Distribution of Salinity and Dissolved Oxygen on Surfaces of Uniform Potential Specific Volume in the South Atlantic, South Pacific, and Indian Oceans[1]

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ABSTRACT

Maps are presented that show the distributions of the salinity, dissolved oxygen, and depth of four potential specific-volume anomaly surfaces: 125, 100, 80, and 60 cl/t. Evidence indicates an anticyclonic circulation of water at intermediate depth in the Atlantic, Pacific, and Indian oceans. Only in the South Pacific does water from the Circumpolar Current penetrate to low latitudes in a relatively unmixed condition. In the South Atlantic and South Indian oceans there is no counterpart for the poleward directed Peru-Chile Undercurrent. Low-salinity water from the Banda and Timor seas penetrates to the western South Indian Ocean on the 125-cl/t surface. The distributions of salinity and oxygen indicate a southward transport of high-salinity, low-oxygen water from the equatorial Indian Ocean through the Mozambique Channel. High-salinity water from the Agulhas Current enters the South Atlantic, but most of this flow is returned to the Indian Ocean. The relatively weak penetration of Antarctic Intermediate Water into the Tasman Sea and the importance of vertical exchange processes there are demonstrated.

Introduction. The distributions in space and time of the potential temperature and salinity in oceanic waters at intermediate depth reflect the combined effect of advection and mixing of different water types. The large-scale distributions of these conservative water properties within the oceanic basins often indicate qualitatively the nature of water exchange within and between these basins. The distributions of nonconservative properties, e. g. dissolved

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oxygen, also reflect local processes of production and consumption and may not be exclusively interpreted in terms of advection and mixing. Since the distributions of both kinds of properties are related to water circulation, any model of circulation must be consistent with the distribution of these properties. The distributions of properties, conversely, often suggest the gross nature of the circulation.

In this paper, distribution maps show the salinity, dissolved oxygen, and depth of four surfaces of constant potential specific-volume anomaly: $\delta_\theta = 125$, 100, 80, and 60 centiliters per metric ton (cl/t). These values correspond to potential sigma-t (σ_θ) values of 26.81, 27.07, 27.28, and 27.49 grams per liter (g/l). Such representation of oceanographic variables was first used by Parr (1938). The method, often referred to as isentropic analysis when applied to the deduction of circulation, has been subsequently used by Montgomery (1938), Clowes (1950), Riley (1951), and Rochford (1958, 1960a,b), among others. These maps were prepared to illustrate primarily the distributions of specific volume, salinity, and dissolved oxygen in the three oceanic basins of the Southern Hemisphere. The North Indian Ocean has been included because it represents only a small increment of the total ocean area considered here. In the discussion of the maps, the circulation of some water types on the surfaces discussed will be suggested on the basis of observed property distributions and surface topographies.

Treatment of Material. In this study, data from 373 hydrographic stations have been used; the stations are distributed as follows: South Atlantic Ocean, 58; South Pacific Ocean, 172; and Indian Ocean, 143. Most of these stations extended to depths greater than 1500 m. This coverage amounts to one station per 5×10^5 km^2 of sea surface, or a $7° \times 7°$ square at the equator. Table I lists the vessel, month, and year for each station in the three oceans, and Fig. 1 shows the geographical position of each station. The distribution of stations does not approach uniformity, except in the South Atlantic, for which the extensive METEOR data have been available. Important gaps occur in the Arabian Sea, in the central South Indian Ocean, and in the central South Pacific Ocean.

For each station the potential temperature at each depth was computed using nomograms prepared by R. B. Montgomery and M. J. Pollak from Helland-Hansen's computations (1930). The depth, salinity, and dissolved oxygen were plotted against potential temperature on a grid furnished with isopleths of potential specific-volume anomaly as functions of salinity and potential temperature. Smooth curves were drawn through the points, and salinity, dissolved oxygen, and depth were interpolated at the four values of potential specific-volume anomaly. In some cases, where the interpolation was for a large depth interval, the first draft of the maps showed a marked discrepancy between adjacent stations; in these instances the station curves were redrawn to give a more consistent picture. In the maps herewith, the isopleths were not drawn everywhere strictly according to the station values. A difference between stations of 0.03‰ salinity and 0.20 ml/l dissolved oxygen was often not considered significant.

The stations have not been selected and treated according to season. In the high latitudes, where the specific-volume surfaces rise to the sea surface, the distributions are clearly subject to strong seasonal influence. Since most of the stations used in the Southern Ocean were occupied during the southern summer, the pertinent maps may be taken as representing this season there. The effect of ignoring the season of occupancy for the lower latitudes, where the 125-cl/t surface shallows to 300 m, has not been evaluated. It is likely that the distortion introduced by combining observations from many expeditions, many of which employed different measuring techniques, is considerably greater than the effects of seasonal influence, except where the specific-volume surfaces approach the sea surface at high latitudes.

