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On Potential Density in the Deep South Atlantic Ocean[1]

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ABSTRACT

There is a great contrast between the relative distributions of potential density referred to 0 decibars and of potential density referred to 4000 decibars in the deep water of the South Atlantic Ocean. Both parameters are useful in a descriptive analysis of deep water; the former is an identifier of water origin, the latter graphically displays stability in the deep ocean and can be used to infer deep-ocean geostrophic flow.

Introduction. In the South Atlantic there are large differences in the deep water characteristics of the basins flanking the mid-Atlantic ridge. Antarctic Bottom Water (AABW), characteristically cold and of low salinity, lies along the bottom of the Brazil Basin (western basin); the overlying North Atlantic Deep Water (NADW) is warmer and more saline. NADW fills the great depths of the Angola Basin (eastern basin) and is nearly homogeneous below 3500 m. The distributions of these characteristics are illustrated in zonal sections presented in atlases by Wüst (1935), who has used the 1925–1927 METEOR data, and by Fuglister (1960), who has used the 1957–1958 International Geophysical Year data. Wüst has also presented sections of the distribution of σ_t; however, the usefulness of this density parameter in analyzing the deep water is doubtful. In this study a zonal section determined from the IGY data is examined in terms of (i) potential density[2] referred to 0 decibars,[3] σ_0, and (ii) the potential density referred to 4000 decibars, σ_4. The distributions
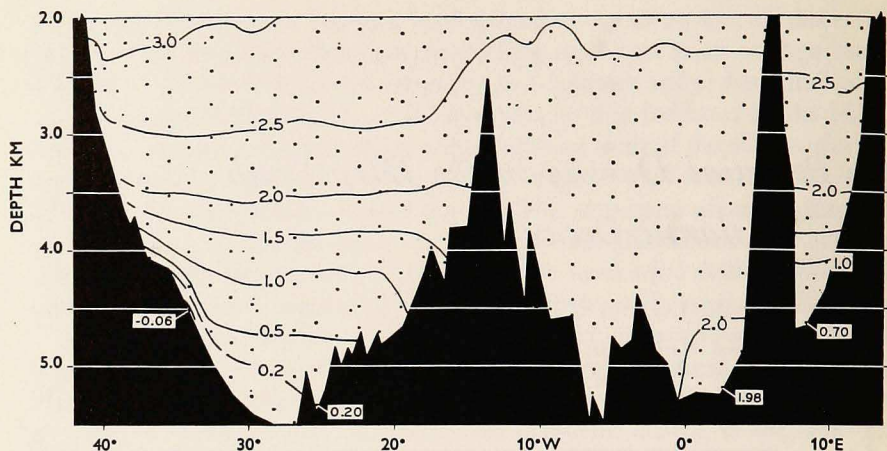
Figure 1. Potential temperature (°C) at depths greater than 2000 m in a section along 24°S in the Atlantic Ocean. The contour interval is 0.5°C except for the dashed line. The major topographic features are South America on the left, the Mid-Atlantic ridge, the Walvis Ridge, and Africa on the right.

of these parameters are useful in a descriptive analysis of the deep water and supplement the temperature and salinity distributions.

In a study of deep and abyssal waters of the world ocean, Lynn and Reid (1968) have presented vertical sections of σ_0 and σ_4 for a nearly meridional line of stations through the western Atlantic. The distribution of σ_0 in the deep ocean has revealed an internal maximum that helps to characterize a water mass and to identify its source and path of flow. However, these authors concluded that, to adequately represent the density stratification in deep water, potential density should be referred to appropriate pressures; the distribution of σ_4 eliminated the inversion and clarified the changes in density along the bottom.

