Equatorial Front in the Eastern Pacific Ocean

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ABSTRACT

The equatorial front in the eastern Pacific Ocean observed during 14 October–7 December, 1971, from R/V \textit{Yaguina} of Oregon State University is discussed. The front is clearly defined at the sea surface by a large horizontal gradient of temperature, salinity, $\sigma_t$ and nitrate. Equatorial upwelling, which is believed to be driven by the prevailing wind and the Equatorial Undercurrent, appears as the primary source of the cold water on the south side of the front in the region west of the Galapagos Islands. In vertical distributions of various properties of the water across the equator, equatorial upwelling is apparent over the equator in the region between the Galapagos Islands and the Ecuadorean coast. It is suggested that the equatorial front in this region is also associated with the equatorial upwelling.

1. Introduction

In the Pacific between the equator and 5S and between the coast of Ecuador and the Galapagos Islands, the large-scale surface circulation is from the southeast most of the year (Wyrtki, 1965). Here the Peru Current merges into the South Equatorial Current. The water of the Peru Current is characterized by low temperature and high salinity ($T<21^\circ\text{C}$, $S>34.5\%$ in October–December, 1971) presumably because of its association with coastal upwelling along the Peruvian Coast.

Between approximately 2N and 10N the surface circulation is subject to considerable seasonal variations which are associated with seasonal fluctuation of the northern boundary of the Peru Current and with seasonal variations of the North Equatorial Countercurrent and the North Equatorial Current. All these variations are believed to be related to prevailing wind conditions. The surface water in the same region is characterized by high temperature and low salinity ($T>23^\circ\text{C}$, $S<33.5\%$ in October–December, 1971) due to an excess of rainfall over evaporation. The boundary between these two distinct water masses is called the equatorial front.

The equatorial front has been described, among others, by Wyrtki (1966), Wooster (1969) and Stevenson \textit{et al.} (1970). According to Wooster (1969): 1) the equatorial front is a shallow feature confined to the upper 100 meters; 2) it is a permanent feature; 3) the location of the front varies seasonally, the prevailing wind being probably the controlling factor; 4) the front is oriented zonally (west-east) between the Galapagos and 84W, and approximately meridionally (northwest-southeast) east of 83W; and 5) the temperature gradients across the front decrease from east to west and tend to be larger during the Southern Hemisphere winter than during the summer.

These characteristic features and their seasonal variations are believed to be related to atmospheric circulation and the dynamic conditions of equatorial ocean circulation in the region. In addition to the above physical considerations, the biological environments are quite distinct between the two water masses. Thus, the front has important biological implications as well. For example, El Niño is associated with abnormal southward displacement of the equatorial front.

In this paper, the equatorial front, as observed during the Yaloc-71 cruise, is discussed and a possible process is proposed for the generation of such an intense front.

2. Observations of the front

During the Yaloc-71 Cruise, R/V \textit{Yaguina} of the School of Oceanography of Oregon State University occupied 152 hydrographic stations between 14 October and 7 December, 1971, at the locations shown in Fig. 1. At each station, a standard hydrocast was made using plastic NIO bottles with reversing thermometers. The sampling depths were 0, 25, 50, 75, 100, 125, 150, 200, 250, 300, 450, 500 and 600 m. The water samples were analyzed for salinity, oxygen concentration, light scattering, particle-size distribution, and nutrient concentrations (silicate, phosphate, nitrate and nitrite). Light scattering was measured with a Brice-Phoenix light scattering photometer (Spilhaus, 1965), particle-size distribution was determined with a Coulter Counter equipped with a 100-μm aperture (Carter, 1970; Sheldon and Parsons, 1967), and nutrients were measured with an Autoanalyzer.
Results of the observations are presented in order of front at the sea surface, front below the surface, location and shape of the front, and suspended matter.

