Circulation and Water Masses in the Eastern Equatorial Pacific Ocean[1]

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ABSTRACT *Geostrophic transports are calculated for the different branches of the currents in the eastern equatorial Pacific Ocean, and a coherent picture of the circulation in this part of the Ocean is derived. The wind-driven westward flow of about 75 $10^{12}cm^3/sec$ in the North and South Equatorial Currents is opposed by an eastward flow of about 50 $10^{12}cm^3/sec$ in the Countercurrent and the Undercurrent, and the difference is made up by meridional flow in the California and Peru Currents. The water carried east in the Undercurrent is chiefly recirculated into the South Equatorial Current.*

The formation of the main surface water masses is explained in relation to the climatic conditions in their regions of formation. Subsurface water masses are analyzed by means of the core layer method. The main subsurface water masses in the area are: 1) the subsurface salinity maximum originating from the Subtropical Surface Water; 2) the oxygen minimum layer; 3) the upper salinity minimum, originating from temperate climatic regions; 4) the lower salinity maximum; and 5) the salinity minimum of the Intermediate Water. The origin and the spreading of these water masses within the circulation system of the eastern Pacific Ocean are discussed.

The Subtropical Surface Water of the South Pacific Ocean extends as a subsurface salinity maximum north, spreads across the equator and occupies the thermocline below the Tropical Surface Water. Its residence time in this area is calculated as ten years. The oxygen minimum layer represents subsurface water of a long residence time in the eastern and equatorial portions of the ocean where the circulation of the subtropical

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anticyclones does not penetrate. The upper salinity minimum is formed by low salinity water, which spreads equatorwards in the eastern boundary currents and slides below the Subtropical Surface Water. The salinity minimum of the Intermediate Water follows an anticyclonic path south of 20°S.; north of this position its spreading seems to take place by lateral mixing.

INTRODUCTION

In the eastern equatorial Pacific Ocean, between the California Peninsula in the north and Peru in the south, the equatorwards-flowing eastern boundary currents turn west and form the more zonal circulation pattern characteristic of the central equatorial Pacific Ocean. These eastern boundary currents, the California Current and the Peru Current are, however, comparatively weak, as shown by Wooster and Reid (1963), and their transports are not sufficient to supply the water masses flowing west in the North and South Equatorial Currents, even if one considers the eastward flow in the Equatorial Countercurrent. The discovery of the eastward-flowing Equatorial Undercurrent in 1952 has completely changed the existing concept of the equatorial circulation and provides an explanation for this discrepancy. The first part of this investigation is an attempt to derive quantitative values of the transports in the different current systems, and to combine them into a coherent picture of the circulation. In the second part, an analysis of the distribution and formation of the characteristic water masses of this region will be undertaken and it will be shown how their distribution is affected by the circulation.

TRANSPORTS IN THE INDIVIDUAL CURRENT SYSTEMS

The circulation in the eastern equatorial Pacific Ocean is dominated by the eastern and equatorial parts of the subtropical anticyclonic gyrals in the North and South Pacific Ocean, as shown in monthly charts of surface currents drawn by Wyrtki (1965a). In the North Pacific Ocean these consist of the California Current and the North Equatorial Current, and in the South Pacific Ocean of the Peru Current and the South Equatorial Current. Between these two gyrals, the Equatorial Countercurrent is developed as long as the intertropical convergence is sufficiently far north of the equator. Because of the configuration of the ocean these two gyrals do not reach into the area of the eastern tropical Pacific Ocean between Cape Corrientes in Mexico and Ecuador, and this area consequently has a variable and apparently complicated circulation. The general westward flow in the North and South Equatorial Currents is opposed by two currents flowing east, the Equatorial Countercurrent between about 4°N and 10°N, and the Equatorial Undercurrent, flowing at the equator below and opposite to the South Equatorial Current. These two currents disintegrate when approaching the coast of America, and their water masses are recirculated into the flow to the west.

Equatorial Undercurrent

The Pacific Equatorial Undercurrent first reported by Cromwell, Montgomery, and Stroup (1954) has been comprehensively described by

Knauss (1960, 1963). This current flowing east in depths between 50 m and 300 m transports about 34 $10^{12}cm^3/sec$ at 150°W according to Montgomery and Stroup (1962), and 40 $10^{12}cm^3/sec$ at 140°W according to Knauss (1960). Although minor short-term variations in the zonal velocity have been observed by Knauss (1960), the hydrodynamics of the system make it unlikely that the current is subject to appreciable seasonal variations. Where the current is fully developed it draws water from both sides of the equator towards its core, as has been shown by Charney (1960) on the basis of theoretical considerations. This water comes out of the discontinuity layer on both sides of the current, is subject to strong mixing processes and is discharged upwards and downwards, or increases the eastward transport of the current. When approaching the Galápagos Islands the current is decelerated due to the combined action of friction and a retarding pressure gradient, as shown by Wyrtki and Bennett (1963). There the Undercurrent discharges all of its water to the north or south, and contributes also to upwelling. East of the Galápagos Islands the Undercurrent is no longer found (Knauss, 1960).

At 150°W the Undercurrent chiefly transports water with temperatures between 12C and 20C and with salinities near 35‰, as shown by Montgomery and Stroup (1962). This water can be traced in subsurface layers far into the eastern Pacific Ocean, and its distribution, which is indicative for the discharge of the Undercurrent water, will be discussed in a later section.

Equatorial Countercurrent

The Equatorial Countercurrent flows from west to east across the entire Pacific Ocean a few degrees north of the equator. It is relatively narrow, only 300 to 700 km wide, and separates the broader westward-flowing North and South Equatorial Currents. As such it acts as the boundary between the great anti-cyclonic gyres of the North and South Pacific Ocean. The speed, width and transports of this current vary considerably with the season, as well as over short periods, as shown by Austin, Stroup and Rinkel (1956). The main flow of this current is concentrated in a shallow surface layer. Velocities decrease rapidly within the thermocline.

Transports of the Countercurrent have been computed for 79 hydrographic sections by Wyrtki and Kendall (1967). Using a two-layer model to estimate transports from bathythermograph sections, transports could be estimated for 50 additional locations. According to these calculations the average transports of the Countercurrent decrease almost linearly from about 40 $10^{12}cm^3/sec$ in the western part of the Pacific Ocean to less than 10 $10^{12}cm^3/sec$ off the coast of Central America. East of 140°W, transports are usually less than 20 $10^{12}cm^3/sec$ and tend to decrease to the east. During the period from July to December the Countercurrent is well developed and extends right to the coast of Central America, while from March to May it is usually absent or markedly weaker. This agrees well with the monthly charts of surface currents by Wyrtki (1965a).

The transfer of water across the southern and northern boundaries of the Countercurrent seems to be variable and to be dependent on short-term fluctuations of the intensity of the current in time and space. In general, however, there seems to be an intake of water across its southern boundary and a loss of water across its northern boundary, as indicated in charts of surface currents (Wyrtki, 1965a). This observation is supported by the fact that in the entire range of the Countercurrent winds blow mostly from east to west, although they are weak, and thereby cause an Ekman transport to the north. Off the coast of Central America the current splits off, and one branch, usually the stronger, turns north around the Costa Rica Dome forming the Costa Rica Coastal Current which feeds the North Equatorial Current. The flow around the Costa Rica Dome is about 20 $10^{12}cm^3/sec$, and the depth of the current increases to about 600 m in the Costa Rica Coastal Current. Only about 40% of this flow takes place in the upper 200 m, while the transport of the Countercurrent is almost completely concentrated in the upper 200 m (Wyrtki, 1964). No reliable estimate can yet be made of the percentage of the water of the Countercurrent turning north or south.

At 150°W the Countercurrent transports chiefly warm water ($>$ 25C) with salinities of less than 35‰ according to Montgomery and Stroup (1962). All this water is surface water of relatively low density; the contribution of water of lower temperatures to the total transports of the current is rather small. As the Countercurrent progresses to the east its salinities decrease due to the great excess of rainfall over evaporation in the vicinity of the intertropical convergence.

California Current

The California Current is a very weak and slow southward flow, spread over more than 1,000 km distance from the coast. Based on observations during the Norpac Expedition, Wooster and Reid (1963) calculate transports of about 12 $10^{12}cm^3/sec$ to the south. Calculations of the transports of the current off lower California between Punta Eugenia (28°N) and a position 500 km offshore from data of the California Cooperative Fisheries Investigations, show that this transport varies between 1 and 8 10^{12} cm^3/sec and therefore includes only a part of the transports of the whole California Current. There is always a flow to the south in the surface layer down to about 100 m to 300 m depth. This flow is strongest the first half of the year (2-8 $10^{12}cm^3/sec$) and much weaker during the second half (1-4 $10^{12}cm^3/sec$). Below this southward flow in the surface layer a northward flow is developed, which carries between 1 and 4 million m^3/sec, and is more often found during the second half of the year. During this period the total transport between the surface and 1,000 m depth, and within 500 km from the coast, can occasionally become northward.