Discussion. These isosteric surfaces[2] are one with the sea surface in the Southern Ocean during the southern winter (Deacon, 1937); the heavy line on the 125- and 100-cl/t maps (Figs. 2–7) indicates the position of this boundary at that time. Water of specific-volume anomaly 100 cl/t is not found continuously south to Antarctica, since water adjacent to Antarctica has a greater specific volume than that to the north. This distribution is related to the lower salinity in the surface layer near the ice pack. According to Deacon (1937), the water near the ice pack maintains its characteristic properties in the summer season and is not significantly mixed with subsurface water of higher salinity. He suggests that, offshore, a higher rate of wind mixing descreases the specific volume in the surface layer, thus accounting for the meridionally discontinuous occurrence of water within a certain range of specific volume at this season. The union with the sea surface of such an isosteric surface undergoes an extensive seasonal migration, moving northward in the winter and southward in the summer (U. S. Navy Hydrographic Office, 1957); the sea-surface isopycnal for $\sigma_t = 27.0$ g/l (107 cl/t) is shown moving 10° to the north between February and August. The indicated presence of 80- and 60-cl/t water to the south of 60°S on the maps presented here no doubt results from the general use of summer data. It is clear that the initial values of temperature, salinity, and dissolved oxygen acquired at the sea surface in the Southern Ocean by water within this range of specific volume vary markedly with season. According to the maps by Muromtsev (1959), water of 60 to 125 cl/t is also found at the sea surface in the Red Sea and Persian Gulf, so that these regions may serve as sources of water for the surfaces considered

[2] In the *Discussion*, the term *isosteric surface* will be used when referring to a surface of uniform potential specific-volume. The difference between these surfaces is insignificant at shallow depths but becomes more important at greater depths.

here. Water in this range of potential specific-volume anomaly extends without interruption into the open ocean from the Red Sea (Neumann and McGill, 1961). Data from the Persian Gulf are not available to determine whether there is similar continuity there.

These surfaces span the salinity minimum of the Antarctic Intermediate Water in the Southern Hemisphere. This minimum in midlatitudes lies at specific-volume anomalies that average between 80 and 90 cl/t in the three oceans. In the South Pacific and South Atlantic the value of the specific volume at the minimum decreases northward. However, in the South Indian Ocean the longitudinal average of the specific-volume anomaly at the minimum is virtually constant from 45°S to 15°S at 82 cl/t. Sverdrup *et al.* (1942) consider water of 2.2°C and 33.8‰ (105 cl/t) as a water type that sinks at the Antarctic Convergence to form the Antarctic Intermediate Water after it mixes with adjacent salty waters. In the South Atlantic, the 125-cl/t surface lies slightly above the upper oxygen minimum, and the 60-cl/t surface coincides with the lower oxygen minimum. These two minima were used by Wüst (1935) as boundaries of the Antarctic Intermediate Water.

In general, the depths of the isosteric surfaces vary least in the South Pacific, which suggests that the rate of circulation of intermediate waters there is less than in the South Atlantic or South Indian oceans. The South Indian Ocean is saltier and warmer north of 40°S, for a given specific volume, than the South Atlantic or South Pacific oceans, with the exception of the region 0° to 20°S on 125 cl/t in the South Indian Ocean (Fig. 2).

Although a comprehensive discussion of the circulation of water types on these surfaces cannot be undertaken with only these data, a number of features appear to have significance for any consideration of the circulation within these oceanic basins.

South Atlantic Ocean. The topographies of the four surfaces (Figs. 4, 7, 10, 13) show several common features. The surfaces descend from the sea surface to maximum depths at about 37°S in the central South Atlantic. On the deeper surfaces the depression becomes closed in the east-west direction. There is a dome on each surface, west of Africa at 10°S to 18°S, coincident with the position of the oxygen minimum on each surface. This dome (cyclone) may account in part for the position of the oxygen minimum if there is a closed circulation of water associated with it.[3] The contours have a northwesterly trend on the eastern side of the ocean from 35°S to 20°S. The 125-, 100-, and 80-cl/t surfaces deepen adjacent to South America, north of 20°S, consistent with the northward flow of Antarctic Intermediate Water; a similar deepening of the 60-cl/t surface is not shown.

3 If the pressure gradient vanishes along a deeper surface and the isosteres do not change slope with depth, the geostrophic current is parallel to the intersection of isosteric and equipotential surfaces. The circulation is cyclonic about domes and anticyclonic about depressions (Montgomery, 1938:13).