a. Front at the sea surface

The equatorial front at the sea surface is clearly indicated in Fig. 2 by large gradients of temperature, salinity, density and nitrate. The maximum horizontal gradients across the front averaged over the station spacing are given in Table 1 for four meridians: 92W, 90W, 88°15'W and 85°30'W. The gradients are largest at 92W and smallest at 90W. Wooster (1969) and Stevenson et al. (1970) reported that the gradient is largest near the Peruvian coast and decreases toward the west. Although our measurements are consistent with these observations from the Ecuadorian coast as far west as the Galapagos Islands, the zonal variation of the gradient is rather small. It is quite clear, however, that the gradients are small on the east side of the Galapagos Islands. Increased mixing from the interaction in this region between the Equatorial Undercurrent and the Galapagos Islands as reported by Knauss (1966), White (1969) and Pak and Zaneveld (1973) could have reduced the gradient. Such interaction produces mixing in a form of lee eddies which reduce the gradient over the extent of the eddies. Our observations of horizontal gradients normal to the front agree closely with the values given by Wooster (1969). Maximum gradients are observed at 93W, on the west side of Isabela Island (the largest island of the Galapagos Islands). Since the maximum gradient is observed at 93W the interaction in the surface layer between the westbound South Equatorial Current and the Galapagos Islands may not be as effective in producing mixing and in destroying the gradient as is the interaction between the Undercurrent and the islands on the east side of the islands.

The cold and saline water on the southern side of the front is also characterized by a high concentration of nutrients. A large horizontal gradient in nitrate distribution across the front is shown in Fig. 2. Distribu-
tions of the other nutrients are not shown here, but they possess similar features. The high concentration of nutrients in the water south of the front suggests that this water may be associated with the equatorial upwelling or with water upwelled along the coast of Peru.

b. Front below the surface

In Figs. 3 and 4, temperature and salinity distributions in the meridional sections at 90°W and 88°15’W are shown. The vertical variation in the positions of the thermocline layer is evident in the figures, and the surface front is shown as the intersection of the isotherms and the sea surface. The topography of the thermocline layer is also shown by horizontal distribution of temperature, salinity, and concentrations of oxygen and nitrate in 25 m depth in Fig. 5. The topography of the thermocline layer shows two regions of low temperature separated by a high temperature zone. The two low temperature zones are related to the separate ridges in the thermocline layer in Fig. 4, and are interpreted by the splitting of the Undercurrent due to blocking of the current by the Galapagos Islands (Pak and Zaneveld, 1973).

From temperature distributions in the two meridi-

Table 1. Horizontal gradients of temperature, salinity, $\sigma_t$ and nitrate across the front in the four meridional sections, at the surface and at a depth of 25 m.*

<table>
<thead>
<tr>
<th>Surface Om</th>
<th>92°00’W</th>
<th>90°00’W</th>
<th>88°15’W</th>
<th>85°30’W</th>
<th>92°00’W</th>
<th>90°00’N</th>
<th>88°15’W</th>
<th>85°30’W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (°C ml⁻¹)</td>
<td>.17</td>
<td>.042</td>
<td>.057</td>
<td>.057</td>
<td>.234</td>
<td>.113</td>
<td>.163</td>
<td>.083</td>
</tr>
<tr>
<td>$S$ (% ml⁻¹)</td>
<td>.041</td>
<td>.0093</td>
<td>.026</td>
<td>.026</td>
<td>.039</td>
<td>.021</td>
<td>.028</td>
<td>.011</td>
</tr>
<tr>
<td>$\sigma_t$ (ml⁻¹)</td>
<td>.086</td>
<td>.033</td>
<td>.035</td>
<td>.035</td>
<td>.109</td>
<td>.054</td>
<td>.073</td>
<td>.035</td>
</tr>
<tr>
<td>$N_{NO}_2$ (μg liter⁻¹ ml⁻¹)</td>
<td>.353</td>
<td>.089</td>
<td>.097</td>
<td>.093</td>
<td>.459</td>
<td>.341</td>
<td>.379</td>
<td>.190</td>
</tr>
</tbody>
</table>

* The gradients are mean values over one frontal zone since they are reduced to per mile from the original values measured from stations 15 or 30 ml apart.
** There are two fronts at this longitude.
onal sections shown in Figs. 3 and 4, we find that the maximum horizontal temperature gradient is located at about 25 m depth rather than at the sea surface. This may be explained by a strong mixing induced by wind stress at the sea surface which reduced the temperature gradient at the sea surface. The maximum horizontal temperature gradient observed is 0.52°C m⁻¹ at 25 m depth on 93W, the westernmost section of our observations.

c. Suspended matter

The concentration of suspended particles ranging in diameter from 2.2 to 10.2 µm were measured by a Coulter Counter equipped with a 100-µm aperture. Size distributions of suspended particles have been shown to be approximately exponential (Carder, 1970). Our observed data, in the diameter range of 2.2 to 10.2 µm, were fitted with an exponential distribution and the
total particle volume concentration calculated by integrating the exponential distribution. Distribution of the volume concentration of suspended particles at the sea surface is presented in Fig. 6a. We can identify a band of maximum particle concentration along the frontal zone.