The water carried south across 30°N in the surface layer of the California Current is cool (15C-20C) and of low salinity (about 33.5‰). Lowest temperatures are found in the upwelling area along the coast. Because

of the slow movements in this current, temperature and salinity increase substantially in the direction of the flow.

North Equatorial Current

The North Equatorial Current is formed by water from the California Current, by water from the Countercurrent, a part of which turns north and west around the Costa Rica Dome, and by water ascending in the eastern tropical Pacific Ocean. The California Current contributes about 12 $10^{12}cm^3/sec$, the Countercurrent about 10 $10^{12}cm^3/sec$, the contribution of both currents varying with the season. Computations of the heat and salt balance in the eastern tropical Pacific Ocean, discussed later, suggest that there is considerable upwelling in the entire region, contributing about 5 $10^{12}cm^3/sec$ to the surface circulation. A certain loss from the region occurs through the subsurface flow to the north in the California Current.

According to recent investigations of the Bureau of Commercial Fisheries, Honolulu, the transports of the North Equatorial Current at 148°W, between 10°N and 27°N, fluctuate between 20 and 26 $10^{12}cm^3/sec$ during twelve surveys within one year (Seckel, personal communication).

Peru Current

The eastern parts of the South Pacific anticyclonic gyral are formed by the Peru Current system, which consists of several more or less independent branches, interacting in a rather complicated way. The divergence associated with equatorward flow requires the development of poleward countercurrents to provide the necessary continuity of mass. Upwelling along the coast of Peru is probably the strongest anywhere in the ocean.

The flow to the north across 31°S between the coast and 100°W has been calculated from observations made by the *Ob*, Cruise 3, as 14 $10^{12}cm^3/sec$ relative to 1,000 decibars, of which 10 $10^{12}cm^3/sec$ are concentrated in the upper 300 m. Changing slightly with the season, but generally at 25°S, this northward flow splits off into the Peru Coastal Current and into the Peru Oceanic Current. Between these two currents the Peru Countercurrent, which is, however, a subsurface current, flows south.

A detailed analysis of the flow in different layers off the coast of Peru has been made by Wyrtki (1963) using data of the Step-I Expedition in October-November, 1960. The Peru Coastal Current transports about 6 $10^{12}cm^3/sec$ to the north across 24°S and reaches to about 15°S, where most of its water has turned away from the coast. North of 15°S the wind-induced surface drift is still to the northwest, but it is shallow, and the southerly flow of the Peru Undercurrent is found immediately beneath the shallow surface layer. South of 15°S the upwelling is supplied by water ascending from the lower layers of the Peru Coastal Current, which is of relatively low salinity.

The Peru Countercurrent flows almost due south along 80°W. It is strongest near 100 m depth, but reaches to about 500 m. At 5°S it transports about 10 $10^{12}cm^3/sec$, but its transports decrease rapidly to 6 10^{12} cm^3/sec at 15°S and to 2 $10^{12}cm^3/sec$ at 22°S. This current carries equatorial subsurface water of high salinity and low oxygen content and supplies most of the water engaged in the upwelling processes along the coast north of 15°S. The system of the Peru Coastal Current, the wind drift to the west and the subsurface Peru Countercurrent are the links in the circulation, which maintain the upwelling along the coast.

The Peru Oceanic Current seems to have little interaction with the complicated processes along the coast. At 24°S and to the west of 82°W it flows north and carries about 8 $10^{12}cm^3/sec$. North of this position it starts to turn northwest and west, is intensified by water from the Peru Countercurrent, and leaves the area transporting about 14 $10^{12}cm^3/sec$. The Peru Oceanic Current extends with appreciable velocities and transports to about 700 m depth, in contrast to the much shallower circulation system closer to the coast.

South Equatorial Current

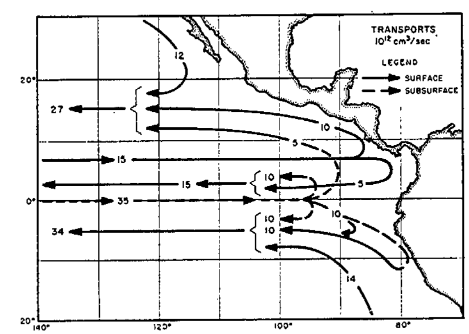
The South Equatorial Current is developed as a result of the southeast trades in the South Pacific Ocean. Since the trade winds extend across the equator into the northern hemisphere, the current also extends to the north of the equator. Its northern boundary is the Equatorial Countercurrent at approximately 4°N. In the south it extends as a well-defined current to about 10°S but continues as a general drift with much smaller and more irregular velocities to the west and southwest. Highest velocities of more than 50 cm/sec are found near the equator where the flow is slightly divergent. At the equator the South Equatorial Current is also shallowest, only 20 m to 50 m thick; the eastward flowing Equatorial Undercurrent is situated underneath. Farther to the south the South Equatorial Current becomes considerably thicker and extends to about 200 m depth.

The transports of the South Equatorial Current between the Countercurrent in the north and 20°S is about 45 to 60 $10^{12}cm^3/sec$. Most sections for which transports have been calculated do not, however, cover the entire current. At 150°W, Montgomery and Stroup (1962) calculate a transport of 63 $10^{12}cm^3/sec$ between 6°N and 7°S, of which half flows north of the equator and half south of it. Calculations for a section at 121°W (Expedition Eastropic, see Table 1) give a flow of 20 $10^{12}cm^3/sec$ between the equator and 7°N and 23 $10^{12}cm/^3sec$ between the equator and 8°S. Another section at 130°W (*Hugh M. Smith,* Cruise 38) gives a transport of 25 $10^{12}cm^3/sec$ between the equator and 18°S, and a section at 135°W (Expedition Equapac, Cruise 35) gives a transport of 39 $10^{12}cm^3/sec$ between the equator and 19°S in the upper 400 m.

It is quite obvious that these enormous transports cannot be supplied by the Peru Current and the small amount of water of the Countercurrent turning south off the coast of Central America. Also the pattern of surface currents in the area south of the Galápagos Islands (Wyrtki, 1965a) shows the considerable increase of the speed and width of the westward flow from the Peru Current to the South Equatorial Current.

If the Peru Current contributes 14 $10^{12}cm^3/sec$ and the Equatorial Countercurrent about 5 $10^{12}cm^3/sec$ to the South Equatorial Current, approximately 30 $10^{12}cm^3/sec$ are still needed to supply this strong current. Such an amount of water can only come from the Equatorial Undercurrent which transports about 35 $10^{12}cm^3/sec$ to the east and discharges this amount of water near the Galápagos Islands. Therefore, it must be assumed that water coming directly or indirectly from the Undercurrent feeds the South Equatorial Current as shown schematically in Fig. 1. The processes by which this subsurface water is converted into the water of the South Equatorial Current still have to be studied. Parts of the water of the Undercurrents seem to come into the Peru Countercurrent and feed the upwelling off northern Peru as suggested by Wyrtki (1963). Other parts definitely participate in the equatorial upwelling to the west of the Galápagos Islands, but the amount of water upwelling along the equator certainly does not exceed a few $10^{12}cm^3/sec$; otherwise the thermal structure would break down. Large parts of the subsurface water of the Undercurrent will continue to remain subsurface water and will be integrated as such into the South Equatorial Current. It seems likely, however, that the upwelling area off the coast of Peru extends northwest towards the Galápagos Islands and is directly connected with the equatorial upwelling west of these islands, at least during the period May through November when surface temperatures in this area are low.

FIGURE 1. Transports in the different branches of the circulation in the eastern equatorial Pacific Ocean during the period from June to December in $10^{12}cm^3/sec$.



THE CIRCULATION SYSTEM OF THE EASTERN EQUATORIAL PACIFIC OCEAN

The results of the previous section can be combined to construct a circulation system for the eastern equatorial Pacific Ocean, which shows the interaction of the various currents and their mass transports. The transports quoted in Fig. 1 are certainly subject to seasonal variations, but are thought to represent approximately the conditions during the period June through December. At 140°W, where the zonal circulation characteristic for the central equatorial Pacific Ocean is fully established, the Undercurrent carries about 35 $10^{12} cm^3/sec$, and the Countercurrent about 15 $10^{12} cm^3/sec$ to the east. This eastward flow is opposed by about 50 $10^{12} cm^3/sec$ flowing west in the South Equatorial Current and 27 $10^{12} cm^3/sec$ in the North Equatorial Current, giving a total transport of about 27 $10^{12} cm^3/sec$ to the west in the equatorial region. This flow is supplied in approximately equal parts by the California and Peru Currents. When the Equatorial Undercurrent approaches the Galápagos Islands and dissolves, its water spreads north and south. The larger part of the water turning south is integrated into the South Equatorial Current and remains subsurface water, while the remainder penerates below the upwelling area off northern Peru and supplies the upwelling. These 20 $10^{12} cm^3/sec$ of water supplied by the Undercurrent result directly or indirectly in the enormous intensification of the South Equatorial Current during its passage from the coast of Peru to about 100°W. More than half of the water of those parts of the South Equatorial Current that are situated south of the equator are supplied from the Undercurrent, and less than half from the Peru Current.

