On the Mid-Depth Circulation of the North Pacific Ocean

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ABSTRACT

The large-scale oxygen distribution within the upper 1500 m of the North Pacific Ocean reveals an extra zone of low oxygen near 30–40°N in the east that is not easily compatible with a simple large-scale subtropical anticyclonic flow at mid-depth. Further examination of the relative flow patterns suggests that the large subtropical gyre generally supposed to obtain at the sea surface has a very strong return flow southward, just east of the Kuroshio, and that this flow turns eastward near 20–25°N and extends eastward at least as far as 160°E. At greater depths, near 1000 m, it continues eastward all across the Pacific. The area of high steric height within the anticyclonic gyre at this depth is thus shaped like the letter C, with two branches extending eastward from the western boundary. Each branch has an eastward flow on its north side and a westward flow on its south side. The highest oxygen values at mid-depth are found near the western boundary, deriving from the South Pacific, and the two eastward flows carry the higher oxygen waters eastward as two tongues of higher oxygen values, leaving an area of lower oxygen near 30–40°N in the east.

1. Introduction

Earlier studies of the near-surface circulation of the North Pacific Ocean (Sverdrup *et al.*, 1942; Reid, 1961; Tsuchiya, 1968; Wyrtki, 1974; Reid and Arthur, 1975) had found one large midlatitude anticyclonic gyre with a higher latitude cyclonic gyre, an equatorial countercurrent north of the equator, and an equatorial flow westward at the surface with an eastward undercurrent beneath.

There has been some slight deviation from this simplified pattern in the west. A strongly intensified return flow just southeast of the Kuroshio, turning eastward for a short distance near 20°N, appeared in the earlier map of surface flow (Reid, 1961). [In a later map (Reid and Arthur, 1975) the eastward extension was more strongly indicated, and reached as far as 170°E.] Uda and Hasunuma (1969) have examined this subtropical counterflow from upper level thermal structure, geopotential anomaly and atlases of the set and drift of merchant vessels, and conclude from those data that it extends at least as far eastward as 160°E and probably farther.

Yoshida and Kidokoro (1967a and 1967b) have discussed this pattern and attempted to account for it in terms of Sverdrup transport derived from an analysis of the wind stress. They propose a substantial eastward transport near 20°N in winter and spring (separate from the west-wind drift of higher latitudes), extending perhaps as far as 140°W.

Suginohara (1973) has used a three-layer model of a wind-driven ocean to examine this flow and finds eastward flow in the uppermost layer with westward flow beneath. The eastward flow at the surface lies near 20°N in the west but is found at higher latitudes—about 35°N—in the eastern area.

The calculations of geostrophic flow at the surface relative to the 500 or 1000 db surface (Reid, 1961; Wyrtki, 1974; Reid and Arthur, 1975) do not reveal such a separate eastward flow at the surface east of about 170°E. However, as will be seen, there is substantial evidence for such an eastward flow at subsurface depths in both the density field and the pattern of dissolved oxygen distribution.

2. The distribution of dissolved oxygen near the surface

Reid (1965) had examined the concentration of dissolved oxygen on a shallow isopycnal (thermosteric anomaly 125 cl ton^{-1}, $\sigma_t = 26.81$), with depth varying from 150 m near 50°N to 350–800 m at 30°N to 400 m along the equator, and accounted for its variation in terms of the flow pattern. High concentrations were found in the northwest, where the stratum lies shallow, decreasing downstream around the anticyclonic flow (the North Equatorial Current) and eastward again with the equatorial counterflow (Fig. 1). The zone between 10 and 20°N in the east, between the eastward flowing countercurrent at 5–10°N and westward flowing limb of the anticyclonic gyre, was interpreted to be a region by-