There are marked salinity and oxygen gradients in the eastern South Atlantic at 20°S. The region of high salinity north of 20°S is separated from the southern region on 125, 100, and 80 cl/t by a gradient of about 0.1 ‰ per degree of latitude (Figs. 2, 5, 8); on 125 cl/t a strong salinity gradient is found across the entire ocean, but on 100 and 80 cl/t the gradient weakens at about 20°W, where the isohalines develop a northwesterly trend and show a concentration of low-salinity water adjacent to South America. The corresponding oxygen gradient is 0.5 to 1.0 ml/l per degree of latitude (Figs. 3, 6, 9). The oxypleths on 125, 100, and 80 cl/t are zonal at 20°S from Africa to 20°W, where they begin to swing parallel to the South American coast in a manner analogous to the salinity. The presence of these strong north-south salinity and oxygen gradients in the eastern South Atlantic and the zonal course of the contours strongly suggest that the water transport is zonal at this latitude, thus virtually isolating the region north of 20°S from the high-oxygen, low-salinity waters at high latitudes.

Northerly transport of Antarctic Intermediate Water across the equator along the western boundary, clearly shown on these maps, was originally deduced by Wüst (1935) on the basis of his "Kernschichtmethode" and was later substantiated by Defant (1941) from his construction of the absolute topographies of selected isobaric surfaces. Westward zonal transport from 20°S to 30°S is, in the author's opinion, the main source of water for this flow. The northerly transport of low-salinity water along the South American coast from 40°S to 20°S, as deduced by Wüst (1935), appears to be too restricted in longitude to be reflected in the distributions presented here. The maps of volume transport between pairs of σ_t surfaces in the interval 26.7 to 27.5 g/l, published by Riley (1951), similarly do not indicate a northerly flow between 40°S and 20°S in the western South Atlantic.

Indian Ocean. The isosteric surfaces south of 40°S in the South Indian Ocean show a deepening into an east-west trough whose extent broadens with depth. This trough, on 100, 80, and 60 cl/t, extends across the entire South Indian Ocean into the southern Tasman Sea. The 125 and 100 cl/t surfaces are at their greatest depths east of the Cape of Good Hope in the vicinity of the southward-flowing Agulhas Current. Toward the equator, where there is generally little variation in depth (of the order of 100 m), the surfaces rise more or less uniformly.

The isohalines in the South Indian Ocean show a marked zonal pattern from the eastern border (100°E) to approximately 45°E; west of 45°E there is a consistent southward displacement of isohalines along the African coast from 10°S to 30°S (discussed below). From the distributions of salinity and oxygen there is no clear evidence of movement of relatively undiluted amounts of water from the Circumpolar Current into the South Indian Ocean. The salinities, which are uniformly high in the Indian Ocean from 20°S to 40°S relative to the other oceans, do not show a freshening on the eastern side of the ocean comparable to that in the South Pacific. Rochford's (1958) maps of salinity on σ_t surfaces 26.8 g/l (126 cl/t) and 27.2 g/l (88 cl/t) in the eastern South Indian Ocean similarly do not show a northward transport of low-salinity waters. On 125 cl/t there is a salinity maximum (> 35.0‰) located at 30°S that must be maintained by vertical exchange with overlying, more saline waters. Rochford (1958) has found that salinities greater than 35.0‰ occur on σ_t = 26.8 g/l only during the period February to September.

A marked transition region occurs between 10° and 20°S on 125, 100, and 80 cl/t; this is similar to transition regions in the eastern South Atlantic and South Pacific oceans. Between 15°S to 18°S there is a pronounced oxygen gradient ranging from 0.6 to 0.25 ml/l per degree of latitude between 125 and 80 cl/t, respectively. The magnitude of this oxygen gradient diminishes west of 60°E, where the oxypleths diverge northward and southward. In contrast to the other two oceans, there is no oxygen minimum on the 125-, 100-, and 80-cl/t surfaces south of the equator. Oxygen decreases northward to its lowest values in the North Indian Ocean. A corresponding pronounced salinity gradient does not occur on 100 and 80 cl/t, but instead the salinity increases northward in a uniform manner. On 125 cl/t, just to the north of the strong oxygen gradient, a salinity minimum is found (discussed below). This region of transition from high-oxygen to low-oxygen waters on the 125-, 100-, and 80-cl/t surfaces lies just to the south of the frontal zone discussed by Tchernia *et al.* (1958) and Ivanov-Frantskevich (1961); they interpret this zone at intermediate depths as the limit of northward penetration of Antarctic Intermediate Water. In the eastern South Indian Ocean, the salinity minimum of Antarctic Intermediate Water is rapidly attenuated between 19°S and 9°S. The water at 9°S is essentially homogeneous in salinity from 200 m to the bottom (Muromtsev, 1959: fig. 41). Since the isosteric surfaces rise toward the equator in this region, as do the surfaces of constant salinity and oxygen, the gradient along isosteric surfaces is considerably less than that along level surfaces. This strong oxygen gradient and the zonal course of the isohalines and depth contours suggest that the main transport is zonal. The southward transport to 30°S at 80°E proposed by Rochford (1958) on σ_t = 27.2 g/l (88 cl/t) does not appear in these distributions. Rochford's interpretation appears to be based on the depth of the σ_t = 27.2 g/l surface at one station (Norsel 23).