The Equatorial Countercurrent splits off when approaching the coast of Costa Rica, and the larger part turns north into the North Equatorial Current, a smaller part turns south. The surface water turning south from the Countercurrent, and the subsurface water turning north from the Undercurrent, jointly form the water of those parts of the South Equatorial Current situated north of the equator. Approximately 5 $10^{12} cm^3/sec$ of the water of the Undercurrent, which turns north, penetrates into the eastern tropical Pacific as a salinity maximum. There it is entrained into upwelling processes and is integrated into the North Equatorial Current. This current is supplied from the California Current, from the Countercurrent, and partly from the upwelling of water in the eastern tropical Pacific.

Summarizing, it can be said the wind-driven westward flow of about 75 $10^{12} cm^3/sec$ is opposed by an eastward flow of about 50 $10^{12} cm^3/sec$, which is primarily caused by the zonal pressure gradient, and the difference in transports is compensated by meridional flow towards the equator in the eastern boundary currents. It is quite obvious that the entire circulation in this region, and especially the intensification of the flow from the Peru Current to the South Equatorial Current, could not be satisfactorily explained before the discovery of the Equatorial Undercurrent.

TABLE 1. List of Expeditions fom which Data used in this Study were obtained

Name	*Ship(s)*	*Year(s)*	*Source*
Dana	Dana	1928	Carlsberg Foundation, 1937
Carnegie, Cruise VII	Carnegie	1928-29	Fleming, J. A., *et al.*, 1945
Albatross	Albatross	1947	Bruneau, L., *et al.*, 1953
California Cooperative Oceanic Fisheries Investigations	U.S. Fish and Wildlife Service and Scripps Institution of Oceanography	1949-64	*Oceanic Observations of the Pacific*
Shellback	Horizon	1952	*Oceanic Observations of the Pacific*
Hugh M. Smith, Cruise 15	Hugh M. Smith	1952	Austin, T. S., 1954
Norpac	Stranger and Spencer F. Baird	1955	*Oceanic Observations of the Pacific*
Eastropic	Spencer F. Baird, Horizon, Hugh M. Smith	1955	*Oceanic Observations of the Pacific* King, J. E., *et al.* 1957
Equapac, Cruise 35	Hugh M. Smith	1956	Austin, T. S., 1957
Hugh M. Smith, Cruise 38	Hugh M. Smith	1957	Wilson, R. C. and M. O. Rinkel, 1957
Downwind	Horizon	1957	*Oceanic Observations of the Pacific*
Dolphin	Horizon	1958	*Oceanic Observations of the Pacific*
Doldrums	Stranger	1958	*Oceanic Observations of the Pacific*
Ob, Cruise 3	Ob	1958	National Oceanographic Data Center
Dorado	Horizon	1959	*Oceanic Observations of the Pacific*
Chiper	Burton Island	1960	National Oceanographic Data Center
Step-I	Horizon	1960	Scripps Institution of Oceanography, Ref. 61-9, 1961
Cruise 00675	Rehoboth	1960	National Oceanographic Data Center
Shoyo Maru	Shoyo Maru	1963-64	Nankai Regional Fish. Agency, Japan

NOTE: Most of these observations have been or will be published in *Oceanic Observations of the Pacific*. Many are published in data reports of the Scripps Institution of Oceanography.

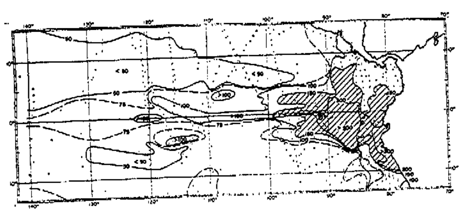
Fig. 1 demonstrates quite clearly why this was the case. Some links in the circulation pattern shown in Fig. 1 have not yet been verified by observations, and in the following analysis of water masses it will also be attempted to demonstrate their validity.

HE DISCHARGE OF HE WATER OF THE EQUATORIAL UNDERCURRENT

At 150°W the primary mode of the flux of the Equatorial Undercurrent has temperatures between 12C and 14C, salinities between 34.8‰ and 35.0‰, and comprises about 1/6 of the total transports of the current according to Montgomery and Stroup (1962). They discuss the spreading of this 13C water in the eastern equatorial Pacific Ocean and state that it accumulates east of 120°W within about 5° of the equator, reaching a thickness of more than 200 m. This 13C water occupies, however, the lower layers of the Undercurrent, which move more slowly than the water near the core. Water near the core has salinities in excess of 35.0‰ and temperatures above 20C, but is subject to much stronger mixing. The layer between the core of the current and the primary mode of the flux given by the 13C water includes about half of the total transport of the Undercurrent at 150°W according to the diagram shown by Montgomery and Stroup (1962, Fig. 30). To demonstrate the spreading of this water in the eastern equatorial Pacific Ocean, the thickness of the layer with temperatures between 13C and 19C is shown in Fig. 2, based on data listed in Table 1.

Along the equator the thickness of this layer increases from west to east, being less than 100 m thick west of 120°W and more than 200 m thick near the Galápagos Islands. The layer is thickest at the equator and becomes thinner to the north and south. In the range of the Equatorial Countercurrent it is less than 50 m thick. East of 100°W the thickness of this layer increases considerably, and extends farther to the north and south. The main accumulation of this water with a thickness exceeding 200 m is to the east, northeast and southeast of the Galápagos Islands. The layer of the Undercurrent water extends with more than 150 m thickness

FIGURE 2. Thickness in meters of the layer with temperatures between 13C and 19C in the eastern equatorial Pacific Ocean, representing the spreading of water from the Equatorial Undercurrent.



to 8°N and to 6°S. Sea surface temperatures at the time the stations off the coast of Peru were taken were less than 19C and the limits of the corresponding area are marked by a heavy broken line in Fig. 2. Within this area the depth of the 13° isotherm is given. It is obvious that there is an accumulation of water with temperatures between 13C and 19C off the coast of Peru to about 11°S. The surface water in this area is of subtropical origin and has salinities of more than 35.0‰, but covers only a thin surface layer. In subsurface layers salinities of this water are slightly less than 35.0‰, indicating that it originates from the Equatorial Undercurrent. The oxygen content of this water is very low, which seems to be due to a comparatively long residence time of the water accumulated in this area after disintegration of the Undercurrent. South of 15°S water of similar temperatures has much lower salinities and higher oxygen content. When discussing upwelling off Peru, it has already been suggested by Wyrtki (1963) that north of 15°S upwelling is supplied by subsurface water of relatively high salinity originating from the Undercurrent.

Between 90°W and 100°W and at 3°N and 3°S two tongues, in which the thickness of the Undercurrent water exceeds 150 m, extend west. Since the Undercurrent discharges its water west of the Galápagos Islands, it can be assumed that these two rather symmetrical tongues represent water which originates from the Undercurrent and flows back west in the lower layers of the South Equatorial Current, as indicated in Fig. 1.

SURFACE WATER MASSES

The region under consideration extends over a wide range of climatic types, and consequently several surface water masses are found with characteristics corresponding to the different climatic regions. There are three basically different types of water involved: 1) tropical surface water of high temperature and low salinity, 2) subtropical surface water of high salinity, which is generally warm but variable in temperature, and 3) surface water of the California and Peru Currents, which is cool and of low salinity and originates in higher latitudes. Naturally, all boundaries between these water masses are subject to seasonal fluctuations, and in most cases they are boundary zones rather than fronts. Fig. 3 shows the distribution of surface salinity and the extreme positions of the 25C isotherm together with the location of the main surface water masses. Their temperature-salinity relations are shown in Fig. 4.

Tropical Surface Water

Tropical Surface Water is found in regions where sea surface temperature is high and its seasonal variation is small, and where salinity is low due to an excess of rainfall over evaporation. In the eastern tropical Pacific Ocean this water can be identified by the area where surface temperature is always higher than 25C (Fig. 3). Within this area, salinity is usually less than 34‰ due to an excess of rainfall over evaporation, which is greater than 50 cm/year according to Dietrich (1957). The area with salinities of less than 34‰ is subject to a seasonal north-south shift and varies also in size, as can be seen from monthly charts of surface salinity prepared by Bennett (1965). The southern boundary of tropical surface water runs from Ecuador to north of the Galápagos Islands and continues west at about 4°N where it coincides approximately with the southern boundary of the Countercurrent. The water carried east with the Countercurrent as well as that carried west in the southern parts of the North Equatorial Current is tropical surface water. The northern boundary of the tropical surface water can be identified approximately with the 25C isotherm which lies near 15°N and fluctuates during the year by about 5° of latitude. Lowest salinities within this water are found in the Gulf of Panama and off the coast of Columbia, where salinity varies from 34‰ to less than 30‰ at the end of the rainy season (Bennett, 1965). The vertical extent of the water is limited to the shallow mixed layer, usually only 20-50 m thick, except along the southern boundary of the Countercurrent, where it can be as much as 100 m deep. Temperature decreases and salinity increases within the sharp discontinuity layer below this mixed layer.

