UPWELLING IN THE COSTA RICA DOME

BY KLAUS WYRTKI

INSTITUTE OF MARINE RESOURCES, SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA[1]

ABSTRACT

The Costa Rica Dome is an area off the coast of Costa Rica where the strong tropical thermocline reaches to within 10 meters of the sea surface. The dome measures about 150 by 300 kilometers. It is situated near lat. 9° N., long. 89° W., at the eastern end of a ridge in the topography of the thermocline along the northern boundary of the Equatorial Countercurrent. This current, the Costa Rica Coastal Current, and parts of the North Equatorial Current form a cyclonic circulation around the dome.

At the surface the dome appears as an area of slightly reduced temperature, higher salinity and phosphate contents, and reduced oxygen saturation, which are indications of upwelling. The balance between the energy available for heating of the surface layer and the ascending of cooler water gives an average ascending velocity of 10^{-4} cm/sec. These movements add only 7×10^{10} cm.^{3}/sec. to the surface layer, compared with transports of about 20×10^{12} cm.^{3}/sec. of the horizontal circulation. The upwelling in the dome is caused by the cyclonic flow around the dome. When the Countercurrent strongly changes direction, the necessary adjustment of its velocity requires a cross-current velocity of about 0.9 cm./sec. which is sufficient to maintain the upwelling. During the Costa Rica Dome survey a deep-reaching eddy transporting 20×10^{12} cm.^{3}/sec. appeared to be separated and to drift north with the Costa Rica Coastal Current.

Comparison of the topography of an isothermal layer during six surveys in the area showed that the dome was always present and maintained its position within 200 km. These observations indicate that the Costa Rica Dome, although a permanent feature, is subject to considerable fluctuations in its structure and circulation and may contribute essentially to large-scale mixing.

The eastern tropical Pacific Ocean is characterized by a very well-developed thermocline separating the warm surface water from the cooler subsurface water. The warm surface layer is comparatively shallow, and the topography of the thermocline is related to the currents in the surface layer as shown by Cromwell (1958). The divergences and convergences associated with the surface circulation, which result in the formation of ridges and troughs in the topography of the thermocline, have particular importance for the fertilization of the surface layer and for the distribution of the standing crop of zooplankton in the area, as shown by Brandhorst (1958) and Reid (1962). A feature of special interest in this connection is the Costa Rica Dome in which the top of the thermocline often comes to within less than 10 m. of the surface. This dome is situated off the coast of Costa Rica at about lat. 9° N. and long. 89° W. and has a diameter of approximately 200 km.

As pointed out to me by Milner B. Schaefer, the Costa Rica Dome was found in 1948, when bathythermograph (BT) observations from vessels en route between California and Panama were examined. Between 1952 and 1958 a number of expeditions crossed or partly surveyed this dome, and confirmed its existence and approximate posi-

---

NOTE.—Approved for publication March 23, 1963.

This investigation was financed by the Bureau of Commercial Fisheries under Contracts 14-17-0007-28 and 14-17-0007-70, with funds made available under the Act of July 1, 1954 (68 Stat. 376), commonly known as the Saltonstall-Kennedy Act. It formed part of the Scripps Tuna Oceanography Research Program of the Scripps Institution of Oceanography.

[1] Contribution from Scripps Institution of Oceanography, New Series.

tion. However, none of these expeditions succeeded in covering the area of the dome sufficiently to allow a detailed analysis. As a consequence of this, a survey of the Costa Rica Dome was undertaken in November and December 1959 under the leadership of M. J. Pollak and E. B. Bennett of the Inter-American Tropical Tuna Commission (Scripps Institution of Oceanography, 1960). The results of this survey, which covered the dome as well as the surrounding area, are used in this paper to analyze the structure of the dome and draw conclusions about its role in the circulation of the eastern tropical Pacific Ocean, except where other expeditions are mentioned.

The objectives of this expedition were to locate the position of the dome properly, to determine its extent, and to study its circulation and its effects on the distribution of biota. Upwelling is thought to occur near the center of the dome, and an analysis of the data of the expedition should give an estimate of its amount and an indication of the sources of the ascending water, as well as an explanation of the upwelling from dynamic principles. From the point of view of physical oceanography, the questions to be discussed in this paper are the following:

i. Where is the upwelling area located, and what is its size?

ii. What is the amount of upwelling?

iii. Where does the ascending water come from?

iv. How is the upwelling conditioned dynamically?

v. Is the Costa Rica Dome a permanent or temporary feature?

These questions have a bearing upon the study of the tuna resources of the eastern tropical Pacific, which are exploited by United States fishermen. It could be expected that the spatial and temporal distribution of tuna would bear some relation to the distribution of upwelling, which, therefore, warrants investigation.

HYDROGRAPHIC STRUCTURE OF THE COSTA RICA DOME

The Costa Rica Dome appears as an area where the homogeneous surface layer is extremely thin and the top of the thermocline often comes to within less than 10 m. of the sea surface. Also, the thermocline itself is more strongly developed than in surrounding waters and temperature gradients usually exceed 1° C. per meter in the range between 25° and 17°. As a consequence of this, the cooler subsurface water is found in a higher position than in the surrounding area. These conditions are shown in figure 1 where the topography of the 24° isotherm, as derived from BT–observations, is drawn, as are two BT–sections across the dome. The 24° isotherm, which coincides fairly well with the top of the thermocline in this region, ascends to less than 10 m. depth in several patches within an area of approximately 350×150 km. On the periphery of the surveyed area this isotherm is found in depths of more than 20 m., its deepest positions being in the southeast. A BT–section (A–A) running from northwest to southeast and drawn from the same data is shown in the upper part of figure 1. The dome is situated between stations 7 and 11 where the thermocline is highest and the temperature gradient is steepest, and also where the cooler subsurface water of 13° reaches its highest position, ascending to less than 90 m. depth. This section does not cut through the shallowest parts of the dome but runs between the two patches in which the top of the thermocline is highest. In the northwestern part of the section another area with a high position of the thermocline is found, but there are not enough observations to relate this feature to the Costa Rica Dome.

A much more satisfactory BT–section (B–B) across the dome was obtained in February 1960 by the vessel *Explorer* (Stewart, 1962). This section is drawn in the lower part of figure 1 and shows that the dome is situated between stations 331 and 369 in approximately the same position as during the Costa Rica Dome survey, with a diameter of about 230 km. The two sections run in the same general direction from northwest to southeast, but there is no shallow thermocline in the northwestern part of the *Explorer* section. Therefore, the shallow thermocline observed during the Costa Rica Dome survey in the northwest may be considered as a transient feature.

At the surface the dome appears as an area of slightly lower temperature, slightly higher salinity, reduced percent of oxygen saturation, and high phosphate concentration, although the centers of the areas defined by these properties do not completely coincide (fig. 2). Temperature near the center of the dome exhibits a more irregular pattern than on its periphery, where it usually exceeds 27° C. Near the center, patches of water of less than 25° C. are found beside patches