The striking salinity minimum on 125 cl/t, with values of less than 34.7‰ to 90°E and less than 34.9‰ to 60°E, is clearly related to the low-salinity water between northwestern Australia and the Indonesian Archipelago. This minimum, noted by Rochford (1958) on σ_t = 26.8 g/l (126 cl/t) appears on the Muromtsev (1959) level-surface distributions at depths from 100 to 600 m. However, there is no indication of the minimum on 100 cl/t at depths of 500 to 600 m. At this specific volume the salinity decreases with depth to the minimum of the Antarctic Intermediate Water, so there is little contrast in salinity on 100 cl/t between water at 30°S and water in the Indonesian seas; the possible penetration of this water into the Indian Ocean cannot be traced as on 125 cl/t. More accurate observations have recently shown the penetration of low-salinity Indonesian waters into the South Indian Ocean at deeper levels (Rochford, 1962). On nine of the fourteen stations in the minimum on 125 cl/t, the salinity increases upward; on the other five stations, east of 90°E, 125 cl/t occurs at a slight salinity maximum in the vertical of about 0.05 ‰; this maximum, according to Wyrtki (1961), represents the remnant of North Indian Ocean water that propagates southward across the equator and persists as a maximum to south of Java. Water in the minimum on the 125-cl/t surface is a mixture of water from three regions: North Indian Ocean, Indonesian Archipelago, and central South Indian Ocean. The longitudinal extent of the minimum is a clear indication of westward advection in the minimum.

The isohalines on all surfaces develop a marked southward trend at 45°E. Salinities in the Mozambique Channel are at least 0.1 ‰ higher than those at comparable latitudes to the east in the South Indian Ocean. South of 20°S these salinities are associated with relatively low oxygen values. On 60 cl/t the southward advection of high-salinity water is indicated in the Mozambique Channel by a deep salinity maximum originally observed by Clowes and Deacon (1935) and designated by them as North Indian Deep Water. Since the salinity is a maximum along the western boundary, both vertically and laterally, it must be maintained by advection from the north. Between 20°S and 25°S there is a strong salinity gradient on 60 cl/t that represents the boundary between waters of this salinity maximum and the salinity minimum of the Antarctic Intermediate Water. On this surface, and probably on the others as well, there is a southward transport of high-salinity, low-oxygen water along the western boundary to at least 20°S. The salinities between 20°S and 30°S on these surfaces are higher adjacent to Africa than to the east.

The consistent upward slope of the surface toward the extreme southeastern African coast indicates the presence of the Agulhas Current to depths of at least 1300 m. On all surfaces the property distributions indicate that a major portion of the water transported southward returns to the South Indian Ocean in the Circumpolar Current. This return flow was named the Agulhas Return Current by Deacon (1937). Adjacent to the southwestern African coast, high-salinity water in the South Atlantic Ocean on all surfaces is maintained by a flow of Agulhas Current water that continues around the Cape of Good Hope to enter the South Atlantic; its presence on these maps is most marked on 100 and 80 cl/t. Clowes (1950), in a detailed study of all data available at the time, concluded that this flow into the South Atlantic appears on the $\sigma_t = 26.5$ g/l (154 cl/t), 26.75 g/l (130 cl/t), and 27.25 g/l (83 cl/t) surfaces. This water may be identified only over four degrees of latitude, in a narrow band adjacent to the continent, before it is diluted by mixing with adjacent low-salinity waters.