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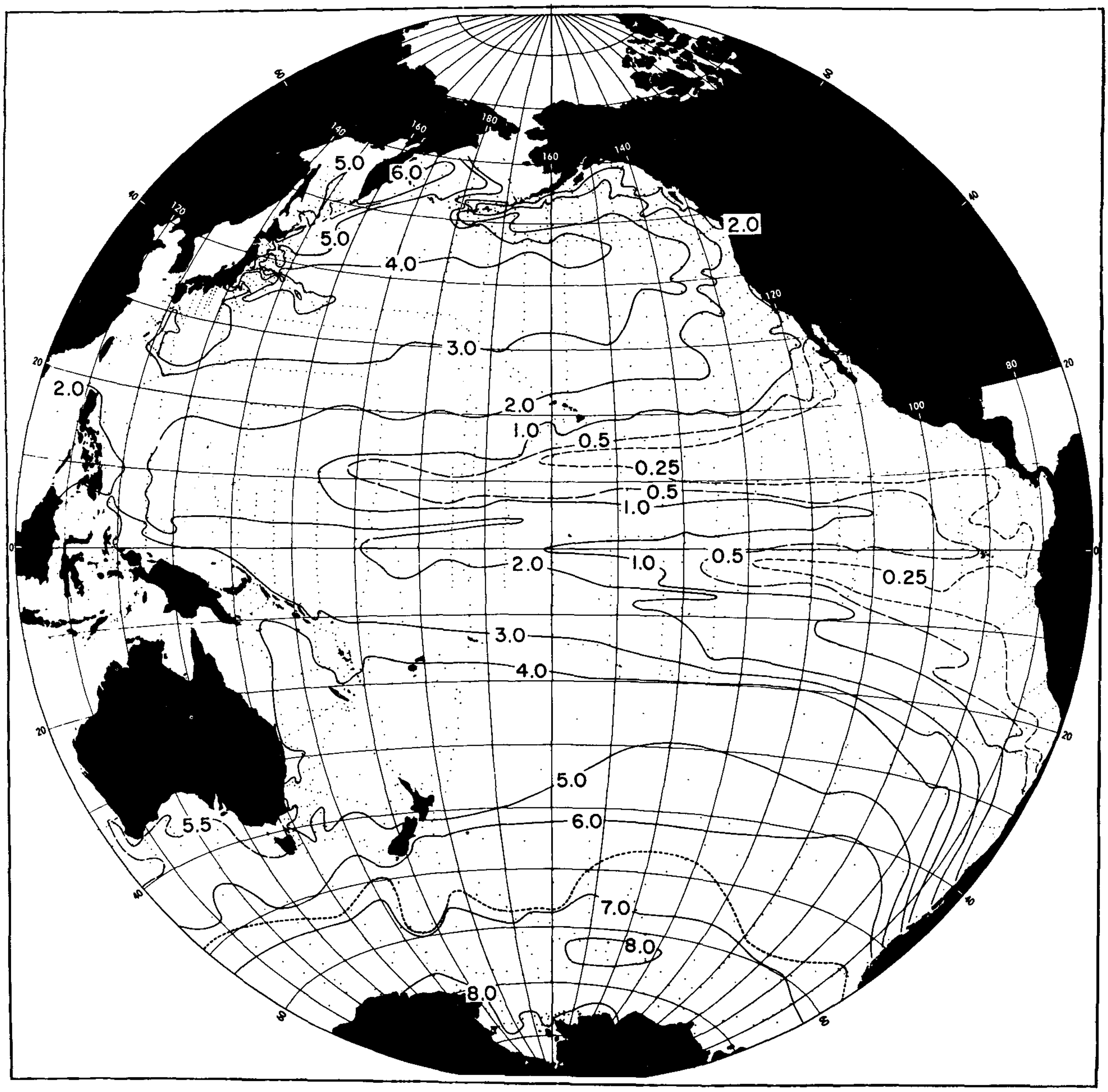

FIG. 1. Oxygen concentration (ml l^{-1}) on the surface where thermosteric anomaly is 125 cl ton^{-1} (σ_t = 26.81). The depth of this surface varies from 150 to 800 m in the north, and the isopycnal outcrops at the sea surface in the south along the dashed line near 50°S. Adapted from Reid (1965).

passed by the principal flow of the renewed water, and thus appears lowest in oxygen and highest in nutrients.

However, at greater depths a more complex pattern is seen in the oxygen distribution. On a deeper isopycnal (thermosteric anomaly 80 cl ton^{-1}, σ_t = 27.281), lying near 800 m depth in middle latitudes, an additional oxygen minimum appeared along 30°N, extending westward from North America to about 140°E. Barkley's (1968) maps of oxygen on σ_t surfaces show the same features: the 30°N minimum appears weakly at a σ_t value of 27.20 and clearly at 27.40.