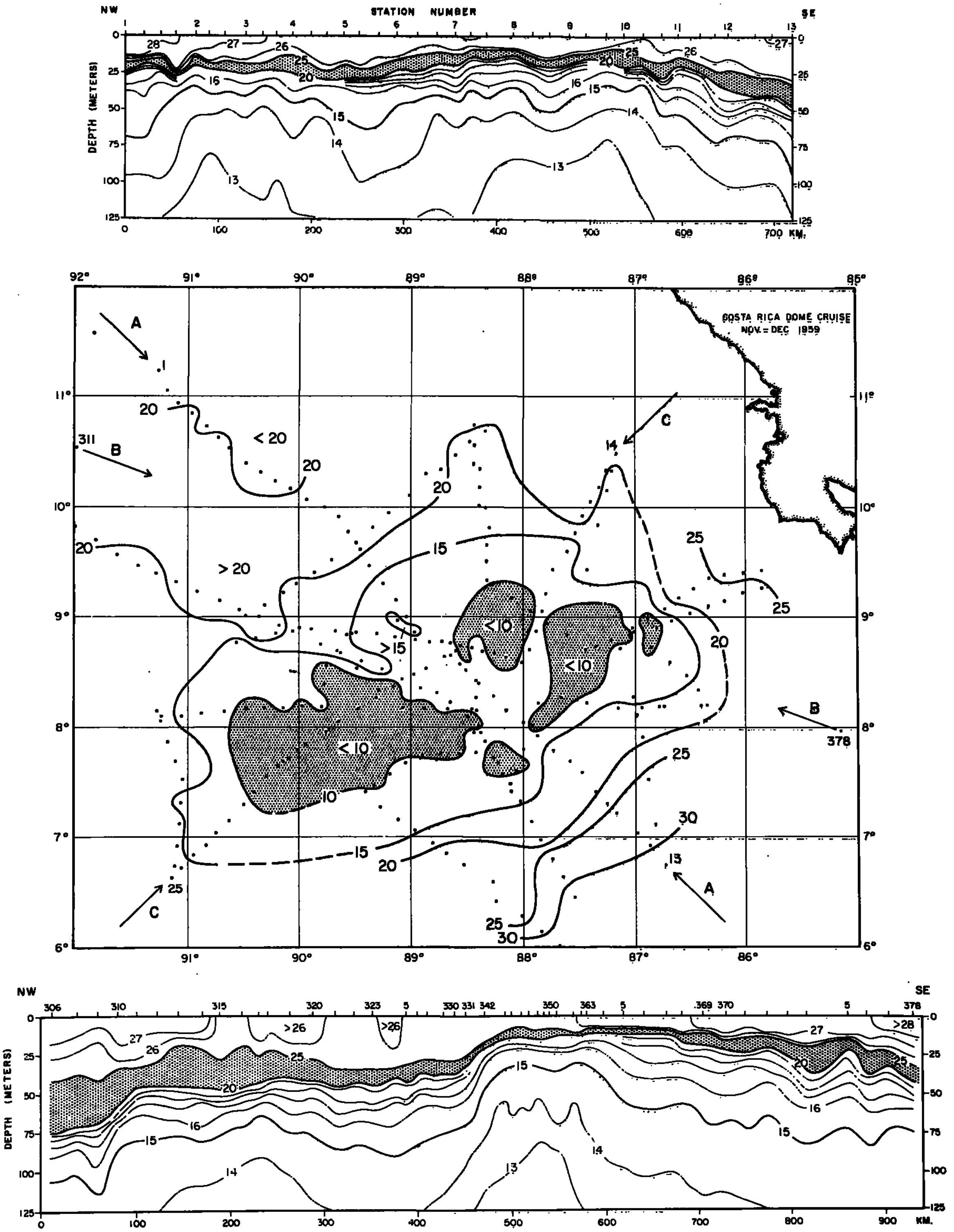

FIGURE 1.—The thermal structure of the Costa Rica Dome from bathythermograph observations. Center: Topography of the 24° C. isotherm during the Costa Rica Dome cruise, in meters, <10 m. shaded. Top: Distribution of temperature along section A–A during the Costa Rica Dome cruise; thermocline between 25° and 20° C. shaded. Bottom: Distribution of temperature across the dome in February 1960 according to observations of the vessel *Explorer* along section B–B; thermocline between 25° and 20° C. shaded.

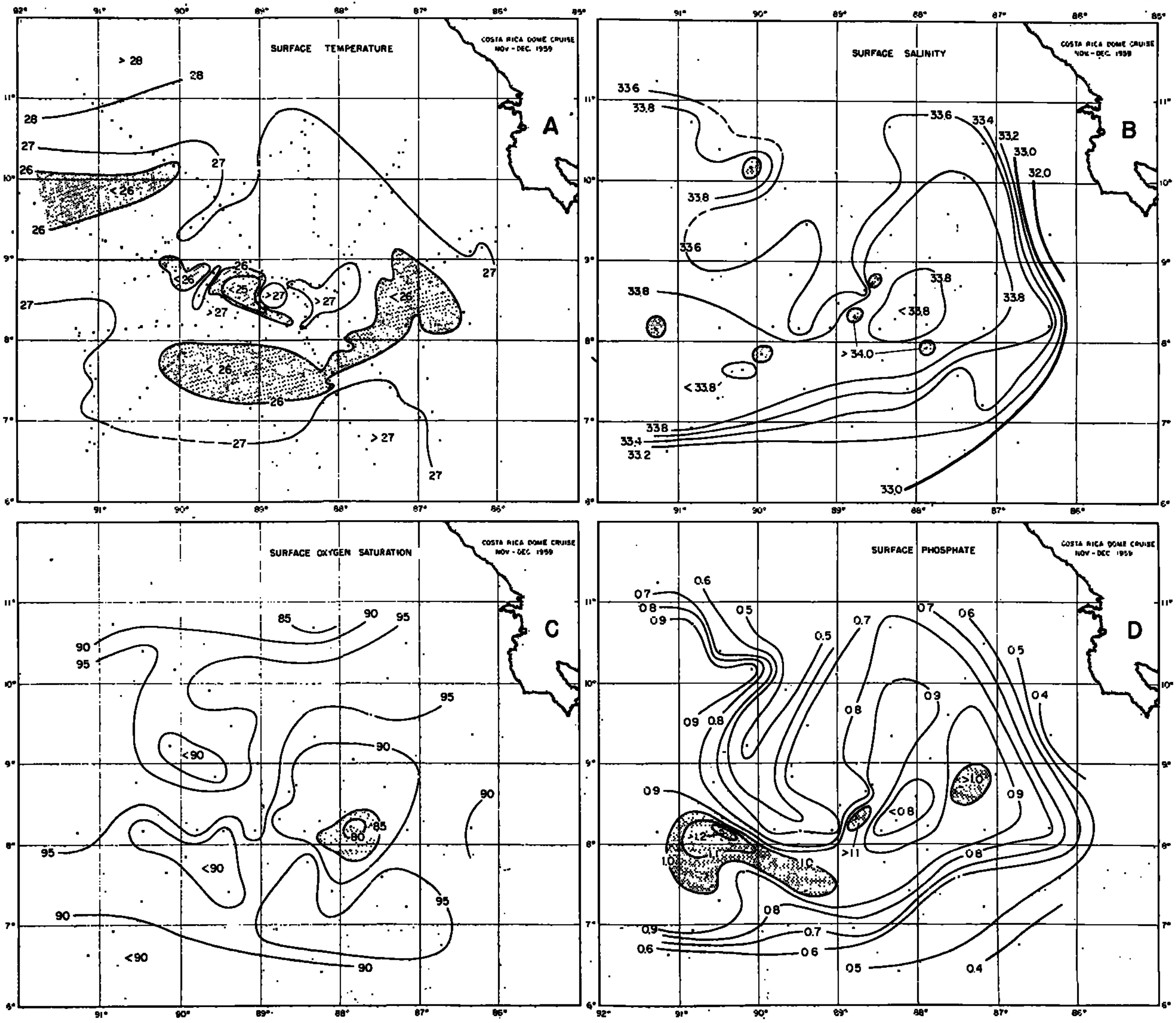

Figure 2.—Distribution of properties at the surface during the Costa Rica Dome cruise. (A) Surface temperature, <26° C. shaded. (B) Surface salinity, >34.0°/₀₀ shaded. (C) Percent of oxygen saturation at the surface, <85 percent shaded. (D) Surface phosphate-phosphorus, >1.0 µg.-atom/L. shaded.

with more than 27° C. (fig. 2A). This pattern indicates a patchiness of the actual upwelling, which occasionally and locally may bring the top of the thermocline right to the surface, but this is definitely an exception. The cooler water is situated between lat. 7.5° and 9° N. and between long. 87° and 90° W. Although the surface temperature shows a drop of as much as 2° C. in some places, it should be noted that during this survey no water within the temperature range of the thermocline reaches right to the surface and in all instances a shallow surface layer is shown in the BT-observations.

The distribution of surface salinity (fig. 2B) shows a tongue of high salinity extending eastwards between lat. 7° and 8° N. The salinity within this tongue is above 33.8°/₀₀, and only in a few places is 34.0°/₀₀ exceeded. East of long. 89° W. the tongue turns north and its salinity is reduced. It seems to reach about lat. 11° N. To the south and to the east a sharp salinity gradient separates the tongue from the water of low salinity (<33°/₀₀) off the coast of Central America. This salinity gradient is not accompanied by a corresponding change of surface temperature.

The surface water is undersaturated with oxygen in the entire area, values being between 88 and 98 percent (fig. 2C). In a small area near lat. 8° N., long. 88° W., oxygen saturation at the surface drops below 85 percent indicating an advection of subsurface water of low oxygen content into the shallow surface layer. The phosphate concentration at the surface is high; only in the range of the low salinity water off Central America are the phosphate values less than 0.6 µg.-atom/L. (fig. 2D). The distribution of the phosphate resembles closely that of surface salinity with a tongue of high phosphate coinciding with the tongue of high salinity. Within this tongue phosphate is in some places as high as 1.0–1.2 µg.-atom/L.

In the center of the tongue of water of high phosphate content, an area near long. 88° W. has phosphate values below 0.8 µg.-atom/L. This area coincides with an area of reduced salinity (<33.8‰) within the tongue of high salinity, and with an area where the surface temperature is above 27°. Because upwelling in the dome should be indicated by low temperature, high salinity, and high phosphate, this patch of abnormal water in the center of the dome suggests that circulation and upwelling in the dome must be subject to fluctuations that can lead to the isolation of a patch of water of this size. The lowest oxygen saturation is found just to the southeast of this patch of abnormal water.

According to this analysis of the topography of the thermocline and of the distribution of properties at the surface, the Costa Rica Dome appears as the end of a ridge in which the thermocline is in a very shallow position. This ridge extends along the left or northern flank of the Equatorial Countercurrent, as shown by Cromwell (1958). When this current approaches the coast of Central America and turns north, the ridge is abruptly terminated, and the Costa Rica Dome is at its end. In this dome the thermocline comes even closer to the surface than is the case along the ridge at the northern boundary of the Countercurrent, indicating that upwelling occurs in the dome area. The dome was situated between lat. 7.5° and 9° N. and between long. 87° and 90° W. during this survey.