For the North Indian Ocean, the available data are sparse and of variable quality. The very high salinity of Red Sea water on these surfaces (35.94–36.66 ‰) is reduced rapidly by the mixing of these waters with Arabian Sea waters, so that at 11°N, 56°E the salinity has been reduced to values of 35.36 to 35.51 ‰; these values are quite close to those over a large region of the Arabian Sea. Waters with very high salinity values in the Gulf of Oman seem also to be quickly diluted by mixing with Arabian Sea waters. The isohalines from 0° to 10°N are zonal east to 75°E. The water east of 75°E is less saline on all surfaces than Arabian Sea water, and on 125 and 100 cl/t it is lower in oxygen. In the eastern North Indian Ocean, the water column exhibits two salinity maxima: the upper and the lower at an average specific-volume anomaly of 120 and 78 cl/t, respectively. Wyrtki (1961) has deduced that the probable origins of these maxima are the Persian Gulf and Red Sea, respectively. The eastward penetration to 80° E of water with salinity greater than 35.1 ‰ on 125 and 100 cl/t and greater than 35.0 ‰ on 80 cl/t agrees with his interpretation of these features in the vertical distribution of salinity. On 125 and 100 cl/t this interpretation of eastward flow agrees with the decrease in oxygen to the east in the North Indian Ocean.

The distribution maps give no indication of a flow from the North Indian Ocean across the equator into the South Indian Ocean along the western boundary. The water is zonally homogeneous in salinity and oxygen along the boundary to 10°S.

From a salinity minimum that may be drawn continuously from the South Indian Ocean to the Gulf of Oman, Tchernia *et al.* (1958) concluded that Antarctic Intermediate Water crosses the equator in the western Indian Ocean and penetrates to the northern boundary of the Arabian Sea. North of the equator the salinity of the minimum increases (35 ‰ at the equator and 35.5 ‰ at 11°N) and the specific-volume anomaly averages 117 cl/t. In the western Indian Ocean the minimum salinity of the Antarctic Intermediate Water at 12°S is 34.7 ‰ and occurs at a specific-volume anomaly of 90 cl/t (Muromtsev, 1959: fig. 37). The increase in specific volume at these minima clearly implies that they are not connected by a line of flow. Ivanov-Frantskevitch (1961) has pointed out that the salinity minimum in the Arabian Sea may be explained by the spreading of deep salinity maximum waters of Red Sea origin at 500 to 800 m underneath surface waters of higher salinity. The maintenance of this salinity minimum, found throughout the Arabian Sea, does not require a flow of Antarctic Intermediate Water across the equator. Consistent with this interpretation, the salinity distributions on 125 and 100 cl/t show a spreading of high salinity water from the Gulf of Aden into the Central Arabian Sea; in no way do they suggest a penetration of low-salinity water into that region. On the other hand, the northwesterly trend of the oxypleths from 10°S to the equator on 125 and 100 cl/t suggests a northward transport of oxygen-rich water west of 60°E. The paucity of oxygen data for the Arabian Sea does not permit an assessment of the northward limit of the displacement of the oxypleths. A critical testing of the suggestion by Tchernia *et al.* (1958) must await better hydrographic coverage of the Arabian Sea.

South Pacific Ocean. All four isosteric surfaces in the South Pacific show a topographic depression (anticyclone). On 125 cl/t a closed trough occurs at 20°S in the western South Pacific; on the three deeper surfaces, the trough is centered at 40°S, 150°W. All surfaces gradually ascend eastward toward South America. Between 0° and 20°S, the depth contours do not exhibit consistent features. The 100- and 80-cl/t surfaces show a ridge at 10°S, west of 150°W, that is not found on either 125 or 60 cl/t.

In the eastern South Pacific there is a northward displacement of low-salinity water that does not have a counterpart in the South Indian or South Atlantic oceans. This feature, found at 90°W on 125, 100, and 80 cl/t, extends to 30°S on 125 and 100 cl/t, and to 40°S on 80 cl/t; it is characterized by salinities of less than 34.4‰ on 125 cl/t and of less than 34.3‰ on 100 and 80 cl/t. On 60 cl/t the water is zonally homogenous west to 180° at 40°S. Only in the South Pacific do the low-salinity waters of the Circumpolar. Current penetrate northward to low latitudes in relatively undiluted amounts. The South American continent, reaching to 55°S, physically obstructs the main eastward flow of the Circumpolar Current; on the other hand, the Australian and African continents reach only to 35°S and consequently are not an important physical barrier to this flow in those regions. Only on 125 cl/t, where there is a 5° northward displacement of the 34.7 and 34.8‰ isohalines, is there a suggestion of propagation of low-salinity waters from the Circumpolar Current into the eastern South Atlantic.

In the central South Pacific, salinity minima occur on 125 cl/t at 20°S, and on 100 cl/t at 28°S. The minimum on 125 cl/t extends into the Coral Sea and lies above the salinity minimum associated with the Antarctic Intermediate Water; the minimum on 100 cl/t coincides with the salinity minimum of the Antarctic Intermediate Water, and thus is can be maintained only by westward advection of low-salinity water carried northward from the Circumpolar Current. The ascent of the 125- and 100-cl/t surfaces towards the equator also indicates zonal westward flow in the minima.