This feature appears also on maps of oxygen distribution on constant-depth surfaces. The NORPAC *Atlas* (NORPAC Committee, 1960) illustrates it clearly at 1000 m; it is not present at 600 m and above.

As Reid (1965) noted, there are in this case more features in the gross oxygen pattern than were recognized in the circulation. An attempt was made to account for this pattern in terms of vertical diffusion associated with the vertical minimum in oxygen, but there seems to be a more likely explanation based on a different field of flow, presented herein. Pytkowicz and Kester (1966) examined oxygen and phosphate at depths between 1 and 2 km in the area east of 150°W and north of 20°N. From the calculated oxygen-utilization patterns on one of their σ_t surfaces (27.42), they postulated flow across 150°W that is eastward at about 45–50°N, westward at about 35–45°N and eastward again at about 20°N. This is consonant with the results reported herein for that area.

3. The deeper oxygen pattern

To examine the two oxygen minima in the North Pacific, we choose an isopycnal surface that cuts through both of them at depths near 1000 m. In the North Pacific, this isopycnal surface lies between 500 and 1000 m depth, and it represents water that would have a density of 1.0320 g cm^{-3} ($\sigma_t = 32.0$) if moved adiabatically to a pressure of 1000 db. This isopycnal rises above 500 m south of 50°S (not illustrated) and beyond there defines the depth of the water that would have a density of 1.02735 g cm^{-3} ($\sigma_0 = 27.35$) if moved adiabatically to the sea surface. [This approximation, and the joining of the two density parameters, has been discussed by Reid and Lynn (1971).]

In general its depth variations (Fig. 2) reflect the sort of density field one would expect from the simple pattern of large-scale anticyclonic flow in middle latitudes (20–50°N) and cyclonic flow north of 50°N. There is, however, a notable trough near 20°N in the east, not apparent in Reid's (1965) earlier maps or in Barkley's (1968) maps at this and greater depths. The earlier data were not sufficient in the eastern tropical area to resolve this feature.

The stratum rises to a minimum depth of about 700 m in the northwestern Pacific, along the axis of the cyclonic gyre, and has a maximum depth of about 1200 m in the western part of the anticyclonic gyre.

The pattern of oxygen on this stratum (Fig. 3) is dominated by the high values entering from the South Pacific (where this stratum outcrops near 60°S in southern winter) and the low values found in the North Pacific, where the stratum lies too deep for any substantial high-latitude renewal by convection or vertical diffusion. North of the equator it lies nearly everywhere below the deep oxygen minimum. Only within the Okhotsk Sea and in a small part of the eastern Bering Sea does it lie at or slightly above the oxygen minimum; in those areas, there is evidence of a very slight renewal from above by vertical processes.

As a result, there is no substantial replenishment of oxygen from the overlying water in the North Pacific; the oxygen along this stratum is supplied almost entirely from the south, either by lateral spreading from the South Pacific or by vertical mixing with the underlying more oxygen-rich waters, which have also entered from the South Pacific.

The oxygen pattern on this stratum is very much like that on the 80 cl ton^{-1} stratum [illustrated and discussed by Reid (1965)], which was chosen to represent the Intermediate Water of the South Pacific. High values from southern high latitudes extend through the anticyclonic gyre (centered along about 40–45°S on this stratum in the central ocean) and reach the equator in the west. From there the higher values extend northward through the Philippine Sea. From their last aeration in the surface layer near 60°S the concentration of oxygen has been decreased substantially by respiration and decay and by exchange with the waters of the overlying oxygen minimum. The northeastern quadrant of the Pacific thus has the lowest concentrations.

In the North Pacific, there are three areas of lateral minima in oxygen on this stratum. One, along about 20°N in the east and extending westward to about 10–15°N at 170°E, is clearly the same feature seen on shallower isopycnals corresponding to the Intermediate Water (Reid, 1965; Barkley, 1968), where it lies between the North Equatorial Current and Countercurrent.

A second minimum lies in the northern and eastern Gulf of Alaska and extends southwestward through about 40°N, 140°W to about 25°N, 140°E.

The third lies in the extreme northwestern area and covers all but the eastern part of the Bering Sea; a small renewal by vertical diffusion provides slightly higher oxygen values (and lower salinity values) near the northeastern continental slope.