Subtropical Surface Water

The Subtropical Surface Water of the South Pacific Ocean is formed in the regions where evaporation greatly exceeds precipitation. It is characterized by high salinity, but temperature in this water mass can vary over a wide range from about 28C to 15C. In the South Pacific Ocean the highest surface salinities are found between 12°S and 25°S, and between 100°W and 150°W where salinity is higher than 36‰. The center of the Subtropical Surface Water coincides with the center of the South Pacific anticyclone. The long residence time of the surface water near its center, where evaporation exceeds precipitation by about 100 cm/year (Dietrich, 1957), allows the salinity to be raised to these high values. In the center of the subtropical anticyclone near 20°S, salinities above 36‰ are found as deep as 200 m, as a result of deep reaching convection in winter when the mixed layer is almost 200 m deep (Wyrtki, 1965b). In summer a shallow mixed layer associated with a summer thermocline is found near the surface. The eastern and northern boundary of the Subtropical Surface Water cannot be determined without ambiguity. Off Peru, Subtropical Surface Water is often separated from the coast by only a narrow belt of upwelling water of lower salinity and temperature. The northern boundary of the Subtropical Surface Water can be identified approximately with the 35‰ isohaline, which, starting from the coast of Ecuador at about 5°S, runs south of the Galápagos Islands to the west and continues along the equator.

The southern boundary of the Subtropical Surface Water is the Subtropical Convergence, where it meets the surface water of the temperate climatic zone. The Subtropical Convergence is situated between 30°S and 40°S and fluctuates slightly with the season (Fig. 3). Off the coast of Chile, the Subtropical Convergence bends north near 90°W and fades out without reaching the coast. The salinity near the Convergence is about 34.5‰ and the temperature near 16C. Off the coast of Chile, salinity increases

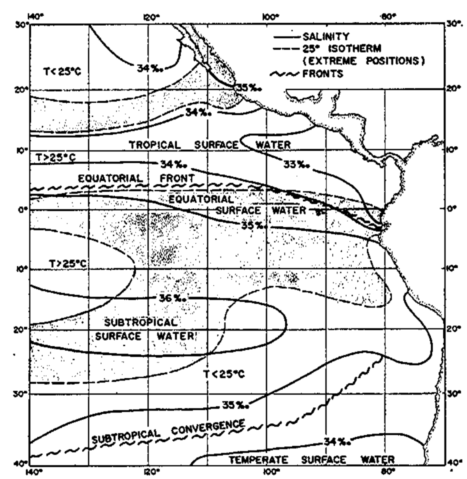
from south to north as a result of high evaporation, and the Temperate Surface Water is gradually transformed into Subtropical Surface Water.

Equatorial Surface Water

The northern boundary of the Subtropical Surface Water of the South Pacific Ocean does not coincide with the southern boundary of the Tropical Surface Water, except close to the coast of Ecuador. Between these two water masses there is another water mass, which is intermediate in properties, and will be called Equatorial Surface Water. This water mass is not a plain mixing product of the other two, but its properties are determined by seasonal advection of cooler water from the Peru Current and by equatorial upwelling. This water mass is typical for those parts of the South Equatorial Current situated at and north of the equator.

At the coast of Ecuador, Subtropical and Tropical Surface Water meet in a very well developed front which stretches northwest towards the Galápagos Islands. Due to a very strong contrast in salinity and also a strong contrast in temperature from May to November, this front is one of the most pronounced fronts in lower latitudes. Bjerknes (1961) and Fedorov (1963) discuss the circulation related to meridional movements of this front which is probably directly connected with the occurrence of El Niño. However, intense mixing along the front and the effects of equa-

FIGURE 3. Distribution of the main surface water masses in the eastern Pacific Ocean (——— surface salinity; – – – – – extreme positions of the 25C isotherm; ~ ~ ~ ~ ~ major oceanic fronts).



torial upwelling to the west of the Galápagos Islands soon destroy the front and form a body of mixed water, which flows west in the northern parts of the South Equatorial Current, situated at or north of the equator. In this water, salinities decrease from 35‰ south of the equator to less than 34.5‰ at the southern boundary of the Countercurrent. Rainfall and evaporation are almost balanced in this zone and the flow is very fast so that salinity changes little with longitude. Temperature, on the other hand, varies considerably within this water. From May to December a temperature minimum is situated along the equator and slightly south of it with temperatures as low as 20C (Wyrtki, 1965b). It is partly caused by advection of cooler water from the Peru Current and partly by equatorial upwelling. During this period a strong thermal front, situated between 2°N and 4°N, separates the Equatorial Surface Water from the Tropical Surface Water. This front is usually developed as a convergence and has been described in some detail by Cromwell and Reid (1956), and Knauss (1957). From January to April the temperature is very uniform in the entire equatorial region, and the Equatorial Surface Water is marked only by the transition in salinity. This water mass seems to be typical only for the region between the Galápagos Islands and about 140°W.

California Current Water

The water of the California Current is of moderate temperature and low salinity due to its origin from the temperate climatic zone of the North Pacific Ocean. During its flow to the south, salinity as well as temperature increases downstream (Reid, Roden, and Wyllie, 1958).

Especially in summer when strong heating forms a shallow summer thermocline (Wyrtki, 1965b), salinity within this shallow layer increases more rapidly than in the lower portions of the current, forming a subsurface salinity minimum. Usually the difference between the salinity at the sea surface and that in the subsurface salinity minimum is small within the California Current but becomes larger farther to the west when surface salinities increase towards values characteristic for the Subtropical Surface Water of the North Pacific Ocean.

Between 30°N and 20°N most of the water in the California Current turns west and continues as part of the North Equatorial Current. In this area, salinity and temperature increase further until the water of the California Current is converted into Subtropical Surface Water, and therefore no real boundary exists between these two water masses, except that water with salinities above 34.5‰ in the North Pacific Ocean can be called Subtropical Water. In the south, the water of the California Current meets Tropical Surface Water, but also no sharp boundary is developed there except near Cape San Lucas at the southern tip of the California peninsula (Griffiths, 1965). Since surface salinity increases towards the south in the California Current and decreases again in the eastern tropical Pacific, the boundary between California Current Water and Tropical

Surface Water is indicated only by a slight salinity maximum at the sea surface which connects the water of high salinity of the Gulf of California with the Subtropical Surface Water farther to the west. Salinity in this area is between 34.0 and 34.5‰ (Bennett, 1965). Temperature increases rapidly towards the south, and the 25C isotherm may be taken as the boundary between these two water masses. Farther to the west, California Current Water and Tropical Surface Water jointly form the water of the North Equatorial Current.

Gulf of California Water

In the Gulf of California, water of high salinity is formed due to an excess of evaporation over rainfall, and it can be classified as Subtropical Water. Salinity within the Gulf is above 35‰, and occasionally in some places it can reach 36‰. Temperature in the Gulf varies considerably from 15C to 30C. This high salinity water leaves the Gulf in the south and spreads according to its temperature either at the surface or as a subsurface salinity maximum. The amount of this high salinity water produced in the Gulf is not very great so that it does not exert much influence outside of the Gulf. At Cape San Lucas it meets the California Current Water of lower salinity and temperature and near Cape Corrientes it meets the Tropical Surface Water of higher temperature and lower salinity, but its seaward extent varies considerably with the season (Roden and Groves, 1959; Griffiths, 1965).

South Pacific Temperate Water

In the South Pacific Ocean south of the Subtropical Convergence, water flows to the east. Within this water, temperature and salinity decrease polewards. The southern portions of this water, situated north of the Antarctic Polar Front, are usually called Subantarctic Water, but it does not seem appropriate to call the northern portions of this water, which have temperatures above 10C, subantarctic. Water with temperatures between 8C and 15C and salinities of less than 34.5‰, is typical for the temperate climatic zone of the South Pacific Ocean and covers a large area, especially in its eastern part off the coast of Chile. This South Pacific Temperate Water flows east under the west wind drift, and when it approaches the coast of Chile, it splits off near 50°S. One branch turns south while the other turns north and flows along the coast of South America as part of the Peru-Chile Current system. Off the coast of southern Chile between 40°S and 50°S the salinity of the surface water is reduced by strong rainfall and runoff from the land and becomes less than 33‰ along the coast. As this cool low salinity water proceeds north its temperature and salinity increase slowly. Between 40°S and 30°S the formation of a seasonal summer thermocline (Wyrtki, 1965b), the increase of salinity in this shallow surface layer by evaporation, and the advection of water of higher salinity from the west, become strong enough to cause the formation of a subsurface salinity minimum near 100 m depth. The formation of the subsurface salinity minimum takes place near 35°S, and west of 90°W it seems to coincide with the Subtropical Convergence. The salinity of the surface water flowing north reaches 35‰ at about 23°S, and from there on it can be called Subtropical Surface Water. In the Peru-Chile Current system there is no sharp boundary between the South Pacific Temperate Water and the Subtropical Water because the first is gradually transformed into the second. South of 15°S along the coast of southern Peru and northern Chile salinity is usually less than 35‰, and temperatures are low due to upwelling of water from the salinity minimum layer situated near 100 m depth and representing South Pacific Temperate Water. North of 15°S the water in the upwelling area is still of the same low temperatures but has higher salinities due to its origin from Equatorial Subsurface Water (Wyrtki, 1963).