Within the strong tropical discontinuity layer, temperature decreases rapidly from about 25° to 15° C. within a depth interval of only 20 to 50 m., and the other properties also change considerably. Salinity and phosphate content increase while oxygen content decreases, as shown by the distribution of these properties between the surface and 800 m. depth along a section crossing the dome area from southwest to northeast (fig. 3). This is section C–C in figure 1. Below 15° C. the

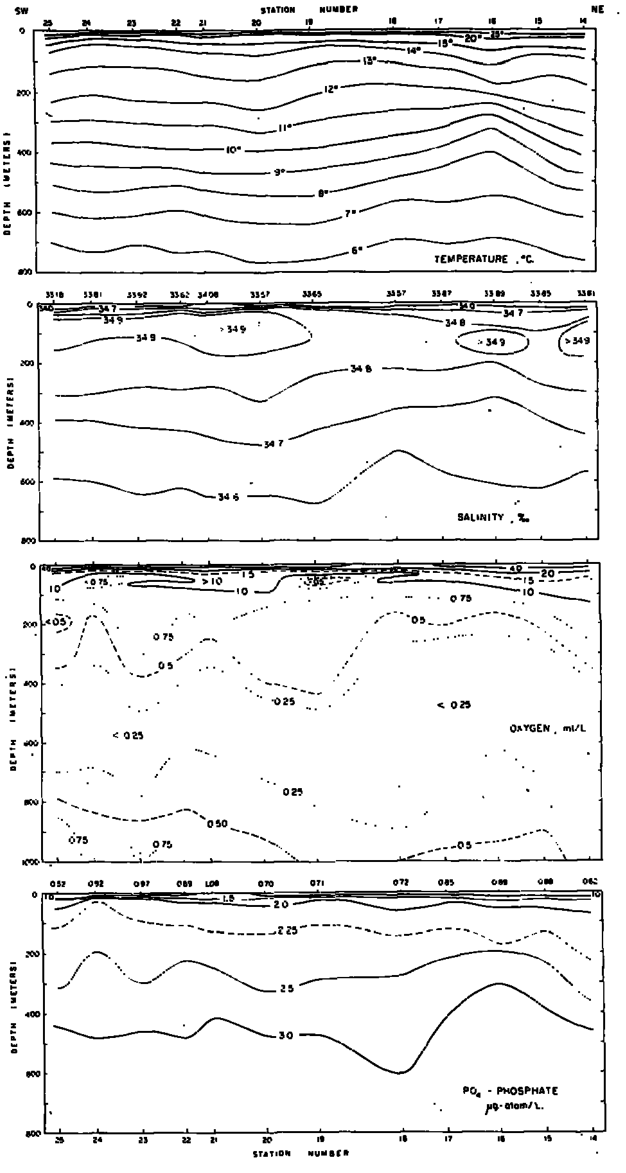

FIGURE 3.—Distribution of temperature, salinity, oxygen content (ml./L.), and phosphate-phosphorus between the surface and 800 m. depth along a section from southwest to northeast across the Costa Rica Dome, on the Costa Rica Dome cruise. The position of the section is shown in figure 1 by the line C–C.

temperature decrease is much slower and the salinity reaches a maximum near 100 m. depth in which salinities are close to 34.9°/oo. In the layer between 50 and 300 m. depth the oxygen content shows a number of maxima and minima before decreasing to values of less than 0.25 ml./L. and reaching the main oxygen minimum. These intermediate oxygen maxima and minima do not exhibit any uniformity with respect to the depth and temperature at which they are found. It is likely that this irregular oxygen distribution results from the local variability of the quantity and activity of oxygen-consuming material, as well as from the horizontal advection of smaller water bodies of higher oxygen content. The main oxygen minimum is found in depths between 400 and 700 m. in which oxygen content is everywhere lower than 0.20 ml./L. Below this layer oxygen increases again and the salinity reaches a minimum near 1,000 m. with salinities below 34.6°/oo which are characteristic for the Intermediate Water. Phosphate, which is already unusually high at the surface, increases to 2.0 μg.-atom/L. at about 50 m. and then much more slowly to values above 3.0 μg.-atom/L. in the lower part of the oxygen minimum layer.

The vertical structure of the water masses in the area of the Costa Rica Dome is shown by the envelopes of all temperature-salinity and temperature-oxygen curves in figure 4. Below the surface layer of high temperature and comparatively low salinity, salinity increases to a maximum which is situated between 30 and 150 m. depth. The salinity in this salinity maximum is charted in figure 5a and varies only between 34.83 and 34.96°/oo. This subsurface salinity maximum is found everywhere in the eastern tropical Pacific Ocean and will be called the Equatorial Subsurface Water. A close analysis of the salinity maximum (not presented here) and of its depth shows that two branches are present in the area of the Costa Rica Dome. One branch is found east of long. 90° W. and the maximum is in depths between 80 and 150 m.; the other branch is found west of long. 88° W. and the maximum is between 30 and 60 m. depth. Between long. 88° and 90° W. the two maxima overlap and a double maximum is found. The salinities in the two branches are not different, and the small gradients seen in figure 5A do not allow one to draw conclusions about the spreading of the two branches. In the center of the dome, where the thermocline is highest, the salinity maximum is lowest and drops in some places below 34.85°/oo. This reduced salinity can be taken as an indication of upwelling in these localities because the ascending motion would tend to reduce the salinity in the maximum.

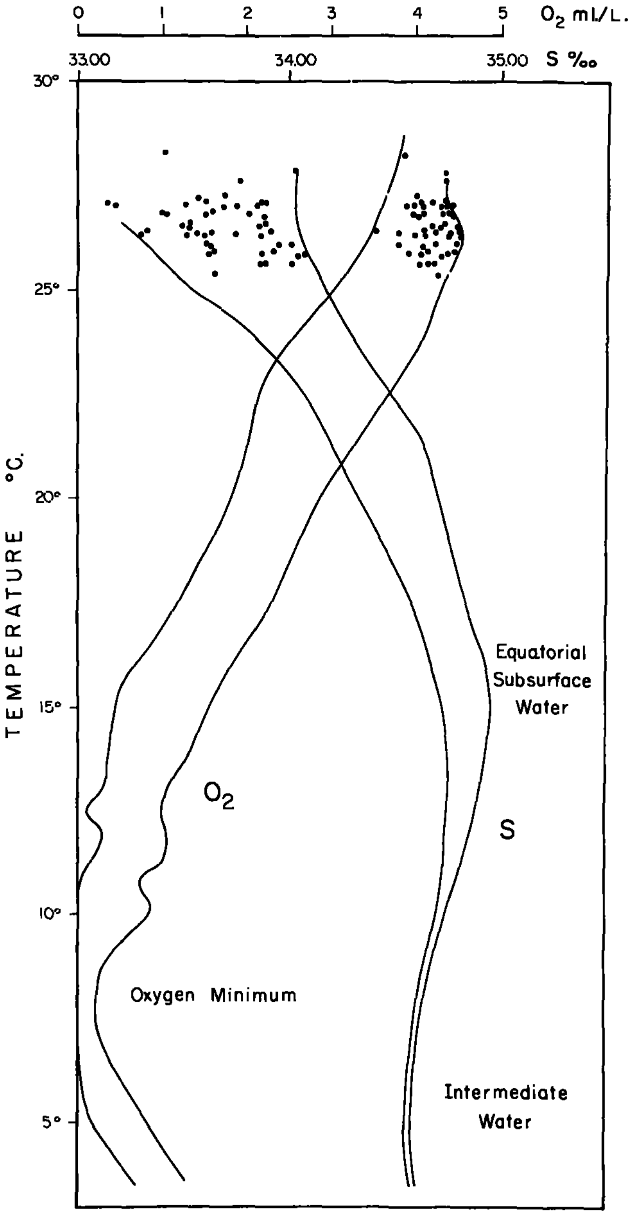

FIGURE 4.—Temperature-salinity and temperature-oxygen diagram showing the envelopes of all TS- and TO_2-curves during the Costa Rica Dome cruise. Surface values are entered by dots, and names of the main water masses are indicated.