Alternatively stated, there are two eastward extensions of high oxygen from the richer waters near the western boundary, along about 20–25°N and about 35–45°N, and one slight local renewal in the northeastern Bering Sea.

It is the minimum near 30–40°N in the east that requires explanation: it does not correspond in a simple way to the anticyclonic flow of the surface waters. Some partial explanation might emerge from the map of shear between the 1000 and 2000 db surfaces prepared by Reid and Arthur (1975); at greater depths, there is clearly a poleward migration of the east-west axis of the anticyclonic gyre. This might suggest a westward return flow around the anticyclonic gyre at a higher latitude than is seen at the sea surface, leaving the area near 40°N unrenewed, but the latitude is not quite right. And in any case, the maximum extending eastward along 20–30°N would remain unexplained.

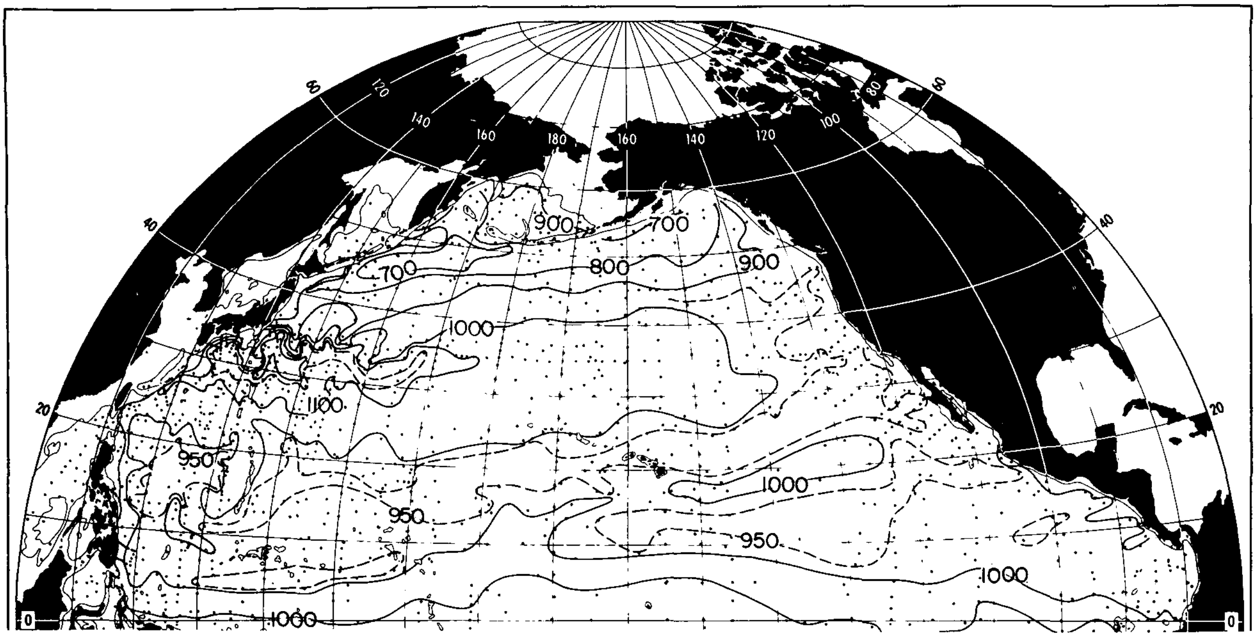

FIG. 2. Depth (m) of the water which would have a density of 1.032 g cm^{-3} (σ_t = 32.0) if moved adiabatically to the depth where the pressure is 1000 db.

4. The circulation near 1000 m depth

In an attempt to examine the flow field we prepared a map (Fig. 4) of the geopotential anomaly at 1000 db relative to 3500 db (steric height 1000/3500 db). It differs considerably from Reed's (1970) map at 1000/3500 db and from the map of Reid and Arthur (1975) at 1000/2000 db. Data were too sparse for Reed's map to resolve the field in the intertropical zone, and the shear field between 1000 and 2000 db is too weak for the map by Reid and Arthur to provide the additional detail seen in Fig. 4.

The important new features are the east-west trough extending from about 40°N at the eastern boundary westward and slightly southward, crossing the Marianas Ridge at about 25°N 145°E, and the east-west ridge lying along about 20°N in the central ocean.

