129-146.

TSUCHIYA, MIZUKI

1968. Upper Waters of the Intertropical Pacific Ocean. Johns Hopkins oceanogr. Stud., 4; 50 pp.

WÜST, GEORG

1935. Die Stratosphäre. Wiss. Ergebn. dtsch. atlant. Exped. "Meteor", 6(1)(2): 109-288.

WÜST, GEORG, and ALBERT DEFANT

1936. Atlas zur Schichtung und Zirkulation des Atlantischen Ozeans. Schnitte und Karten von Temperatur, Salzgehalt und Dichte. Wiss. Ergebn. dtsch. atlant. Exped. "Meteor", 6 (Atlas): Beil. I-CIII.