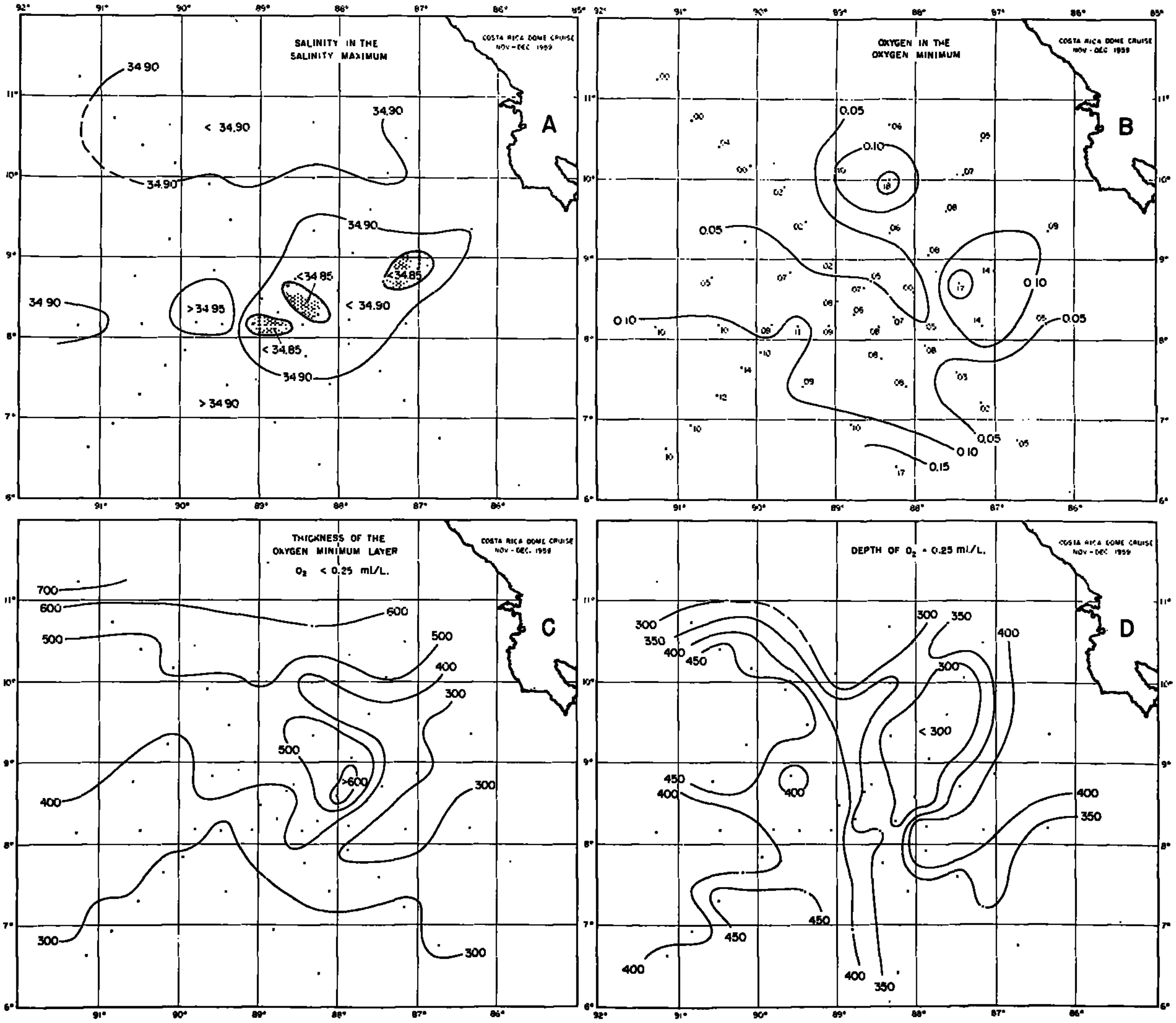

FIGURE 5.—(A) Distribution of salinity in the salinity maximum of the Equatorial Subsurface Water, <34.85°/oo shaded. (B) Minimal oxygen content in the oxygen minimum layer, in ml./L. Values at station positions are in 0.01 ml./L. (C) Thickness of the oxygen minimum layer (where O_2 <0.25 ml./L.) in meters. (D) Depth of the upper boundary of the oxygen minimum layer, given by the depth of the 0.25 ml./L. surface in meters.

In the range of the Equatorial Subsurface Water, oxygen content varies widely but is, in general, low, between 2.0 and 0.25 ml./L., and shows intermediate maxima and minima.

In depths near 900 m. the Intermediate Water is found, characterized by a salinity minimum at a temperature of about 5° C. The salinities in the minimum are uniform and range only between 34.56 and 34.58°/oo in the entire area surveyed.

The main oxygen minimum is situated between the Equatorial Subsurface and the Intermediate Water and extends over a considerable interval of depth. Oxygen concentrations in the minimum are everywhere in the area below 0.20 ml./L. (fig. 5B) and in some places they are close to zero. Because the oxygen content remains at this low level within a fairly thick layer, it is not possible to chart the depth of the minimum with confidence and it is advisable to chart instead, the thickness of the layer that has an oxygen content of less than 0.25 ml./L. (fig. 5C) and the upper limit of the oxygen minimum layer as given by the depth of an oxygen content of 0.25 ml./L. (fig. 5D). The thickness of the oxygen minimum layer increases from about 250 m. in the south to more than 600 m. in the north. Only underneath the dome, at lat. 9° N. and long. 88° W., is this regular increase in thickness interrupted and the oxygen minimum layer reaches a thickness of 600 m. in contrast to only 400 m. in the immediate vicinity. The upper limit of the oxygen minimum, as given by the depth where the oxygen content is 0.25 ml./L. shows a more irregular pattern. The highest position of this surface is found near lat. 9° N., and long. 88° W., considerably displaced relative to the position of the dome as indicated in the topography of the thermocline. This displacement will be discussed in detail when the dynamics of the system is treated. In the north of the area, the 0.25 ml./L. oxygen surface is also in a very high position but this is due to the great thickness of the oxygen minimum layer.

HORIZONTAL CIRCULATION

The Costa Rica Dome is north of the Equatorial Countercurrent. This current approaches the coast of Central America between lat. 4° and 8° N. during all seasons, with the exception of February and March when it seems to be absent or only weakly developed as shown in the surface current charts drawn by Cromwell and Bennett (1959). Along the coast of Costa Rica a coastal current flows northwest, separating the dome from the coast. It will be called the Costa Rica Coastal Current. This coastal current seems to carry away part of the water that is accumulated by the Countercurrent off the coast of Panama and Costa Rica. North of about lat. 10° N., the flow is to the west and the water movements are part of the system of the North Equatorial Current. The center of this cyclonic circulation off the coast of Costa Rica is the Costa Rica Dome as revealed from the topography of the thermocline.

The circulation in the vicinity of the Costa Rica Dome is shown in figure 6 by the topography of four surfaces relative to 1,000 decibars. The topography of the sea surface (fig. 6A) shows a strong current entering the region from the west and southwest turning north and later, northwest. The right flank of this current coincides with the strong salinity gradient seen in the chart of surface salinity (fig. 2B). This flow represents the northern part of the Equatorial Countercurrent which is south of lat. 7° N. when entering the area at long. 91° W. East of long. 89° W. parts of the Countercurrent turn northeast and pass over into the Costa Rica Coastal Current. This map does not show how close this current reaches to the coast because the easternmost station is almost 100 km. offshore. In the northwestern part of the area the flow is from the north but turns west before reaching lat. 8° N. To the west of the Costa Rica Coastal Current an eddy has its center near lat. 8.5° N., long. 88° W., but the closed circulation in this cyclonic eddy is small compared with the strength of the coastal current. Another part of a cyclonic circulation can be seen at lat. 7.5° N., long. 91° W., where some water from the Countercurrent turns north and passes over into a flow to the west.

The circulation at 50 m. depth (fig. 6B) has substantially decreased in intensity as compared with the surface circulation. The Equatorial Countercurrent has lost in strength or may be found farther south. Also, the coastal current is weaker. However, the closed circulation in the eddy, whose center has shifted to about lat. 10° N., long. 88° W., has increased. This change in the circulation between the surface and 50 m. depth reflects the influence of the strong discontinuity layer situated between about 10 and 50 m. depth. The topography of the 100-decibar surface is almost identical to that of the 50-decibar surface if 10 dynamic centimeters are subtracted, so this chart is not shown.

The circulation at 200 m. depth (fig. 6C) is completely dominated by the huge eddy which is now centered near lat. 10° N., long. 88° W. The only other feature worth mentioning is the cyclonic circulation around a point near lat. 8° N., long. 91° W., which was already indicated in the topography of the sea surface. Below 300 m. depth velocities in the eddy decrease progressively, but even in depths near 700 m. this eddy is still shown in charts of the topography of isothermal layers. Thus, for instance, the 6° isotherm rises to less than 680 m. in the center of the eddy compared to more than 750 m. at its periphery, but the map is not shown here.

The vertical distribution of velocity and the transports across some sections are shown in figure 7 and the positions of the sections are