Instead of simply a poleward migration of the axis and meridional contraction of the anticyclonic gyre at increasing depths, consonant with westward flow along about 30°N, this map suggests an additional eastward flow along about 20°N.

In effect, the anticyclonic gyre, while still a continuous feature along the western boundary, extends eastward in two branches, one from 35°N in the west to 45°N in the east and one from about 20°N in the western and central areas to about 30°N in the east.

Although there is some complexity in the geopotential pattern in the west, caused in part by the bottom topography (the Marshall-Gilbert chain of islands along about 170°W, the Caroline Islands, the ridge extending from New Guinea to Japan along about 140–145°E, and the Kyushu-Palau Ridge within the Philippine Sea along about 135°E), the field shows a narrow but continuous northward flowing western boundary current from about 5°N to Japan and feeding into the two eastward flows.

5. Conclusion

It appears that the circulation pattern proposed in Fig. 4 can account for the oxygen distribution on this stratum in the North Pacific Ocean. Oxygen-rich water enters in the west from the South Pacific and passes across the equator and northward with the western boundary current. From there two eastward-flowing branches carry the newer water across the North Pacific toward 45 and 30°N in the east. The adjacent westward flows, reduced in oxygen content, extend westward as wedges of low oxygen between the branches carrying the newer waters.

6. Notes on the treatment of the data

a. The western Pacific

Because the baroclinic signal is so low in low latitudes and in the deeper parts of the Philippine Sea, the available data from the various tracks of the earlier expeditions did not reveal a very clear