SUBSURFACE WATER MASSES

Subsurface water masses formed in the region under consideration are the Subtropical Subsurface Water of high salinity and the layer of the oxygen minimum. All other water masses are formed outside this region and penetrate into it by horizontal flow and large-scale horizontal mixing. This is the case for the water of the upper salinity minima in the California and Peru Currents, for the Intermediate Water, characterized by a salinity minimum in 700 m to 900 m depth, and for the Pacific Deep Water.

The following analysis of water masses in the eastern Pacific Ocean is based on data listed in Table 1. Not all of these data include salinity as well as oxygen determinations so that the coverage is slightly different for the two properties. Salinity determinations on Expedition Shellback were not reliable, but the large number of oxygen data could be used. The core layer method developed by Wüst (1935) is used to analyze the different water masses and to chart their distribution. A temperature-salinity diagram in Fig. 4 summarizes the characteristics of these water masses.

Subtropical Subsurface Water

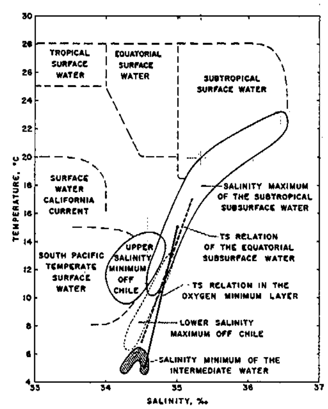
The eastern parts of the Equatorial Pacific Ocean between the California Current system in the north and the Peru Current system in the south are characterized by a low salinity of its shallow surface layer, by a high position of the thermocline, and by a salinity maximum situated within the thermocline in about 50 m to 150 m depth. Above the salinity maximum, salinities decrease rapidly to the low values in the surface layer, while below the maximum salinities decrease much more slowly to values near 34.55‰ in the salinity minimum of the Intermediate Water (see inset in Fig. 5). In this way the salinity maximum layer separates the water of the surface layer from those in deeper layers. This salinity maximum originates, however, in the South Pacific Ocean and penetrates across the equator to the northern hemisphere. The salinity maximum of the North Pacific Subtropical Subsurface Water has little influence on the area under consideration as will be shown later.

In the South Pacific Ocean a subsurface salinity maximum is found north of a line running from Ecuador to the center of the surface salinity maximum (Fig. 5). South of this line the salinity maximum is at the surface and surface salinity is shown in Fig. 5. Near the center of the South

Pacific anticyclonic gyral, surface salinities become as high as 36.5‰ and during winter the surface layer of high salinity and relatively low temperature is homogeneous down to depths of more than 150 m (Wyrtki, 1965b). The coldest water of this high salinity being formed has temperatures near 23C (Fig. 6) and a specific volume anomaly of 300 cl/ton. The formation of this water is probably not restricted to the area of maximum surface salinity, but takes place everywhere in the vicinity of the broken line shown in Fig. 5. This is indicated by the high oxygen content south of 5°S (Fig. 7). From there a subsurface salinity maximum extends equatorwards underneath the surface layer of lower salinity. This salinity maximum is situated near 100 m depth (Fig. 8) in the upper portions of the thermocline. The flow in these depths is to the west with the South Equatorial Current. The transverse circulation superimposed upon this current consists of a wind-driven component to the south at the sea surface and of a component towards the equator within the thermocline (Sverdrup et al., 1942, p. 711), causing the water of the salinity maximum layer to spread equatorwards. Towards the equator salinity and temperature decrease, but the specific volume anomaly remains constant close to 300 cl/ton. This is shown by all the points in the temperature-salinity diagram in Fig. 9, which have salinities in excess of 35.4‰ and represent stations south of the equator.

When approaching the equator, the salinity maximum layer comes under the influence of the Equatorial Undercurrent, which draws water out

FIGURE 4. Temperature-salinity diagram showing the range of properties of the main surface and subsurface water masses.



of the range of the thermocline towards the equator according to its meridional circulation explained by Charney (1960). Near the core of the Undercurrent the salinity maximum layer is subject to considerable mixing, indicated by the strong meridional gradient of salinity and temperature. This mixed water is carried east with the Undercurrent, whereby its temperature and salinity decrease. The temperature-salinity relations of the salinity maximum at stations at the equator are shown by circles in Fig. 9, and demonstrate clearly that the salinity maximum becomes situated at progressively lower temperature and higher density, because the upper portions of the salinity maximum layer are destroyed by mixing. Only the mixed water discharged by the Undercurrent reaches the northern hemisphere, and this water is indicated by the cluster of points with temperatures of less than 16C and salinities of less than 35.0‰, representing stations north of the equator.

The water discharged by the Undercurrent spreads slowly over the entire eastern tropical Pacific Ocean north of the equator and forms the salinity maximum in the lower portions of the thermocline. Salinity and

FIGURE 5. Salinity within the core layer of the salinity maximum of the Subtropical Subsurface Water in ‰. The southern and northern boundaries of the subsurface salinity maximum are shown by broken lines; outside these lines surface salinity is shown. The inset shows the vertical distribution of temperature and salinity at three locations.

FIGURE 6. Temperature in the core layer of the salinity maximum in °C.

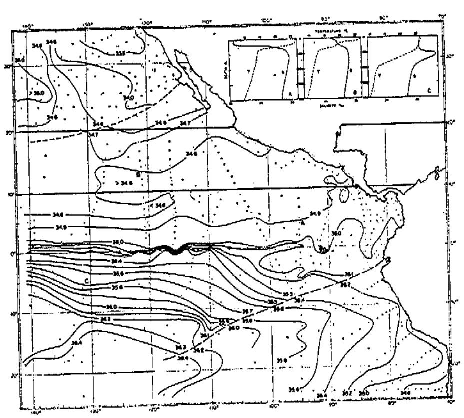


FIG. 5

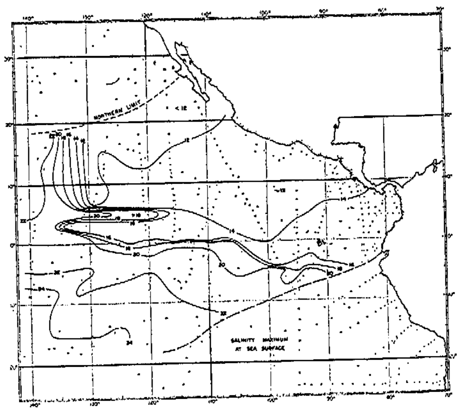


FIG. 6

temperatures of this water change only from 35.0 to 34.7‰ (Fig. 5) and from 14C to 12C (Fig. 6), while oxygen content decreases considerably to values of less than 0.25 ml/L (Fig. 7). This decrease of oxygen content indicates either a long residence time and a slow spreading of the water or a high organic production in the surface layer, or both. The spreading of the Subtropical Subsurface Water in the eastern tropical Pacific Ocean seems to follow a cyclonic path, as stated by Holmes (1966), and supported by some direct current measurements. Starting from the Galápagos Islands it spreads to the northeast, then northwest in the lower portions of the Costa Rica Coastal Current around the Costa Rica Dome (Wyrtki, 1964), and later west with the North Equatorial Current. The spreading along this path is slow, and lateral mixing smoothes the distribution of properties considerably.

Southwest of the Galápagos Islands at about 3°S a tongue of lower salinity (35.0-35.1‰), lower temperature and lower oxygen content (< 2.0 ml/L) extends west and coincides with the corresponding tongue of Undercurrent water discussed in the section dealing with the Equatorial Undercurrent. This is further evidence for the transfer of water from the Undercurrent to the South Equatorial Current southwest of the Galápagos Islands.

FIGURE 7. Oxygen content in the core layer of the salinity maximum in ml/L.

FIGURE 8. Depth of the core layer of the salinity maximum in meters (<50 m hatched; >150 m shaded).