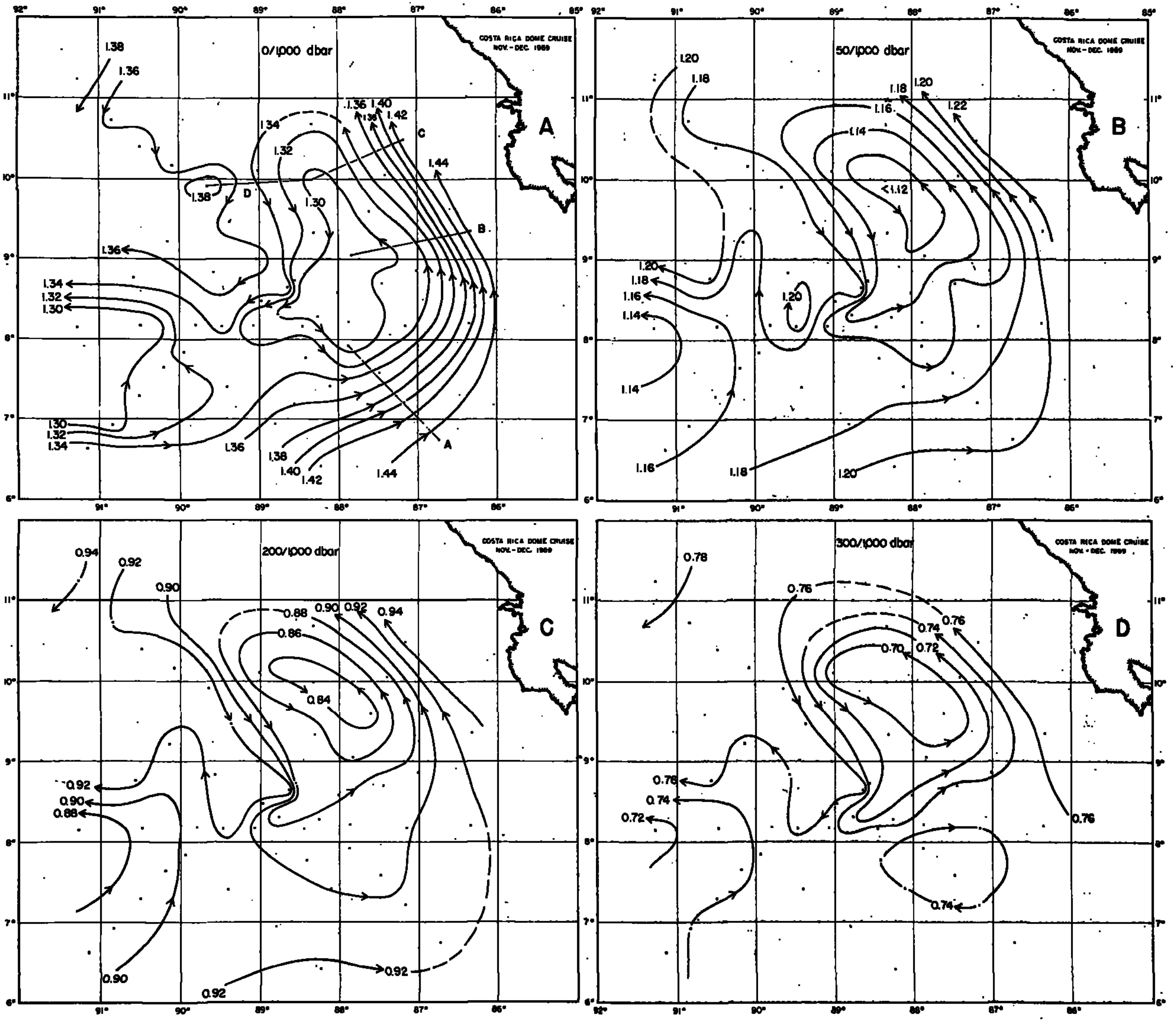

FIGURE 6.—Geopotential topographies of the sea surface, and of the 50-, 200-, and 300-decibar surfaces relative to 1,000 decibars during Costa Rica Dome cruise, in dynamic meters. The positions of sections for which transports have been calculated are marked in figure 6A by the lines A, B, C, and D.

indicated in figure 6A. Section A, between stations 10 and 13, crosses the Countercurrent just before it turns north. The average velocity at the surface is 43 cm./sec., but velocities of more than twice this value have been observed near the center of the current by surface drogues. The velocity decreases rapidly with depth and the total transport of 7.2 million m.^{3}/sec. between these two stations is chiefly concentrated in the upper 150 m. From the topographies of the subsurface layers it can, however, be seen that this section does not include the transport in the east-going branch of the eddy in subsurface layers because station 10 is situated to the south of this flow. Section B, which cuts across the north-flowing part of the eddy, still shows a thin surface layer moving more rapidly than the subsurface layer, but most of the transport of 16.7 million m.^{3}/sec. is due to the flow in layers between 50 and 400 m. depth. Sections C and D have each a transport of about 20 million m.^{3}/sec. flowing north and south, respectively. These transports are concentrated between the surface and 400 m. depth, and the velocities are almost uniform from the surface to that depth, especially in section D.

The circulation pattern in this area is characterized by the Equatorial Countercurrent flowing eastwards in the southern part of the area and by parts of the North Equatorial Current flowing west in the northern part of the area. Along the coast the northward flowing Costa Rica Coastal Current transfers water from the Countercurrent, which accumulates water off the coast, to the North Equatorial Current. A trough in the topography of the sea surface and a ridge in the topography of the discontinuity layer are developed between the flow to the east and the flow to the west. This trough is terminated by the north-flowing coastal current and does not reach the coast. The ridge in the topography of the thermocline is simultaneously terminated. The Costa Rica Dome is the very pronounced end of this ridge that separates the Equatorial Countercurrent from the North Equatorial Current. Around the eastern end of this ridge there is a strong cyclonic circulation.

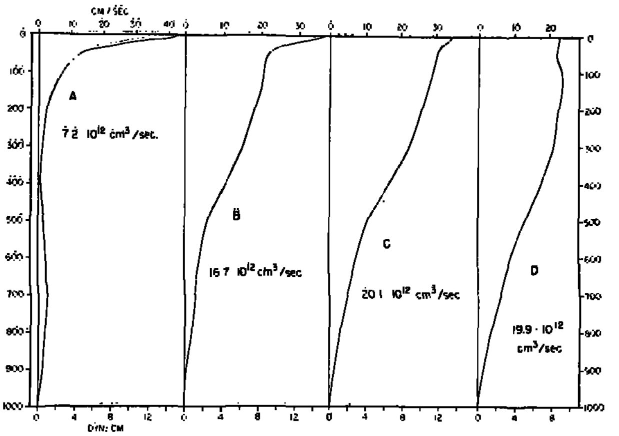

FIGURE 7.—Vertical distribution of the average geostrophic velocity (cm./sec.) relative to 1,000 m. depth in different branches of the circulation in the Costa Rica Dome. (The sections for which the transports have been calculated are shown by A, B, C, and D in figure 6A.)

Although this general picture of the circulation seems to be quite simple, there are some problems and observed features requiring an explanation. The flow in the North Equatorial Current, as well as the flow in the countercurrent, were comparatively weak and shallow during this survey, and this is generally the case, as can be seen from surface current charts. Therefore, it is not obvious how these currents can maintain an eddy of considerable depth with a circular transport of the order of 20 million m.^{3}/sec. If this eddy should be a stationary feature, it would require additional energy for its maintenance. Winds in this region, however, are weak and variable in direction, so that they cannot really be considered as a source of energy for such a strong, limited eddy. Moreover, there is little vertical shear in the eddy, as demonstrated by the weak velocity gradients between 50 and 300 m. depth in the eddy (fig. 7). Since there is no obvious source of energy to supply a stationary eddy in this position, the eddy may be considered as transient and the motion around the Costa Rica Dome as nonstationary. This assumption is partly supported by the fact that the center of the eddy in subsurface layers (fig. 6B, C, D) does not coincide with the center of the Costa Rica Dome (fig. 1) which is the area where the highest thermocline is.

To solve this problem, it should be investigated whether a similar eddy was found during other surveys of the same region. During the Eastropic Expedition in November 1955 (Scripps Institution of Oceanography, 1956) the area of the Costa Rica Dome was also surveyed although the station network was less dense. The data from that survey were used to plot the distribution of surface salinity and the topography of the sea surface relative to 1,000 decibars (fig. 8) for comparison with the situation during the Costa Rica Dome cruise. The difference is quite obvious. There is again a cyclonic circulation around a point at lat. 9° N., long. 89.5° W., but there is no separate eddy, at least not east of long. 90° W. The water entering the area with the Equatorial Countercurrent turns north, and later, northwest, but nowhere is a flow to the south indicated as in figure 6a. The center of the cyclonic flow coincides with an area of lowest surface temperature (<25° C., fig. 8B) and highest surface salinity (>33.8°/₀₀, fig. 8A). The low salinity water of the Costa Rica Coastal Current occupies a larger area but is displaced to the northwest.

From this comparison it may be concluded that the cyclonic circulation around the eastern end of

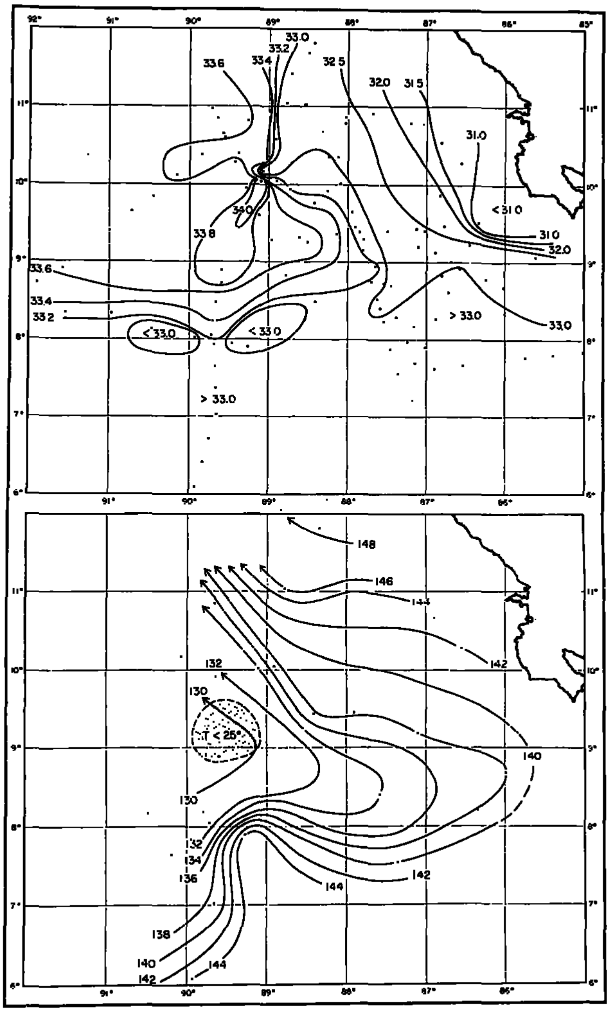

FIGURE 8.—A. Surface salinity (°/₀₀) during Eastropic Expedition. B. Geopotential topography of the sea surface relative to 1,000 decibars during Eastropic Expedition, in dynamic cm. (The area with surface temperatures below 25° C. is shaded.)

the trough separating the Countercurrent from the North Equatorial Current is not very stable and separates eddies from time to time. One of these eddies has been met during the Costa Rica Dome survey. This eddy seems to drift north or northwest on the left flank of the Costa Rica Coastal Current, as indicated by the displacement of its center towards the northwest, relative to the center of the dome. The reasons for the separation of such eddies are probably fluctuations in the strength and transports of the Countercurrent. Knauss (1961) has reported fluctuations in the transport of the Countercurrent by as much as an order of magnitude, and it can be assumed that as a result of each of these major fluctuations one big eddy will be separated near the Costa Rica Dome where the Countercurrent ends. This eddy is similar in size to an eddy separate from the Gulf Stream which was observed by Fuglister and Worthington (1951).