The oxygen distributions on the four surfaces show a northward displacement of high-oxygen water in the eastern South Pacific. This feature, most striking on 125 and 100 cl/t, provides further support for the concept of water transport northward from the Circumpolar Current. The oxygen maximum on 100 cl/t coincides with an oxygen maximum in the vertical.

Adjacent to the South American coast, on the 125- and 100-cl/t surfaces, the marked southerly trend of the isohalines and oxypleths, south of 20°S, is evidence of a southerly flow of high-salinity, low-oxygen water. Wooster and Gilmartin (1961) concluded from salinity and dissolved oxygen distributions, geostrophic computations, and direct current measurements that there is a southerly subsurface flow to at least 41°S underneath the Peru Current; they called this the Peru-Chile Undercurrent. They concluded that the core of this Undercurrent occurs at depths of 150 to 200 m and at thermosteric anomalies of 160 to 140 cl/t. The 125- and 100-cl/t surfaces lie below the salinity maximum and oxygen minimum used by these authors as indicators of the core of the Undercurrent. The distributions on these surfaces demonstrate that the Undercurrent extends in depth to at least 500 m, and south possibly to 50°S. The position of the southerly trend of the isopleths indicates roughly that the Undercurrent influences the salinity and oxygen over a band of five to eight degrees of longitude. There is no suggestion of a poleward undercurrent of comparable scale at the eastern boundaries of the South Indian or South Atlantic oceans. Hart and Currie (1960) have presented evidence for a poleward flow underneath the Benguela Current, but it appears to be of a more coastal character than the Peru-Chile Undercurrent.

In the eastern South Pacific on all four surfaces there is a marked dissolved oxygen gradient that separates the equatorial low-oxygen waters from the more highly oxygenated waters in the high latitudes. This gradient decreases in magnitude from 0.5 to 0.3 ml/l per degree of latitude on 125 to 60 cl/t. This sharp transition is comparable to the transitions mentioned in the discussions of the South Indian and South Atlantic oceans, but it extends to lower specific volumes. The oxypleths have a northwesterly trend to 150°W, where they become largely zonal. The oxypleths cross the equator in the west and might reveal an exchange between the South and North Pacific when considered with the North Pacific distributions. The low oxygen values in the equatorial eastern South Pacific are probably related to the westward turning of the high-oxygen, low-salinity water from the Circumpolar Currrent at 20°S to 30°S.

The salinity, in contrast to the dissolved oxygen, is zonally uniform north of 10°S on 125 cl/t and north of 20°S on the lower surfaces. The broad interval between stations (ca. 5°) precludes identification of features such as the South Equatorial Countercurrent (Reid, 1959), whose horizontal extent is of the order of station distance. Several features, such as the domes at 10°S in the western Pacific on 100 and 80 cl/t, might be associated with this flow.

The salinity and oxygen in the Tasman Sea show distinctive features that demonstrate the importance of vertical exchange. On 125 cl/t the salinity in the Tasman Sea is a maximum for the entire 125-cl/t surface in the South Pacific; on 100 and 80 cl/t the salinity in this region is a zonal maximum, but less so than at the equator. The salinity increases toward the sea surface at specific-volume anomalies of 125 and 100 cl/t in the Tasman Sea, so that the exchange of salt must be downward in order to maintain the high salinity. Rochford (1960b) concluded from a detailed study of the water types on σ_t = 26.8 g/l (126 cl/t) that the source region for this high-salinity water was in the southwestern Tasman Sea. The higher salinity there is related to the weak penetration of Antarctic Intermediate Water from the south. In contrast to waters at these latitudes to the east, the intermediate water enters the Tasman Sea from the east after it has mixed with the more saline waters in the lower latitudes (Wyrtki, 1962).

On the 125-, 100-, and 80-cl/t surfaces there is a westward extension of the high-salinity water from the Tasman Sea north and east of North Island, New Zealand. On 125 and 100 cl/t a salinity maximum at 35°S is clearly found eastward to 165°W. Although the maximum has been shown to exist farther east to 140°W on 125 and 100 cl/t, the continuity of this maximum cannot be established because of a lack of stations between 165°W and 140°W. Associated with the salinity maximum on 125 and 100 cl/t is an oxygen minimum that extends only to 175°W. Rochford (1960a, b) and Wyrtki (1962) have deduced an eastward flow from the Tasman Sea into the South Pacific north of North Island, New Zealand. The high salinity and low oxygen tongues are an expression of this flow out of the Tasman Sea.