Temperature and Salinity. The zonal section at 24°S, derived from data taken on R/V CRAWFORD Cruise 22, 1958 (Fuglister 1960), crosses the core of the AABW as revealed by the potential-temperature and salinity isopleths. At this latitude the AABW is banked against the western side of the Brazil Basin (Figs. 1, 2). At the bottom, the salinity is 34.67 to 34.69 °/oo and the potential temperature is near 0°C. (The temperature section referred to here differs from the one given by Fuglister (1960) in that he used *in situ* temperature.) The great overlying salinity maximum, near 2300 m, is approximately 34.94 °/oo and the corresponding temperature is approximately 2.9°C. The deep water in the Angola Basin, in great contrast to that in the Brazil Basin, is nearly homogeneous. Below 3500 m the vertical trends in salinity are nearly imperceptible; the median is 34.891 °/oo. The potential temperature at the bottom is approximately 2.0°C and differs from that at 3500 m by 0.1°C.
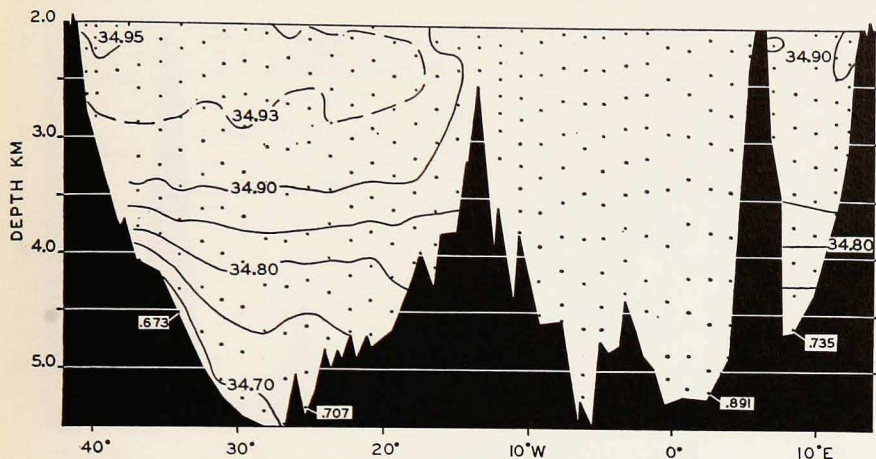
Figure 2. Salinity (%) at depths greater than 2000 m in a section along 24°S in the Atlantic Ocean. The contour interval is 0.5% except for the dashed line.

The potential temperature and salinity at the bottom in the Cape Basin east of the Walvis Ridge are less extreme than those in the Brazil Basin, but they also exhibit the influence of AABW.

Potential Densities σ_0 and σ_4. In the deep Atlantic, σ_0 has a very weak gradient (Fig. 3). An internal σ_0 maximum is spread across most of the Brazil Basin near 3500 m and has about the same values (slightly greater than 27.90) as the waters below 3800 m in the Angola Basin. A faint σ_0 maximum (greater than 27.88) is found near 3500 m in the Cape Basin. Waters having these high values of σ_0 are part of the NADW and are traceable by means of this extreme characteristic to a latitude north of 40°N in the western North Atlantic (Wüst 1933, Lynn and Reid 1968, Reid and Lynn, in press). The AABW, though having lesser values of σ_0 than NADW, is colder, hence more compressible; and at the great pressures in the deep ocean it is more dense than NADW. In this zonal section the water column is everywhere stable.

The potential density referred to 4000 decibars (σ_4) increases monotonically to the bottom. The σ_4 density has a considerably larger gradient than σ_0 (Fig. 4); the contour interval used for σ_4 is five times greater than that used for σ_0. The AABW is the densest, and the least-dense bottom water is in the Angola Basin. Here and in the meridional section (Lynn and Reid 1968), the σ_0 maximum coincides closely with the 45.93 σ_4 isopycnal, which is nearly level across the Brazil Basin. In the AABW the σ_4 isopycnals parallel the potential-temperature and salinity isopleths.

There is a large difference in the relative distribution and in the gradients between the potential densities referred to 0 and to 4000 decibars. The rele-
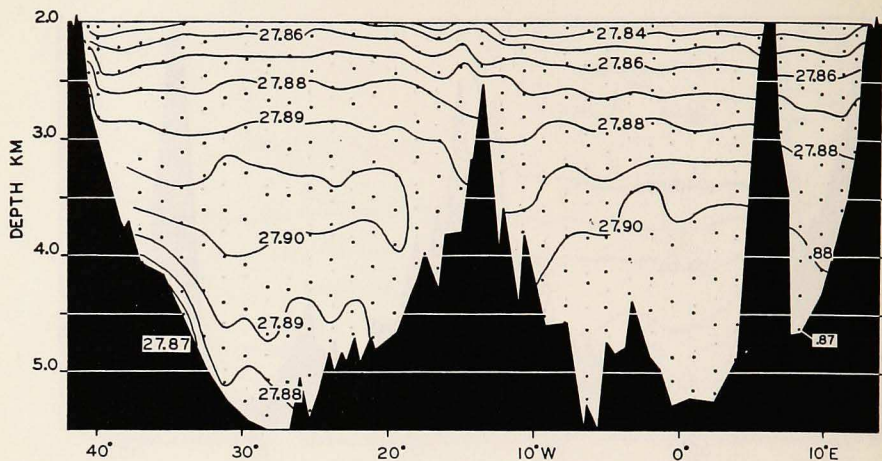
Figure 3. Potential density referred to a hydrostatic pressure of zero (symbol σ_0 or σ_θ) for the temperature and salinity fields given in Figs. 1 and 2. Contour interval is 0.01.