The other feature to be explained is the different position of the center of the deep eddy and that of the thermal dome during the Costa Rica Dome cruise. Such a separation did not occur during the Eastropic Expedition when the lowest surface temperatures and the highest surface salinities coincided with the center of the cyclonic circulation (fig. 8). During the Costa Rica Dome survey, on the other hand, the center of the deep eddy was found near lat. 10° N., long. 88° W., while the thermal dome was situated between lat. 7.5° and long. 9° N. and between lat. 90.5° and long. 87° W. The discussion of the geopotential topographies mentioned that the circulation above the thermocline was substantially different from that at 50 m. depth, thus indicating the presence of a fairly independent surface layer. This finding leads to the conclusion that the thermal dome is related to the circulation within the thin surface layer and little or not at all influenced by the circulation in deeper levels. This conclusion will be substantiated in the next section.

The structure of the deep eddy, as well as the fact that the dome is developed in a different position, indicates that this eddy is already separated from the remainder of the circulation. This is also emphasized by the development of another cyclonic circulation near lat. 8° N., long. 91° W., where parts of the Countercurrent turn north and west into the North Equatorial Current (fig. 6). This cyclonic circulation is probably the start to re-establish the old circulation after the separated eddy in the northeast has decayed and disappeared.

UPWELLING

The structure of the thermocline, which comes to within a few meters of the sea surface, the lowered surface temperature, and the higher salinity and phosphate content are clear indications of upwelling in the Costa Rica Dome. The ascending movements bring water out of the range of the thermocline into the thin suface layer in

716-687 O—64——8

which it is removed horizontally. This continuous addition of cooler water from beneath requires that the ascending water be heated in order to maintain the temperature in the surface layer. The fact that the top of the thermocline does not reach to the surface but is, perhaps with occasional local exceptions, always covered by a thin surface layer demonstrates that the circulation in the dome area is in thermal balance and, therefore, the maximal possible ascending velocity is limited by the amount of energy available for the heating of the surface layer. In order to determine this maximal upwelling velocity a few calculations of the heat balance of the dome will be made in the following.

For the purpose of the calculations the dome will be considered as circular with the radius r. There will be a homogeneous surface layer of thickness D with the temperature T_0 (fig. 9). Underneath this surface layer is the thermocline; and within this thermocline a constant ascending velocity w is assumed. The ascending water is assumed to come from the layer immediately beneath the thermocline out of a depth between 75 and 200 m. where the temperature is between 12° and 14° C. and the temperature gradient considerably weaker (figs. 1 and 3). This layer is assumed to form the reservoir for the ascending water, and its temperature is T_D. The water entering the surface layer from beneath is thought to flow horizontally away within the surface layer with the velocity u. The thermocline is assumed to be without horizontal motion. The water balance is then given by

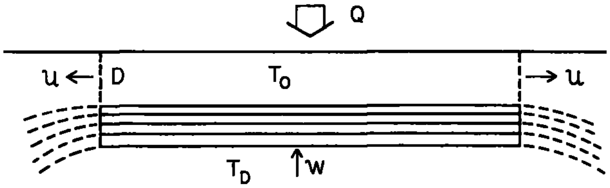

FIGURE 9.—Notations used for the calculation of the heat balance of the Costa Rica Dome.

$$2r\pi Du = r^2\pi w \qquad (1)$$

and the heat balance by

$$2r\pi DuT_0 = r^2\pi wT_D + r^2\pi\,\frac{Q}{\rho c} \qquad (2)$$

where Q is the energy available for heating of the surface layer, ρ is the density, and c the specific heat of sea water. The energy available for heating the surface layer of the ocean results chiefly from the difference between incoming and outgoing radiation less the energy used for evaporation. Budyko (1956) has charted these quantities for the entire earth, and, according to his maps, about 110 cal.cm.$^{-2}$ day^{-1} are available for the heating of the surface layer in the region of the Costa Rica Dome. Because the annual variations in the terms of the heat balance in this area are small, it is satisfactory to use the estimate by Budyko for the period of the Costa Rica Dome cruise.

Combining equations (1) and (2) gives the simple relation

$$w(T_o - T_D) = \frac{Q}{\rho c} \qquad (3)$$

which is independent of the size r of the area. With $Q = 1.27 \times 10^{-3}$ cal. cm.$^{-2}$ sec.$^{-1}$, $T_o = 25°$ C. and $T_D = 13°$ C. the ascending velocity within the thermocline is $w = 10^{-4}$ cm./sec. which is equal to 8.6 cm./day or 2.6 m./month. A velocity of this order will not disturb the temperature structure in the dome but will maintain it. A much greater velocity will be needed if "outcropping" of the thermocline should occur, but this seems to be the exception in the Costa Rica Dome. The vertical velocity calculated above, however, represents an average value for the entire area and locally higher or lower values are possible. Also the vertical velocity does not give any information about the structure of upwelling, and it is not unlikely that the actual upwelling occurs in smaller patches, in which temperature anomalies disappear rapidly as a result of horizontal mixing.

The horizontal velocity at the periphery of the dome is given by $u = \frac{rw}{2D}$ and with a radius $r = 1.5 \times 10^7$ cm. $=$ 150 km. the velocity is $u = 0.38$ cm./sec. The total amount of upwelling in the dome is given by $T = wr^2\pi = 7 \times 10^{10}$ cm.^{3}/sec. This is less than a tenth of a million $m.^3$/sec. and very small compared with the strength of the horizontal circulation.

Knowledge of the approximate value of the vertical velocity within the thermocline allows the calculation of the vertical exchange coefficient A within this strong tropical thermocline. The equation of the vertical diffusion of heat is given by

$$\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(wT-A\frac{\partial T}{\partial z}\right). \tag{4}$$

If the thermocline is considered to be stationary $\left(\frac{\partial T}{\partial t}=0\right)$, the advection of cooler water from below must be compensated by a turbulent flow of heat from above. Taking w and A as a constant within the thermocline, equation (4) can easily be integrated

$$T=T_D+(T_o-T_D)e^{\frac{w}{A}z} \tag{5}$$

where z has its origin at the top of the thermocline and is positive upwards. Taking $T_o=25°$ C., $T_D=13°$ C. and a temperature $T=15°$ C. at 25 m. below the top of the thermocline, as is observed, a value $w/A=7.2\times10^{-4}$ cm.$^{-1}$ results. With $w=10^{-4}$ cm./sec. it follows that $A=0.14$ cm.^{2} sec.$^{-1}$. This value is reasonably close to that calculated by Montgomery (1939), who finds a maximal value of $A=0.4$ cm.^{2} sec.$^{-1}$ for the equatorial Atlantic Ocean.

The downward flow of heat Q_v is given by

$$Q_v=\rho cA\frac{\partial T}{\partial z}=\rho c(T_o-T_D)we^{\frac{w}{A}z} \tag{6}$$

and decreases exponentially with depth. At the top of the thermocline ($z=0$) this flow is given by

$$\rho cA\left(\frac{\partial T}{\partial z}\right)_0=\rho c(T_o-T_D)w=Q$$

being the same equation as (3), which was derived from considerations of the heat balance of the entire dome, and shows that all the heat available in the surface layer diffuses down and that the heating of the ascending water takes place within the thermocline. At 25 m. below the top of the thermocline this vertical flow of heat has decreased to 0.2×10^{-3} cal. cm.$^{-2}$ sec.$^{-1}$. Consequently, it can be stated that in areas with no upwelling, where such a downward flow of heat will not be opposed by ascending cooler water, either the layers below the thermocline will be heated, or, more likely, the thermocline will descend with time, as is usual in higher latitudes with summer heating.

With the application of these calculations, it follows from the observed temperative distribution that the upwelling in the Costa Rica Dome, at least in the climatological average, is in thermal balance. This thermal balance limits the average ascending velocity to approximately 10^{-4} cm./sec. The amount of upwelling is of the order of 7×10^{10} cm.^{3}/sec. The ascending water is supplied from a layer immediately beneath the strong thermocline. The lower values of salinity in the salinity maximum, discussed in the section on "Hydrographic structure", indicate that water from these depths is ascending. All these results show that the Costa Rica Dome is a very shallow feature and must be closely related to and caused by the surface circulation. This is also strongly suggested by the fact that the circulation is appreciably different at the surface and below 50 m. depth as shown in the section on "Horizontal circulation".

The balance equations for phosphate can be studied now that the vertical circulation has been estimated from the heat balance equation. This is done by replacing the temperature in equation (3) with phosphate concentration, and the right-hand side then becomes the phosphate consumption

$$w(P_D-P_o)=X$$

Taking $P_D=2.3$ µg.-atom/L. for the water ascending from the layer between 50 and 200 m. depth, $P_o=0.5$ µg.-atom/L. for the water flowing horizontally away from the dome, and $w=10^{-4}$ cm./sec. as calculated from the heat balance, the phosphate consumption becomes $X=155$ µg.-atom/m.^{2}/day. When this figure is converted into weight and a relation $P:C=1:41$ is used the phosphate consumption is equivalent to 196.8 mg. C/m.^{2}/day. Measurements of *in situ* organic production in the Costa Rica Dome give values between 160 and 440 mg. C/m.^{2}/day (Holmes, personal communication), which agree very well with the calculated value of phosphate supply to the surface layer.