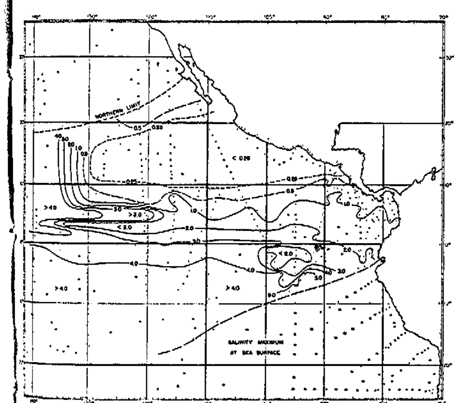


FIG. 7

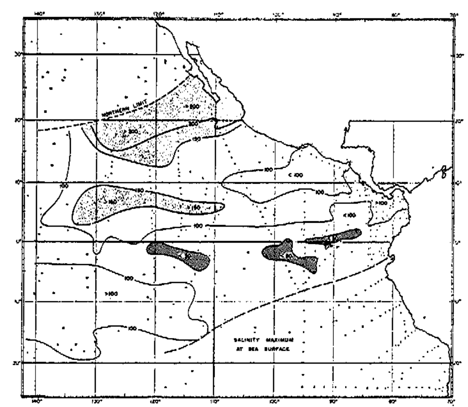


FIG. 8

water flowing north reaches 35‰ at about 23°S, and from there on it can be called Subtropical Surface Water. In the Peru-Chile Current system there is no sharp boundary between the South Pacific Temperate Water and the Subtropical Water because the first is gradually transformed into the second. South of 15°S along the coast of southern Peru and northern Chile salinity is usually less than 35‰, and temperatures are low due to upwelling of water from the salinity minimum layer situated near 100 m depth and representing South Pacific Temperate Water. North of 15°S the water in the upwelling area is still of the same low temperatures but has higher salinities due to its origin from Equatorial Subsurface Water (Wyrtki, 1963).

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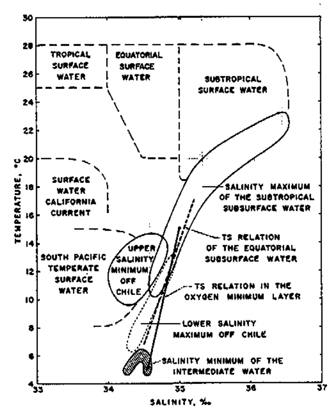


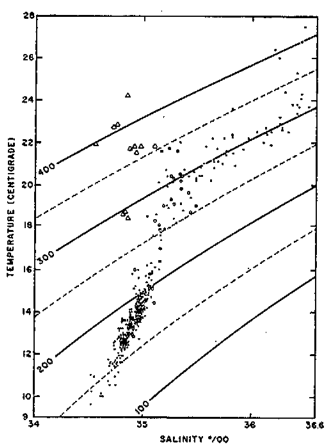
The lower portions of the salinity maximum of the Subtropical Subsurface Water spread north beyond 20°N where they meet water of the California Current, and their northern boundary is shown by a broken line (Figs. 5 and 8). There the salinity maximum is found in depths of more than 200 m.

West of 130°W and north of 4°N temperature and oxygen content in the salinity maximum are again much higher. This water, shown by triangles in Fig. 9 is the Subtropical Subsurface Water of the North Pacific Ocean, which originates near the center of the North Pacific anticyclonic gyre. It spreads equatorwards and is carried east in the lower layer of the Countercurrent and is marked by tongues of lower salinity (< 34.8‰, Fig. 5), higher temperature (> 18C, Fig. 6), and higher oxygen content (> 3.0 ml/L, Fig. 7). This tongue extends to about 115°W.

The depth of the salinity maximum (Fig. 8) resembles the general features of the topography of the thermocline as shown by Wyrtki (1965b, Fig. 54). A closer comparison shows, however, that south of the equator the salinity maximum is situated above the center of the permanent thermocline, whereas north of the equator it is situated below the center of the permanent thermocline.

The rate of formation of the Subtropical Subsurface Water is difficult

FIGURE 9. Temperature-salinity diagram of the core layer of the Subtropical Subsurface Water. Temperature-salinity values of stations along the equator are shown by circles, those of stations in the Equatorial Countercurrent west of 120°W by triangles. Curves give the specific volume anomaly.



to assess, especially because only a part of the area of its formation is covered by the maps presented. Montgomery (1959) estimates the residence time of the Subtropical Surface Water in the central South Pacific Ocean as twelve years. On the other hand, it is possible to estimate the losses which the salinity maximum layer suffers in the eastern tropical Pacific Ocean by exchange with the low salinity surface layer.

Over the area of the eastern tropical Pacific Ocean covered with Tropical Surface Water the excess of precipitation over evaporation (P-E) is about 75 cm/year according to Dietrich (1957) and average surface salinity is 33.5‰ in the corresponding area. To maintain this surface salinity, water of higher salinity must ascend into the surface layer from the salinity maximum layer. If H is the thickness of the layer that annually ascends into the surface layer, and $S = 34.8‰$ the salinity of the ascending water, the simple relation

$$(P - E)\, S = H \triangle S$$

must hold. With $\triangle S = 1.3‰$ it follows that $H = 20$ m. This means that the top 20 m of the salinity maximum layer ascend annually into the surface layer and are lost from the Subtropical Surface Water. This value of H corresponds to an average ascending velocity of 7 10^{-5}cm/sec in the eastern tropical Pacific Ocean, which is much larger than the average ascending motion of about 2 10^{-5}cm/sec calculated for the lower latitudes of all oceans (Wyrtki, 1961). This demonstrates that the ascending motion, at least in higher levels, is concentrated in certain parts of the oceans, and the extremely shallow thermocline in the eastern tropical Pacific Ocean is a confirmation of this fact. In the Costa Rica Dome ascending motion of 10 10^{-5}cm/sec have been calculated (Wyrtki, 1964), demonstrating that upwelling in the dome is stronger than in other parts of the eastern tropical Pacific Ocean.

If 20 m of the layer of maximum salinity are lost annually and the thickness of the whole layer is about 200 m, a residence time of this water mass is approximately 10 years, which is about the same value as found by Montgomery (1959) for the residence time of the Subtropical Surface Water in the area of its formation. The area of the eastern tropical Pacific Ocean in which the ascending movements occur is about 7 10^{16}cm^2, and therefore the salinity maximum layer suffers a loss of water at the rate of 5 10^{12}cm^3/sec. This amount is only part of the water discharged by the Equatorial Undercurrent to the northern hemisphere near the Galápagos Islands, as indicated in Fig. 1.

It seems unlikely that the salinity of the Tropical Surface Water can be maintained by vertical eddy diffusion, because in this case the enormous heat gain of this part of the ocean (Wyrtki, 1965c) would not be compensated by ascending of cooler subsurface water.

Oxygen Minimum Layer

Although all other water masses will be identified and characterized by their temperature and salinity, being conservative properties, the oxygen minimum layer is identified by a non-conservative property, which is subject to consumption within the water mass. The oxygen minimum layer can be called a water mass, because its water has common characteristics and is formed in a definite area by one characteristic process. Since definition of the water mass of the oxygen minimum layer is by a different property, it does not correspond to any one water mass defined by temperature-salinity relations, but includes parts of several of these water masses.

An oxygen minimum layer is present throughout the entire region considered, even though the oxygen content in this minimum varies strongly (Fig. 10). The layer in which the oxygen content is less than 1 ml/L is more than 1,200 m thick off the coast of Mexico and more than 800 m thick off Peru (Fig. 11B). Along the equator its thickness is less than 300 m, thus dividing the two huge bodies of water with extremely low oxygen content. Within the central parts of these water bodies oxygen content becomes less than 0.25 ml/L, but no formation of H_2S has been observed. The actual minimum lies between 300 m and 500 m depth (Fig. 11A). The upper boundary of this oxygen minimum layer, as defined by the surface with an oxygen content of 1.0 ml/L, comes to within 50 m of the sea surface off Central America and off Perú (Fig. 11D). Along the equator, the upper boundary is deeper at 250 m depth due to

FIGURE 10. Oxygen content in the oxygen minimum in ml/L.