vance of a potential density referred to a particular pressure depends on its use and interpretation. We have seen that σ_0 in the deep ocean can be used as a conservative characteristic to trace water-mass origin while σ_4 shows the deep ocean stratification. The latter feature is explained in the following consideration. In practice, the Hesselberg (1918) stability parameter, $E = (1/\varrho)\,(\delta\varrho/\partial Z)$, is applied to the incremental observations derived from Nansen bottles. The density difference, $\delta\varrho$, is taken between two vertically adjacent observations after the lower is adiabatically raised to the depth of the upper. Where this depth happens to be the depth at which the pressure is 4000 decibars (3932 m), $\delta\varrho$ and $\Delta\sigma_4 \times 10^{-3}$ are equivalent. Thus, at the depth of the reference pressure,

$$\frac{\partial \sigma_p}{\partial Z} \times 10^{-3} = \left(\frac{\delta\varrho}{\partial Z}\right)_p.$$

In the vicinity of this depth the relationship is approximate, becoming less accurate at increasing intervals from the depth. As an example for this section, CRAWFORD St. 428 (27°W) has been examined: near 3000 m and again near 5000 m, $E = 7 \times 10^{-8}$. Estimated from the vertical gradient of σ_4, we have 8×10^{-8} and 6×10^{-8}, respectively. Thus, within an appropriate depth range, the vertical section of σ_4 shows a density stratification that graphically reflects the stability. (Between 2000 m and 2500 m there is a decreasing trend from west to east in temperature and salinity. In this depth range the σ_0 and σ_4 isopycnals have opposing zonal slopes in the central part of the basin. The σ_2 isopycnals, which represent better the density structure in this depth range, have a slope that is intermediate between the others, i.e., nearly level).
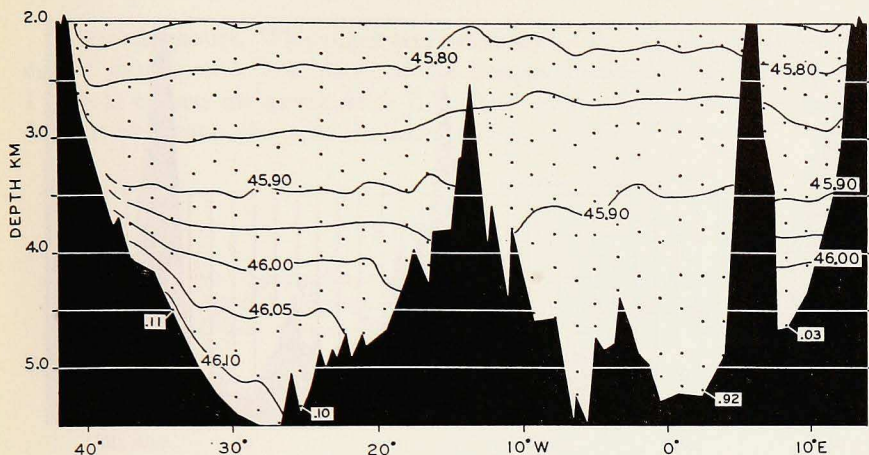
Figure 4. Potential density referred to a hydrostatic pressure of 4000 decibars (symbol σ_4) for the temperature and salinity fields given in Figs. 1 and 2. Contour interval is 0.05.

Deep Geostrophic Flow. The slope of the σ_4 isopycnals in the AABW suggest a mass distribution associated with geostrophically balanced motion. The horizontal density gradients below 4000 m in the Brazil Basin would be associated with a northward net motion in the bottom water relative to the overlying water. This is in agreement with the accepted pattern of circulation. (The horizontal gradients of σ_0 are of opposite sign, hence misleading). Wüst (1933, 1935) has described the deep circulation and the bottom circulation of the Atlantic as determined from the temperature, salinity, and oxygen distributions. Further, using the METEOR data, he analyzed deep and bottom geostrophic flow relative to Defant's "level of no-motion" (Wüst 1957, Defant 1941). In the South Atlantic he found northward flow of AABW along the western slope. At 24°S, Defant's "level of no-motion" varies at about a depth of 1200 m; the northward flow along the bottom (4000 m) was 3 cm/sec.