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Summary. The salinity, dissolved oxygen, and depth distributions of four isosteric surfaces (125, 100, 80, and 60 cl/t) have revealed a number of features suggestive of the circulation on these surfaces.

(1) In each ocean of the Southern Hemisphere there is a region with a strong north-south oxygen gradient in the waters of specific-volume anomaly range between 60 and 125 cl/t. This gradient is most intense on the upper surfaces and is more highly developed in the east than in the west.

(2) The South Indian Ocean is generally more saline at these specific volumes than the other oceans, except in the region of penetration of low-salinity waters at 10°S into the South Indian Ocean on 125 cl/t.

(3) On all surfaces in the eastern South Pacific and South Atlantic oceans there is an oxygen minimum, with the lowest values in the South Pacific. The Indian Ocean possesses no oxygen minimum south of the equator.

(4) The penetration of low-salinity water from the Banda and Timor seas into the South Indian Ocean on 125 cl/t is seen in a salinity minimum that extends westward to 60°E at 10°S.

(5) On all surfaces in the South Indian Ocean, the salinity and oxygen distributions indicate transport of high-salinity, low-oxygen water from the equatorial zone southward along the western boundary through the Mozambique Channel. The contour maps of the surfaces suggest the persistence of the Agulhas Current to depths of 1300 m. On 100 and 80 cl/t, significant

amounts of Agulhas Current water are transported around the Cape of Good Hope into the eastern South Atlantic.

(6) On 125 and 100 cl/t, low-salinity, high-oxygen water from the Circumpolar Current extends into the eastern South Pacific. This water is traced across the Pacific to 150°W–180°W by means of a salinity minimum. This circulation must be related to the extension of South America to 55°S. In neither the South Atlantic nor the South Indian Ocean is there a marked northward propagation of Circumpolar Current water on the eastern side.

(7) The high-salinity, low-oxygen water immediately adjacent to South America on 125 and 100 cl/t represents water that is brought south in the Peru-Chile Undercurrent. In the South Atlantic or South Indian oceans there is no indication of a poleward flow comparable in scale to that of the Peru-Chile Undercurrent.

(8) The Tasman Sea is characteristically a region of high salinity on these surfaces. Rochford (1960a,b) and Wyrtki (1962) have shown that the Antarctic Intermediate Water does not enter the Tasman Sea in large amounts in an undiluted form from the south; rather it enters from the east after being mixed with more saline equatorial and subtropical waters. This lack of entry of low-salinity waters from the south and vertical exchange with overlying water of higher salinity explains the high level of salinity found there.

(9) The main flow in the South Atlantic on 100 and 80 cl/t, north of 20°S, appears to be northward along the coast of South America as originally deduced by Wüst (1935). The predominant source for this flow appears to be the water carried westward in zonal flow from the eastern Atlantic. There is no evidence from these distributions of a continuous northward propagation of low-salinity water from the high latitudes along the coast of South America.

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TABLE I. List of Stations.

INDIAN OCEAN

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Albatross (A)	183–4, 200, 205, 220, 223	5	1948	II, III, IV
Dana (Da)	3676, 3804, 3813, 3893, 3906, 3912, 3915, 3917, 3920, 3942	10	1929	III, VIII, IX XI, XII
Discovery (D)	428, 431	2	1930	VII, IX
Discovery (D)	848, 850, 852, 854, 864, 866, 874, 884, 893, 894, 895	11	1932	IV, V, VI
Discovery (D)	1533, 1572, 1575, 1577, 1581, 1583, 1586, 1584, 1615, 1616, 1618	11	1935	II, IV, V, XI
Discovery (D)	1689, 1690, 1692, 1694, 1727, 1740, 1744, 1746, 1752, 1754, 1756, 1758, 1760, 1763	14	1936	III, IV, V
Discovery (D)	2094, 2113, 2119, 2131, 2145, 2146, 2153	7	1937	XI, XII
Discovery (D)	2166, 2180, 2192, 2412, 2524	5	1938	I, VIII, XII
Discovery (D)	2690	1	1950	VI
Discovery (D)	2782, 2802, 2805, 2888, 2890, 2891, 2901	7	1951	I, II, IX, XI
Mabahiss (Ma) *John Murray*	61, 76, 95	3	1933	XI, XII
Argo (Mo) *Monsoon*	IV–5	1	1960	XII
Norsel (N)	11	1	1955	XI
Norsel (N)	23, 25	2	1956	II
Norsel (N)	38, 40, 42, 46	4	1958	III

TABLE I. List of Stations (Continued).