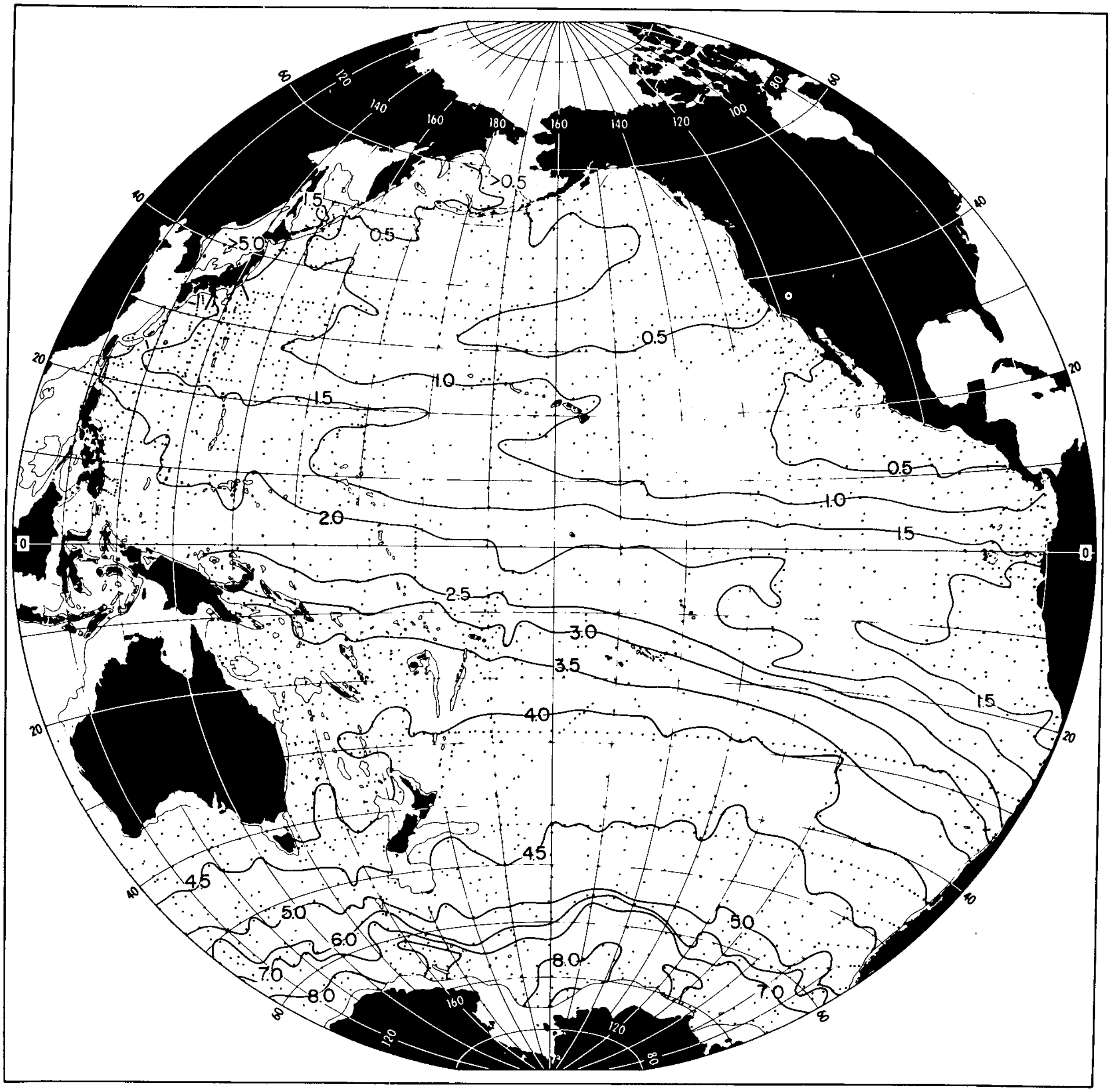

FIG. 3. Concentration of dissolved oxygen (ml l^{-1}) along the isopycnal defined by Fig. 2.

signal in substantial parts of the area. Two expeditions were carried out to resolve the field. One was *Eurydice* Leg 10, in the area of the Marshall-Gilbert-Ellice island chain, and the other was *Indopac* Legs II and III along the Mariana-Bonin Ridge and within the Philippine Sea. These, with the various expeditions of the Cooperative Study of the Kuroshio, helped to define the density field somewhat and gave some guidance in the handling of the earlier data.

Near the equator and in the deeper parts of the Philippine Sea the horizontal variation of salinity determined from more modern measurements is very small in terms of the measurement errors of the earlier investigations, before the salinometer came into use (Moriyasu, 1972). Likewise, the field of geopotential anomaly at depths below 2 km determined from the more recent data does not show a wide range of values, and erratic or biased salinity measurements can cause substantial distortions in the calculated density and geopotential anomaly.

It seemed worthwhile to try to make use of the many hydrographic stations which appeared to have good measurements of temperature but values of salinity that, for any reason, appeared to be wrong. To do this, the modern data were examined, and