Geostrophic flow for the deep ocean was computed from CRAWFORD data relative to 3500 m — the depth of the σ_0 maximum — and relative to 1200 m. In the first calculation, the field of velocities (Fig. 5) relates the motion of AABW to an assumed no-motion in the overlying lower NADW, which may be moving southward. In this frame of reference, AABW has the only significant transport. The velocity increases with depth. The highest value (2.0 cm/sec) is located near the bottom; the calculation is limited in this critical region to computations for the depth of the shallowest of each pair of stations. The remainder of the field (velocities of less than 0.4 cm/sec not shown) shows lesser velocities, which often alternate their direction north and south between adjacent pairs of stations.[4] In the Brazil Basin the direction of flow represented by

4. Using the accuracies of the temperature and salinity measurements given by Fuglister (1960) for the IGY data (0.01°C and 0.005‰) and employing the methods of Wooster and Taft (1958), the
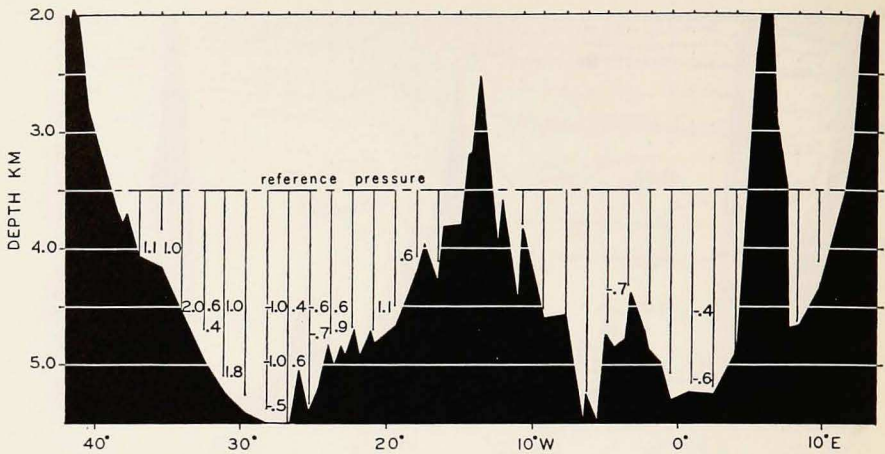
Figure 5. Geostrophic velocity (cm/sec) of the deep water relative to an assumed no-motion at 3500m. Only values for 0.4 cm/sec and greater are given. Negative values indicate southward flow.

the larger values is still predictable from the σ_4 distribution. The velocities in the Angola Basin may be the result of small measurement errors. Two of the stations used in the determinations contain slight instabilities at great depth.

This analysis is intended to show that relative geostrophic motion in the near-bottom water is evidenced in the σ_4 distribution. It is probable, however, that the water at 3500 m is also in motion. Indeed, west of 25°W there is a southward flow of slightly less than 1 cm/sec at 3500 m if 1200 m is chosen as the reference level (not shown). In this second calculation, the vertical shear between 3500 m and near the bottom remains unchanged, hence the velocity of the AABW is reduced by the same amount. Higher velocities are found elsewhere; values greater than 4 cm/sec northward are found at 3000 m along the eastern edge of both the Brazil and Cape basins. However, it is difficult to infer geostrophic motion from the density field except where the horizontal density gradients are persistent across several stations.

Summary. Potential density is more descriptive of conditions in the deep ocean than has been popularly believed. For the South Atlantic section, and as seen in Lynn and Reid (1968), potential density referred to 0 decibars is an identifier of water origin. Referred to 4000 decibars, its distribution aids in the description of the water-mass distribution and circulation and shows a graphic display of the stability. Other potential densities are useful in other strata. The slopes of these isopycnals give the same indications of relative geostrophic flow as do the slopes of σ_t and σ_o in shallower layers and are subject to the same limitations and interpretations.

corresponding error in geostrophic current speeds for 24° latitude and 150-km station spacing is less than 0.5 cm/sec.

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