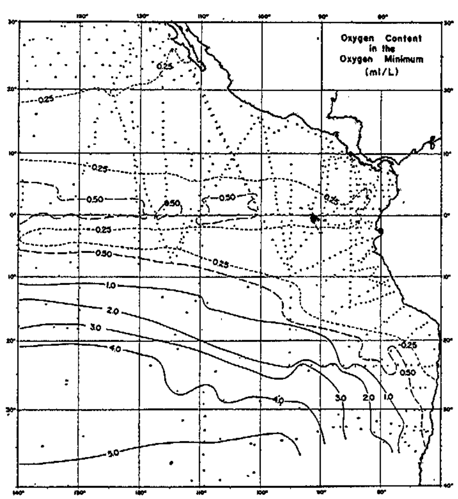
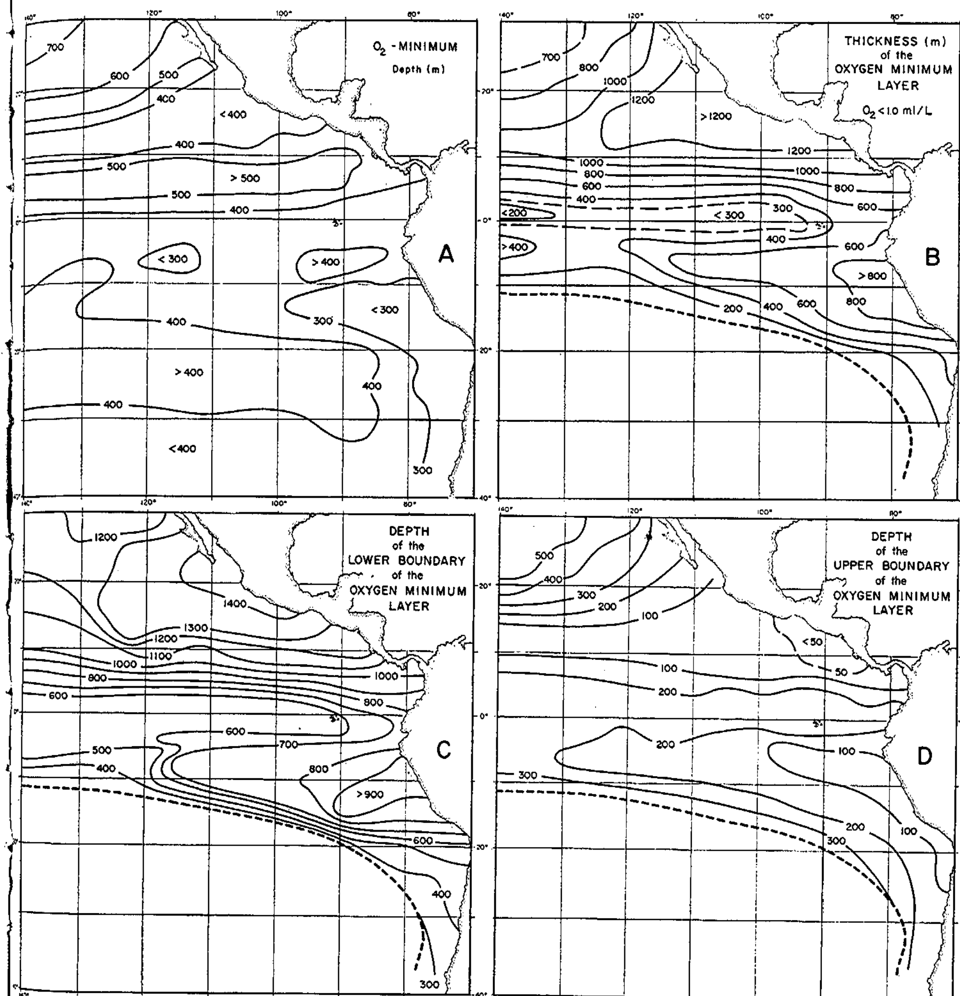


FIGURE 11. The oxygen minimum layer. A. Depth of the oxygen minimum in meters; B. Thickness of the layer with an oxygen content of less than 1 ml/L in meters; C. Depth of the lower boundary of the oxygen minimum layer as given by the surface where $O_2 = 1$ ml/L; D. Depth of the upper boundary of the oxygen minimum layer as given by the surface where $O_2 = 1$ ml/L.



the influence of the Equatorial Undercurrent. The lower boundary is much deeper in the northern hemisphere than off Peru, and is again higher along the equator (Fig. 11C).

In each hemisphere these oxygen minima seem to develop at subsurface levels in the eastern and equatorial portions of the ocean basins into which the circulation within the subtropical anticyclones does not penetrate. Because of the sluggish circulation, the residence time of the water in these strata is long and the consumption of oxygen is high due to the high productivity in the surface layer in large parts of this region (Reid, 1962). In the absence of a strong circulation, oxygen is supplied to the oxygen minimum layers only by vertical diffusion from above and below, by horizontal diffusion, and by water ascending from deeper levels (Wyrtki, 1962). The oxygen minimum off Mexico is more extensive than that off Peru because in general the North Pacific Ocean has a lower oxygen content.

Most of the water discharged by the Equatorial Undercurrent near the Galápagos Islands in 100 m to 200 m depth seems to penetrate into the oxygen minimum layer to the north and to the south, and to supply these layers with oxygen and also with water of relatively high salinity (> 34.9‰). The water spreading into the northern hemisphere supplies the salinity maximum layer of the Subtropical Subsurface Water and this water forms the upper portions of the oxygen minimum layer (see Fig. 4). The water spreading southest towards Peru is also of high salinity, but covered by surface water of still higher salinity, so that no salinity maximum is formed. This water is of low oxygen content and supplies the upwelling off northern Peru, as shown by Wyrtki (1963). In this region upwelled water can probably be identified by its low oxygen content, as some surface oxygen samples during Step-I Expedition demonstrate. Circulation in these depths seems to be cyclonic in each hemisphere, as can be seen in charts of the topography of the 180 and 140 cl/ton surfaces and its acceleration potential (Bennett, 1963). This circulation is also indicated in Fig. 1.

Off the coast of Central America the oxygen minimum layer with an oxygen content of less than 1 ml/L extends over a temperature range from 17C to less than 4C. In its lower portions it includes, therefore, Intermediate Water, which is characterized by a salinity minimum at temperatures of about 5C. All the water between the core layer of the salinity maximum and that of the salinity minimum is mixed water between these two water masses and is characterized by an almost linear temperature-salinity relationship between 15C, 35.0‰ and 5C, 34.55‰ (Fig. 4). This mixed water, which is identical with the Equatorial Pacific water mass defined by Sverdrup et al. (1946, p. 707), is however, strictly a subsurface water mass, which is never found at the sea surface in this region, and contains the oxygen minimum layer.

Off Peru the situation is similar, the oxygen minimum extends over a temperature range from 15C to 5C, and the temperature-salinity relationship is almost the same. This water has been called the Equatorial Subsurface Water by Wyrtki (1963); it is in large parts of the region identical with the water of the oxygen minimum layer and has an enormous volume. Off Peru the upper portions of the Equatorial Subsurface Water are prevented from spreading south across 15°S by water of lower salinity flowing north in the Peru Current. The lower portions of the Equatorial Subsurface Water, having temperature of less than 12C, continues to spread south in depths between 200 m and 400 m forming a salinity maximum which coincides with an oxygen minimum. The spreading of this water to the south is accomplished by the Peru Countercurrent (Wooster and Gilmartin, 1961; Wyrtki, 1963). These two water masses will be discussed later.

The depletion of oxygen at a particular location depends on the amount of oxidizable material present and on the supply of oxygen to this location by circulation and diffusion. Riley (1951) has shown that oxygen consumption decreases considerably with depth, and Wyrtki (1962) explained that this decrease is exponential according to the decrease of oxidizable substances. In the range of the Subtropical Subsurface Water in 50 m to 250 m depth, the horizontal circulation is still relatively strong and the residence time of this water in the eastern tropical Pacific Ocean has been estimated as 10 years. However, the supply of oxidizable substances is very high immediately beneath the very productive surface layer. Consequently, oxygen is consumed rapidly, but is also supplied at a reasonable rate by horizontal circulation, chiefly from the Equatorial Undercurrent and by vertical diffusion from the surface layer. Below the salinity maximum layer there is probably a similar, although weaker, cyclonic circulation like that discussed in connection with the Subtropical Subsurface Water. Residence time of this water will be longer, but the consumption of oxygen will be weaker than immediately beneath the surface layer. The lowest portions of the oxygen minimum layer belong to the Intermediate Water, and it will later be shown that its spreading in the eastern equatorial Pacific Ocean is chiefly effected by large scale horizontal mixing. The residence time of this water is therefore very long, but the supply of these deeper layers with oxidizable material is also small, so that a balance of supply and consumption of oxygen is reached. It seems that the residence time of the water in different depths of the oxygen minimum layer and the supply of oxidizable substances from above is balanced in such a way that similar oxygen values result over a wide depth range. It would be extremely interesting to set up a mathematical model and to calculate numerical values for the parameters involved.

Upper Salinity Minimum

Off the coast of Chile and off the coast of California a salinity minimum is found in shallow depths. Off Peru, salinity increases and oxygen content decreases towards the north due to mixing with the water above and below the minimum. The temperature-salinity characteristics of this water, shown in Fig. 4, indicate that it originates in the temperate zone of the South Pacific Ocean. South of the Subtropical Convergence, South Pacific Temperate Water with salinities of less than 34‰ and temperatures of less than 15C is situated. Off the coast of Chile in the eastern portions of the anticyclonic gyral in the South Pacific Ocean this water flows north. At about 35°S in the vicinity of the Subtropical Convergence, it slides under the Subtropical Surface Water of higher temperature and salinity, but lower density. Actually, the formation of the upper salinity minimum seems to be related to the seasonal variations of the thermal structure. In summer, the uppermost portion of the water flowing north is heated, and a shallow summer thermocline develops (Wyrtki, 1965b). Water above the summer thermocline continues to be heated and simultaneously the salinity of the thin surface layer is increased by evaporation, while the water below the summer thermocline is shielded from both effects. In this way the salinity minimum near 100 m depth is formed. Both the surface layer and the layer of the salinity minimum, now situated within the main thermocline, move north. The spreading of the salinity minimum can be followed to about 14°S. Along the coast of southern Peru and northern Chile it is situated within less than 50 m of the sea surface and supplies the upwelling. The salinity minimum extends to about 95°W, where it is found in more than 250 m depth. The topography of the salinity minimum resembles that of the main thermocline, in which it is situated.