As the upwelling in the Costa Rica Dome has been found to be a very shallow process, its dynamics must be closely related to the circulation in the surface layer. This upwelling is situated at the northern flank of the Countercurrent in a position where this current turns sharply to the north. It will be assumed that the Countercurrent is in geostrophic balance when it approaches the area from the west. When turning to the north, the current has to attain a different balance and it will be shown that the necessary adjustment results in upwelling along the left flank of the turning current.

Winds in this area are irregular and weak, and wind charts do not indicate a permanent feature in the wind field, with the overall dimensions of the Costa Rica Dome, that could locally be important for maintaining the upwelling in the dome. Therefore, an effect of the local wind on the circulation and the upwelling in the dome will not be considered in the following discussion.

To describe the motion, natural co-ordinates (s, n) will be used, ds being tangential, dn normal to a trajectory. V is the velocity along the trajectory, which in the stationary case is also a streamline. The equations of a stationary motion in this system are

$$V\frac{\partial V}{\partial s}=-\frac{1}{\rho}\frac{\partial p}{\partial s} \qquad (7)$$

$$KV^2+fV=-\frac{1}{\rho}\frac{\partial p}{\partial n} \qquad (8)$$

where f is the coriolis parameter depending on the latitude, p the pressure and ρ the density. $K=\frac{1}{R}$ is the curvature of the trajectory, R the radius of curvature, both are functions of s.

It will be assumed that the current, represented by its isobars, enters the area from the west, as shown in figure 10. At point N the current may gradually start to turn north and reach its strongest curvature at point M. West of point N the curvature of the current is zero, $K=0$, and its velocity is given by

$$fV=-\frac{1}{\rho}\frac{\partial p}{\partial n}=f_oV_g$$

as follows from (8). V_g is the geostrophic velocity and f_o the value of the Coriolis parameter at the latitude of the Countercurrent. At point M the trajectory may have a radius of curvature $R=120$ km., as can be seen from figure 6A. It will be assumed that the normal pressure gradient remains constant along the trajectory, $-\frac{1}{\rho}\frac{\partial p}{\partial n}=f_oV_g$. With this assumption equation (8) becomes

$$KV^2+fV=f_oV_g$$

With $1/K=120$ km., $f=2.15\times10^{-5}$ sec.$^{-1}$ at latitude 8.5°, $f_o=1.65\times10^{-5}$ sec.$^{-1}$ at latitude 6.5°, and a geostrophic velocity $V_g=55$ cm./sec., it follows that $V=37$ cm./sec. at point M. This shows that the velocity decreases along the trajectory from 55 cm./sec. at point N to 37 cm./sec. at point M. The length of the trajectory between points N and M is approximately 450 km., thus the value of $\frac{\partial V}{\partial s}$ in equation (7) can be calculated. It follows that $\frac{1}{\rho}\frac{\partial p}{\partial s}=1.8\times10^{-5}$ cm. sec.$^{-2}$. Expressed in terms of dynamic topography, this means that the particle arrived at point M at a value 0.83 dynamic cm. higher than when it left point N, compared with a total difference of about 14 dynamic cm. across the current. The trajectory crosses the isobars at a very small angle, which is given by $tg\alpha=\frac{\partial p}{\partial s}\Big/\frac{\partial p}{\partial n}$. With $\frac{1}{\rho}\frac{\partial p}{\partial n}=90.7\times10^{-5}$ cm. sec.$^{-2}$ it follows that $\alpha=1.1°$.

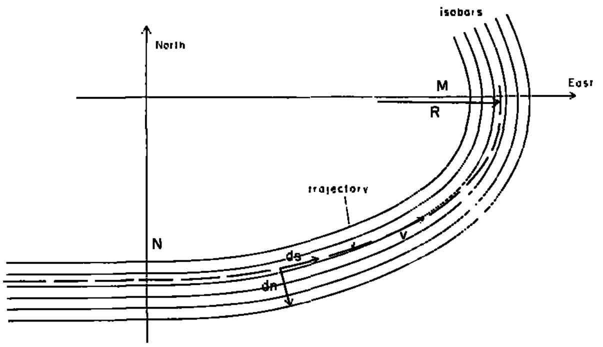

Figure 10.—Diagram showing schematically the isobars of a current flowing east and turning north. (The broken line is a trajectory, cutting the isobars under a small angle, R is the radius of curvature.)

Because the trajectories cut the isobars, the velocity V along the trajectory can be split into one component v parallel to the isobars and another component u normal to the isobars. The angle between the two sets of curves is so small that v will be almost as big as V, while u can be calculated from the relation $u/v=\frac{\partial p}{\partial s}\Big/\frac{\partial p}{\partial n}$, giving $u=0.92$ cm./sec. Over a distance of 450 km. and a depth of 20 m. this velocity normal to the isobars causes a transport of 8.3×10^{10} cm.^{3}/sec. across the isobars from the left side of the current to its right side. This calculation of the cross isobar transport compares very well with the figure of 7×10^{10} cm.^{3}/sec. calculated for the amount of upwelling from the thermal balance of the dome. Consequently, I conclude that the upwelling in the Costa Rica Dome is an effect of the northward turning of parts of the Countercurrent. The cross isobar circulation associated with such a turning current causes the upwelling, which is situated along the left flank of this cyclonic flow. This upwelling is, however, especially effective in the Costa Rica Dome, because the thermocline along the left flank of the Countercurrent is already in a shallow position before the current starts turning. As a consequence of this, an intense enrichment of the thin surface layer with nutrients is possible in the Costa Rica Dome.

In order to conserve the mass transport of the current, the product *V D*, where *D* is the depth of the current, must remain constant along a trajectory. This increase in the depth of the current in the direction of its flow is well documented in figure 7, where its depths increase progressively as the current proceeds from section *A* to sections *B* and *C*. The difference of dynamic height across the current remains unchanged during its progress, while the surface velocity decreases and the depth of the current increases. Thus the transport across the isobars can be interpreted as upwelling on the left flank of the current and sinking on its right flank.

PERMANENCE OF THE COSTA RICA DOME

The above discussions of the structure of the dome and its circulation have been based chiefly on one survey, but it is worthwhile to investigate whether or not the Costa Rica Dome is a permanent feature of the circulation and how far it is subject to seasonal variations. So far eight expeditions (table 1) have crossed or touched the area of the Costa Rica Dome, and all of them have found the dome in approximately the same position. As the dome is characterized by an extremely high position of the thermocline, the depth of the 19° C. isotherm, which coincides approximately with the center of the thermocline, is charted for six of the expeditions in figure 11. On the eighth crossing of the dome in February 1960 only BT observations were taken (fig. 1). During all these expeditions the 19° C. isotherm was found to be in less than 20 m. depth in the dome area. Along the periphery of the dome it was always below 40 m. Because some of the expeditions did only touch the dome or may not have crossed through its center, the size of the dome cannot be determined. The position of the dome during the different expeditions is given in table 1 and it can be seen that the dome maintains its position within 2° of latitude and longitude. It is situated between lat. 8° and 10° N. and between long. 88° and 90° W. Although the position of the dome was approximately the same during all these surveys, the circulation around the dome seems to have been considerably different, as indicated by the topographies of the 19° C. isotherm.

TABLE 1.—*Positions of the Costa Rica Dome on different expeditions*

Expedition	Date	Position of the dome		Reference for data
		Latitude °N.	Longitude °W	
Shuttle	May 1952	9.5	90	Unpublished.[1]
Shellback	July–Aug. 1952.	9	88	Unpublished.[1]
Eastropic	Oct.–Nov. 1955.	9	89.5	Scripps Institution of Oceanography, 1956.
Scope	Nov.–Dec. 1956.	8.5	89	Holmes and others, 1958.
Scot	May 1958	10	89	Holmes and Blackburn, 1960.
TO–59–1	Feb. 1959	9	89	Blackburn and others, 1962.
Costa Rica Dome.	Nov.–Dec. 1959.	8	88	Scripps Institution of Oceanography, 1960.
Explorer	Feb. 1960	9	89	Stewart, 1962.

[1] Data available at Scripps Institution of Oceanography, and will be included in Oceanic observations of the Pacific, 1952, to be published by the University of California Press.

Six of these expeditions, made between 1952 and 1959, cover the months between May and December; during this period the Countercurrent is always present. During February and especially in March, the Countercurrent is absent in this area and the cyclonic circulation is only weakly developed, as indicated in the surface charts by Cromwell and Bennett (1959). Thus, it might be possible that the dome would not be developed during this period. In February 1959 the area of the dome was crossed on expedition TO–59–1, and in February 1960 it was crossed by the vessel *Explorer*. On both crossings the dome was found to be in about the same position as during the other expeditions, and the 19° C. isotherm was well above 20 m. depth, as can be seen from the BT section taken by the *Explorer* (fig. 1). It is, however, not known whether or not the Countercurrent was developed during these times, or whether the Costa Rica Dome is persistent enough to remain for an appreciable time during the period in which the Countercurrent is not indicated in the surface current observations.