INDIAN OCEAN (Continued)

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Ob (O) *Cruise 1*	93, 97, 101, 107, 110, 124, 125, 127, 129, 131, 132, 135, 138, 141, 144, 146, 148	17	1956	V, VI
Ob (O) *Cruise 2*	297, 302, 305, 307, 309, 311, 312, 314, 318, 320, 322, 324, 326, 327	14	1957	IV, V
Snellius (S)	22, 127, 146	3	1929	IV, X, XI
Snellius (S)	187, 212, 311, 355, 376	5	1930	II, III, VII, X, XI
Umitaka Maru (UM)	2, 6, 7, 8, 9, 15, 16	7	1956	XI, XII
Vema (V) *Cruise 14*	47, 49, 53, 59, 60	5	1958	IV, V, VI
Vema (V) *Cruise 16*	50, 51, 52, 56, 60, 63, 66, 69	8	1960	I, II

SOUTH PACIFIC OCEAN

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Albatross (A)	52, 93, 138	3	1947	IX, X, XII
Albatross (A)	143	1	1948	I
Brategg (B)	1	1	1947	XII
Carnegie (C)	61	1	1928	XII
Carnegie (C)	76, 81, 83	3	1929	II, III
Dana (Da)	3558, 3561, 3563, 3570, 3577, 3580, 3585, 3587, 3602, 3620, 3624, 3628, 3630	13	1928	IX, X, XI, XII
Dana (Da)	3653, 3656, 3663, 3665	4	1929	I, II
Discovery (D)	731	1	1931	XI
Discovery (D)	905, 923, 949, 964, 967, 970, 974, 975, 976, 978	10	1932	VI, VII IX, X

TABLE I. List of Stations (Continued).

SOUTH PACIFIC OCEAN (Continued)

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Discovery (D)	1241, 1243, 1245, 1255, 1259, 1280, 1283, 1291	8	1934	I, II
Discovery (D)	1665, 1667, 1684	3	1936	I, II
Discovery (D)	2198, 2204, 2208, 2217, 2226, 2232, 2250	7	1938	I, II
Discovery (D)	2769	1	1950	XI
Discovery (D)	2819, 2833, 2835, 2837	4	1951	V, VI
Horizon (DW) *Downwind*	9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 28	16	1957	XI, XII
Horizon (DW) *Downwind*	30, 36, 37, 38, 39, 40, 41, 42	8	1958	I, II
Horizon (H) *Equapac*	17, 23, 30	3	1956	VIII
Stranger (S) *Equapac*	24, 28, 32	3	1956	VIII, IX
Hugh M. Smith (HS) *Equapac*	62, 73, 83, 91, 102, 113, 122, 130, 153, 164	10	1956	VIII, IX
Argo (Mo) *Monsoon*	VII–14, VII–16 VII–22, VII–24	4	1961	III
Ob (O) *Cruise 1*	85	1	1956	IV
Ob (O) *Cruise 3*	384, 387, 388, 389, 390, 392, 393, 396, 397, 408, 409, 411, 413, 415, 417, 419, 421, 423, 425, 426, 427, 429, 430, 433, 435, 436, 437, 439, 440, 442, 444, 447, 448, 449, 450	35	1958	IV, V
Horizon (ST) *Step I*	1, 9, 14, 19, 23, 32, 37, 47, 55, 63, 66, 68, 71, 74, 77, 82	16	1960	IX, X, XI, XII

TABLE I. List of Stations (Continued).

SOUTH PACIFIC OCEAN (Continued)

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Umitaka Maru (UM)	11, 17, 21, 27	4	1959	I
Vityaz (Vi) *Cruise 26*	3812, 3818, 3823	3	1957	XII
Vityaz (Vi) *Cruise 26*	3827, 3833, 3838, 3845, 3847, 3852, 3854, 3858, 3862	9	1958	I, II

SOUTH ATLANTIC OCEAN

Vessel (Abbr.), Expedition	Station Numbers	No. of Sts.	Year	Month
Discovery (D)	72	1	1926	VI
Discovery (D)	1517	1	1935	II
Discovery (D)	2455	1	1938	X
Meteor (M)	3, 9, 12, 15, 18, 23, 31, 35, 37, 46, 51, 56, 58, 60, 62, 67, 73, 75, 77, 79, 81, 83, 85, 88	24	1925	VI, VII, VIII, IX, X, XI, XII
Meteor (M)	108, 116, 118, 121, 124, 128, 130, 131, 140, 145, 148, 152, 157, 159, 168, 171, 174, 178, 180, 188, 191, 194, 199, 211, 241, 243	26	1926	I, II, III, V, VI, IX, X, XII
Meteor (M)	247, 251, 257	3	1927	I, II
General San Martin (SM)	12, 13	2	1959	I

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