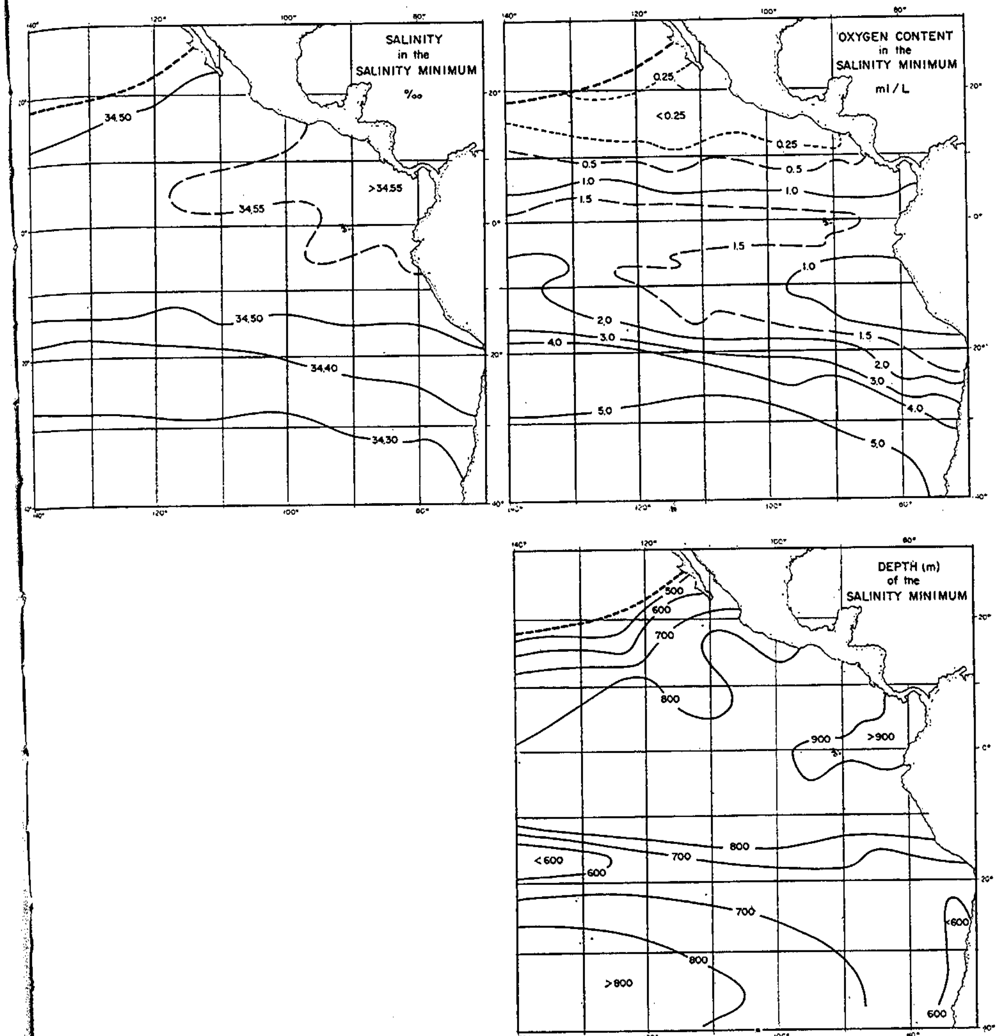
Off the coast of California an analogous salinity minimum is formed although salinities in this minimum are slightly lower.

Lower Salinity Maximum

As the water of the upper salinity minimum spreads north off the coast of Chile, a layer of Equatorial Subsurface Water remains underneath and a salinity maximum appears on top of this layer. The horizontal extent of this lower salinity maximum coincides with that of the upper salinity minimum. The temperature-salinity relation in the lower salinity maximum (Fig. 4) demonstrates this situation. The salinity maximum is situated about 100 m to 200 m below the salinity minimum, and its existence has first been charted by Gunther (1936). The water of the salinity maximum layer originates from the oxygen minimum layer, which is clearly indicated by its low oxygen content. Its spreading to the south is an effect of the Peru Countercurrent (Wooster and Gilmartin, 1961; Wyrtki, 1963), which flows south near 80°W; its lateral spreading is due to horizontal mixing.

Off the coast of California a similar hydrographic situation exists, but the resulting salinity maximum is so weak that at most stations it is hardly noticeable (Reid et al. 1958).

FIGURE 12. The core layer of the salinity minimum of the Intermediate Water, showing salinity and oxygen content in the salinity minimum and its depth.

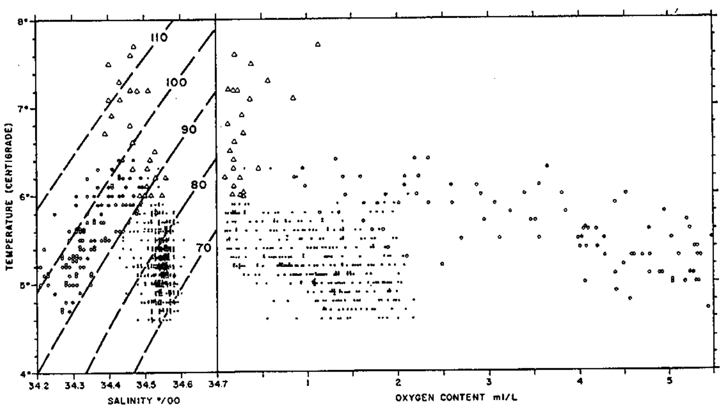


Intermediate Water

In depths between 600 m and 900 m the salinity minimum of the Intermediate Water is found in the entire region (Fig. 12). South of 15°S the salinity is less than 34.5‰ and the oxygen content is high. The temperature-salinity relation in the salinity minimum south of 15°S, which is shown by circles in Fig. 13, demonstrates that the specific volume anomaly in the minimum is between 90 and 100 cl/ton, and the spreading in the minimum takes place along a surface of almost constant density. South of 20°S the salinity minimum more or less coincides with an oxygen maximum, indicating its origin at the sea surface. This water is the Antarctic Intermediate Water which is formed near the Antarctic Polar Front, and spreads north, whereby its salinity and temperature increase, while its oxygen content decreases, as seen in the temperature-oxygen diagram in Fig. 13.

The salinity minimum is situated in less than 600 m depth off the coast of Chile, from where a ridge in its topography extends west near 20°S. The minimum is deeper than 800 m in the central South Pacific Ocean between 30°S and 40°S, and its topography suggests that the Antarctic

FIGURE 13. Temperature-salinity and temperature-oxygen diagram of the core layer of the Intermediate Water. Curves in the temperature-salinity diagram give specific volume anomaly. Circles represent stations south of 15°S, dots, stations north of 15°S, and triangles, stations close to the northern boundary between 15°N and 20°N.



Intermediate Water in this region participates in an anticyclonic circulation. The oxygen maximum related to the salinity minimum is found only in the area where oxygen content is greater than 2 ml/L, being south of the ridge in the topography of the minimum, where probably an active horizontal circulation exists. In this area the minimum itself also coincides with an isentropic surface. These results are in agreement with the circulation in these depths derived by Reid (1965) by means of an analysis of the flow on the 80 cl/ton surface.

North of 15°S the salinity minimum is situated deeper and at a lower specific volume anomaly between 85 and 70 cl/ton. Temperature-salinity and temperature-oxygen values in this water are shown by dots in Fig. 13. Lowest temperatures of less than 5C and highest salinities above 34.55‰ in the salinity minimum are found in the eastern tropical Pacific Ocean off the Gulf of Panama. They coincide with the region where the salinity minimum is deeper than 900 m (Fig. 12). North of 15°S the salinity minimum layer occupies the lower portions of the oxygen minimum layer, and it can be assumed that it is maintained by large scale horizontal mixing rather than by advection. The map of the acceleration potential on the surface of 80 cl/ton shown by Reid (1965) supports this assumption. The temperature-salinity diagram (Fig. 13) also demonstrates that the salinity minimum north of 15°S, indicated by dots, is not identical or directly derived from the minimum south of 15°S. The salinity minimum is found at lower temperatures and higher densities, indicating that the downward diffusion of heat and salt from higher levels causes the minimum to appear deeper. The fact that the rather slow process of downward diffusion can have an influence on the temperature of the salinity minimum clearly points to a long residence time of this water, which in turn is verified by its low oxygen content.

Between 15°N and 20°N the salinity minimum rises again, its temperature becomes higher, above 6C, and its salinity lower. The corresponding temperature salinity values are shown by triangles in Fig. 13. This water belongs to the North Pacific Ocean. Off the coast of California the deep salinity minimum is not developed, since salinities decrease steadily towards the surface (Reid et al. 1958).

The higher values of oxygen content (> 1.5 ml/L) in the salinity minimum along the equator (Fig. 12) represent an influence of the Equatorial Undercurrent, which carries water of relatively high oxygen content east and increases the supply of oxygen to these deeper layers from above.

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