From the comparison of the results of these eight expeditions it can be concluded that the

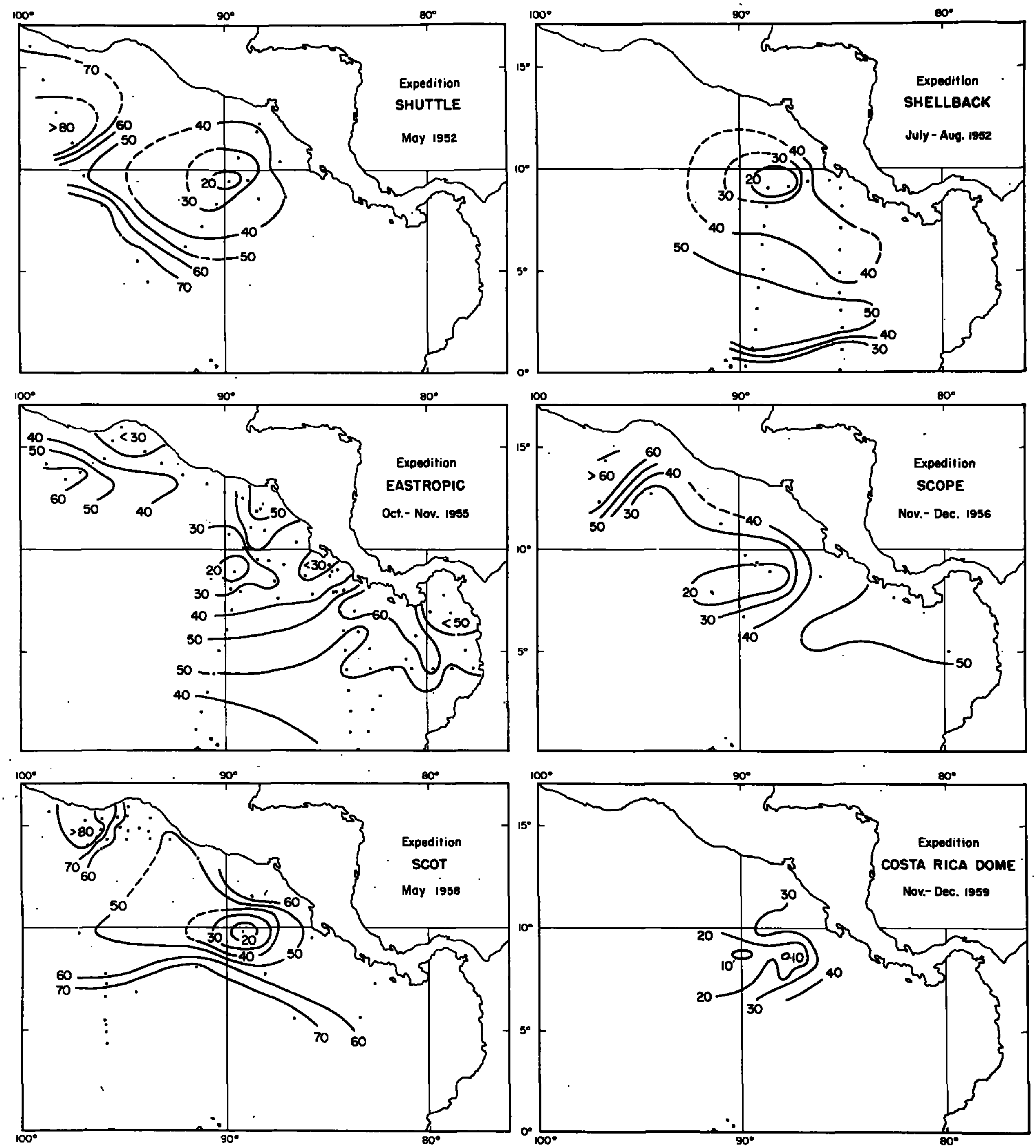

FIGURE 11.—Topography of the 19° C. isotherm in meters during six expeditions in the area of the Costa Rica Dome and its vicinity.

Costa Rica Dome is a permanent feature of the thermocline topography in the eastern tropical Pacific Ocean and that it varies very little in its position. A comprehensive survey of the Costa Rica Dome in February and March would be desirable to confirm the existence of the dome during these months and to determine the character of the associated circulation.

CONCLUSIONS

The analysis of the hydrographic structure of the Costa Rica Dome and of its circulation, based on the Costa Rica Dome cruise and the comparison with seven less complete surveys, leads to the following conclusions:

1. The Costa Rica Dome is a more or less circular area where the thermocline is extremely high and extremely sharp and where the top of the thermocline reaches to within a few meters of the sea surface. This area, about 200 km. in diameter, is characterized by slightly lower surface temperatures, higher salinity and phosphate contents, and reduced percentage of oxygen saturation. The average position of the dome is lat. 9° N., long. 89° W., and the fluctuations of the center of the dome are within ±1° of latitude and longitude, as a comparison of eight surveys demonstrates. Thus, the Costa Rica Dome is a permanent feature of the circulation in the eastern tropical Pacific Ocean.

2. The circulation around the dome is determined by the Equatorial Countercurrent in the south, the Costa Rica Coastal Current in the east, and parts of the North Equatorial Current in the north. Off the coast of Costa Rica these currents form a cyclonic circulation in the center of which the dome is situated. The Costa Rica Dome is the very pronounced eastern end of a ridge in the topography of the thermocline extending along the northern boundary of the Countercurrent. From the cyclonic circulation around the dome large eddies seem to separate and to contribute to large-scale mixing. One of them was observed during the Costa Rica Dome survey transporting 20 million m.^{3}/sec.

3. The northward turning of the Countercurrent requires an adjustment of its velocity distribution and causes a cross-circulation which produces upwelling in the dome. The upwelling in the dome must be in thermal balance which limits the average ascending velocity to 10^{-4} cm./sec. The total contribution of the upwelling is only 7×10^{10} cm.^{3}/sec., and the ascending water comes from layers immediately beneath the strong thermocline out of 75–200 m. depth where the temperature is 12°–14° C.

4. The upwelling in the Costa Rica Dome is a shallow process restricted to the surface layer and the thermocline. The amount of upwelling is very small because the intensity is less and the area much smaller than, for instance, that off the coast of Peru (Wyrtki, 1963). However, the effect of this upwelling on the enrichment of the surface layer in the Costa Rica Dome is considerable because of the much higher initial position of the thermocline and of the abundance of nutrient rich water immediately beneath the thin surface layer.

LITERATURE CITED

BLACKBURN, MAURICE, RAYMOND C. GRIFFITHS, ROBERT W. HOLMES, AND WILLIAM H. THOMAS.
1962. Physical, chemical, and biological observations in the eastern tropical Pacific Ocean: three cruises to the Gulf of Tehuantepec, 1958–59. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 420, 170 pp.

BRANDHORST, WILHELM.
1958. Thermocline topography, zooplankton standing crop, and mechanisms of fertilization in the eastern tropical Pacific. Conseil Permanent International pour l'Exploration de la Mer, Journal du Conseil, vol. 24, No. 1, pp. 16–31.

BUDYKO, M. I.
1956. The heat balance of the earth's surface. Leningrad, 255 pp. Translated by U.S. Department of Commerce, Weather Bureau, 1958.

CROMWELL, TOWNSEND.
1958. Thermocline topography, horizontal currents and "ridging" in the eastern tropical Pacific. Inter-American Tropical Tuna Commission Bulletin, vol. 3, No. 3, pp. 135–164.

CROMWELL, TOWNSEND, AND EDWARD B. BENNETT.
1959. Surface drift charts for the eastern tropical Pacific Ocean. Inter-American Tropical Tuna Commission Bulletin, vol. 3, No. 5, pp. 217–237.

FUGLISTER, FREDERICK C., AND L. V. WORTHINGTON.
1951. Some results of a multiple ship survey of the Gulf Stream. Tellus, vol. 3, No. 1, pp. 1–14.

HOLMES, ROBERT W., AND OTHERS.
1958. Physical, chemical, and biological oceanographic observations obtained on Expedition Scope in the eastern tropical Pacific, November-December 1956. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 279, 117 pp.

HOLMES, ROBERT W., AND MAURICE BLACKBURN.
1960. Physical, chemical, and biological observations in the eastern tropical Pacific Ocean: Scot Expedition, April–June 1958. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 345, 106 pp.

KNAUSS, JOHN A.
1961. The structure of the Pacific Equatorial Countercurrent. Journal of Geophysical Research, vol. 66, No. 1, pp. 143–155.

MONTGOMERY, RAYMOND B.
1939. Ein Versuch, den vertikalen und seitlichen Austausch in der Tiefe der Sprungschicht im äquatorialen Atlantischen Ozean zu bestimmen. Annalen der Hydrographie und Maritimen Meteorologie, Band 67, pp. 242–246.

REID, JOSEPH L., JR.
1962. On circulation, phosphate-phosphorus content. and zooplankton volumes in the upper part of the Pacific Ocean. Limnology and Oceanography, vol. 7, No. 3, pp. 287–306.

SCRIPPS INSTITUTION OF OCEANOGRAPHY.
1956. Data collected by Scripps Institution vessels on Eastropic Expedition. SIO Reference Report 56–28, 156 pp. (mimeo.)

SCRIPPS INSTITUTION OF OCEANOGRAPHY.
1960. Physical, chemical and biological data Costa Rica Dome cruise. SIO Reference Report 60–20 33 pp. (mimeo.)

STEWART, HARRIS B., JR.
1962. Oceanographic cruise report, USC & GS Ship Explorer—1960. U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D.C. 162 pp.

WYRTKI, KLAUS.
1963. The horizontal and vertical field of motion in the Peru Current. Bulletin of the Scripps Institution of Oceanography, vol. 8, No. 4, pp. 313–346.