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On Potential Density in the Deep South Atlantic Ocean

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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 $\sigma_t$; 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 $\sigma$ referred to 0 decibars, $\sigma_0$, and (ii) the potential density referred to 4000 decibars, $\sigma_4$. The distributions

1. Presented before the American Geophysical Union Meeting in San Francisco on December 3, 1968.
2. Accepted for publication and submitted to press 15 February 1971.
3. The density parameter used is actually $\sigma = 10^3 (e-1)$, where $e$ is the specific gravity, not density. Density in g/cm$^3$ is slightly greater than $e$, but the term "density" is preferred over "specific gravity" for brevity of expression and to remain compatible with earlier usage.
4. The usual symbol is $\sigma_0$. The newer notation is chosen to be compatible with the subsequent use of $\sigma_4$, in which the subscript specifies the reference pressure in decibars $X 10^{-3}$. 
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 ω₀ and σ₄ for a nearly meridional line of stations through the western Atlantic. The distribution of ω₀ 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 σ₄ 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‰ 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‰ 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‰. The potential temperature at the bottom is approximately 2.0°C and differs from that at 3500 m by 0.1°C.
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** $\sigma_0$ and $\sigma_4$. In the deep Atlantic, $\sigma_0$ has a very weak gradient (Fig. 3). An internal $\sigma_0$ 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 $\sigma_0$ maximum (greater than 27.88) is found near 3500 m in the Cape Basin. Waters having these high values of $\sigma_0$ 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 $\sigma_0$ 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 ($\sigma_4$) increases monotonically to the bottom. The $\sigma_4$ density has a considerably larger gradient than $\sigma_0$ (Fig. 4); the contour interval used for $\sigma_4$ is five times greater than that used for $\sigma_0$. 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 $\sigma_0$ maximum coincides closely with the 45.93 $\sigma_4$ isopycnal, which is nearly level across the Brazil Basin. In the AABW the $\sigma_4$ 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 relev-
Figure 3. Potential density referred to a hydrostatic pressure of zero (symbol $\sigma_0$ or $\sigma_\theta$) for the temperature and salinity fields given in Figs. 1 and 2. Contour interval is 0.01.

Variance of a potential density referred to a particular pressure depends on its use and interpretation. We have seen that $\sigma_0$ in the deep ocean can be used as a conservative characteristic to trace water-mass origin while $\sigma_4$ shows the deep ocean stratification. The latter feature is explained in the following consideration. In practice, the Hesselberg (1918) stability parameter, $E = (1/\rho) \left( \frac{\partial \rho}{\partial Z} \right)$, is applied to the incremental observations derived from Nansen bottles. The density difference, $\delta \rho$, 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), $\delta \rho$ and $\Delta \sigma_4 \times 10^{-3}$ are equivalent. Thus, at the depth of the reference pressure,

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

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 $\sigma_4$, we have $8 \times 10^{-8}$ and $6 \times 10^{-8}$, respectively. Thus, within an appropriate depth range, the vertical section of $\sigma_4$ 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 $\sigma_0$ and $\sigma_4$ isopycnals have opposing zonal slopes in the central part of the basin. The $\sigma_2$ isopycnals, which represent better the density structure in this depth range, have a slope that is intermediate between the others, i.e., nearly level).
Deep Geostrophic Flow. The slope of the $\sigma_4$ isopyncals 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 $\sigma_0$ 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 $\sigma_0$ 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. In the Brazil Basin the direction of flow represented by

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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
the larger values is still predictable from the $\sigma_4$ 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 $\sigma_4$ 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 $\sigma_4$ and $\sigma_5$ in shallower layers and are subject to the same limitations and interpretations.
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