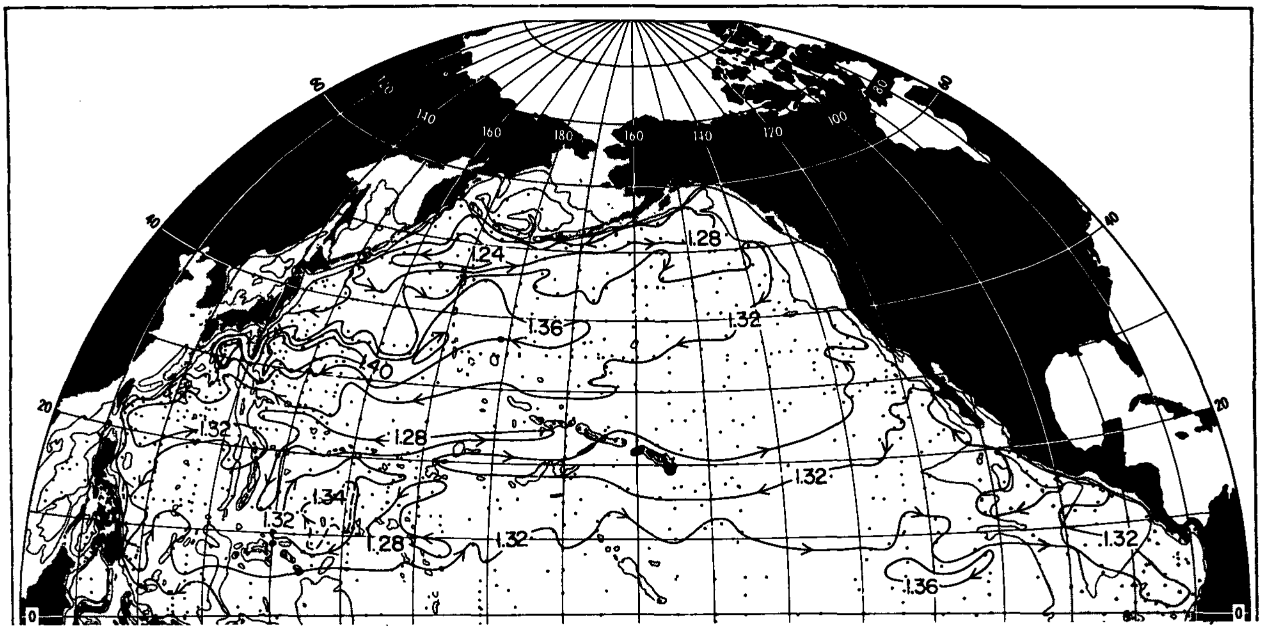

FIG. 4. Geopotential anomaly (steric height) at the 1000 db surface relative to the 3500 db surface, in units of dynamic meters ($10\ m^2\ s^{-2}$ or $10\ J\ kg^{-1}$).

from these the characteristic curves of salinity as a function of temperature were prepared for various areas within the Philippine Sea. From these curves the temperatures measured at the earlier stations could be used to determine the corresponding salinities. This procedure was used for depths below 1500 m. At each station the average offset of the original deeper salinities was determined and used to adjust the individual measurements in the upper 1500 m.

b. *The enclosed basins*

The Guatemala, Peru and Panama basins are not connected with the open Pacific Ocean at 3500 m. To calculate the steric heights within those basins, we have assumed zero shear below effective sill depths of 2500 m for the Guatemala and Peru basins and 2000 m for the Panama Basin.

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REFERENCES

Barkley, R. A., 1968: *Oceanographic Atlas of the Pacific Ocean*. University of Hawaii Press, 20 pp., 156 Figs.

Moriyasu, S., 1972: Deep waters in the western North Pacific. *Kuroshio—Its Physical Aspects*, H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 517 pp.

NORPAC Committee, 1960: *Oceanic Observations of the Pacific: 1955, The NORPAC Atlas*. University of California Press and University of Tokyo Press, 123 plates.

Pytkowicz, R. M., and D. R. Kester, 1966: Oxygen and phosphate as indicators for the deep intermediate waters in the northeast Pacific Ocean. *Deep-Sea Res.*, **13**, 373–379.

Reed, R. K., 1970: Geopotential topography of deep levels in the Pacific Ocean. *J. Oceanogr. Soc. Japan*, **26**, 331–339.

Reid, J. L., Jr., 1961: On the geostrophic flow at the surface of the Pacific Ocean with respect to the 1000-decibar surface. *Tellus*, **13**, 489–502.

——, 1965: Intermediate waters of the Pacific Ocean. *Johns Hopkins Oceanogr. Stud.*, No. 2, 85 pp.

——, and R. J. Lynn, 1971: On the influence of the Norwegian-Greenland and Weddell seas upon the bottom waters of the Indian and Pacific oceans. *Deep-Sea Res.*, **18**, 1063–1088.

Reid, J. L., and R. S. Arthur, 1975: Interpretation of maps of geopotential anomaly for the deep Pacific Ocean. *J. Mar. Res.*, **33**(Suppl.), 37–52.

Suginohara, N., 1973: An eastward flow at lower middle latitudes derived from a three-layer model of a wind-driven ocean circulation. *J. Oceanogr. Soc. Japan*, **29**, 227–235.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming, 1942: *The Oceans: Their Physics, Chemistry, and General Biology*. Prentice-Hall, 1087 pp.

Tsuchiya, M., 1968: Upper waters of the intertropical Pacific Ocean. *Johns Hopkins Oceanogr. Stud.*, No. 4, 50 pp.

Uda, M., and K. Hasunuma, 1969: The eastward subtropical countercurrent in the western North Pacific Ocean. *J. Oceanogr. Soc. Japan*, **25**, 201–210.

Wyrtki, K., 1974: The dynamic topography of the Pacific Ocean and its fluctuations. Hawaii Inst. Geophys. Rep. No. HIG-74-5, 19 pp.

Yoshida, K., and T. Kidokoro, 1967a: A subtropical countercurrent in the North Pacific. *J. Oceanogr. Soc. Japan*, **23**, 88–91.

——, and ——, 1967b: A subtropical countercurrent (II)—A prediction of eastward flows at lower subtropical latitudes. *J. Oceanogr. Soc. Japan*, **23**, 231–246.