Light scattering at a 45° angle from the incident light beam at a wavelength of 436 nm was measured with a Brice-Phoenix light scattering photometer. These measurements are used to calculate the volume scattering function at 45°, $\beta(45)$ [m sr]$^{-1}$, a parameter related to the concentration of suspended particles (Beardsley et al., 1970; Jerlov, 1968), which is determined by an entirely independent method from the volume concentration of suspended particles. Fig. 6b, indicates maximum values of $\beta(45)$ along the frontal zone.

In a cumulative particle size distribution given by $g(D) = No^{-A}$, where $N$ is the total number of the particles, $D$ particle diameter, and $A$ the parameter which determines the slope of the distribution. $A$ is inversely related to the mean particle size. The distribution of $A$ at the sea surface (Fig. 7) reveals a band of minimum $A$ and thus a band of maximum mean size of the suspended particles along the frontal zone.

The frontal zone is the band along the maximum horizontal gradients in temperature, salinity $\sigma_t$ and nitrate (Fig. 2). Width of the frontal zone is variable from one place to another, but it is approximately 60 km.

3. Frontogenesis

The equatorial front has been described by Wyrtki (1966), Wooster (1969) and Stevenson et al. (1970), among others, as a permanent front, which extends from the coast of Peru toward the Galapagos Islands and separates the cold, saline waters of the Peru Current from the warm and fresher tropical waters lying to the north. In light of more recent observations, it appears that the front may be better understood by studying the processes of generation and intensification from detailed frontal structures.

A band of low temperature over the equator extending from the South American continent to about 180W shows remarkable contrasts with adjacent waters on both northern and southern sides in every sea surface temperature map of the equatorial Pacific Ocean (Svendrup et al., 1946; Bennett, 1963; Reid, 1969; Love,
Such a cool band strongly suggests upwelling along the equator. Rotshi (1970) reported observations of equatorial upwelling across the equator along 170E, in eight out of ten crossings from October 1963 to May 1968. The Peru current has been considered as a partial source of the cool band (Austin, 1960; Wyrzki, 1966). Wyrzki called it equatorial surface water, and suggested that its properties are determined by seasonal advection of cooler water from the Peru Current and equatorial upwelling. Cromwell (1953), on the other hand, suggested that the cold band is associated with a continuous renewal from below in order to explain the high concentration of inorganic phosphate. Bjerknes (1961) also treated the two sources of cold water separately in his El Niño study. Thus, it becomes clear that the cold water derived from equatorial upwelling is a part of the equatorial front system.

Equatorial upwelling is associated with two independent processes, longitudinal divergence of the surface layer on or near the equator (depending on the wind direction) induced by the southeast trade, and vertical mixing by the Equatorial Undercurrent.

**a. Cromwell's model**

Cromwell (1953) presented a qualitative discussion of equatorial upwelling resulting from a meridional divergence under the southeast trade wind. Since the deflecting force vanishes at the equator, the direction of the Ekman transport, under a constant southerly wind, changes from westward to northward, and finally to eastward as one moves northward across the equator. Thus, meridional divergence occurs over the equator (or south of the equator) and meridional convergence occurs a few degrees to the north of the equator. Cromwell places the equatorial front at the convergence zone.

Cromwell's model may be oversimplified, especially since the pressure gradient is not considered in the model. Nevertheless it does show that meridional divergence may occur on or near the equator and convergence on the north side of the divergence zone under a southeast or south wind. The upwelled cold water is transported toward the north by the wind and tends to sink along its $\sigma_T$ surface. A frontal zone, which separates the upwelled cold water from the warm surface water on the north, is formed along the convergence zone (the zone of active sinking of the cold water). The wind-driven divergence-convergence is related to the equator, and if the wind tends to be persistent (southeast trade), the front will accordingly persist.

**b. The Equatorial Undercurrent**

While we do not know all the features of the Equatorial Undercurrent, especially its temporal and spatial variations, we noticed an important relation between the equatorial upwelling and the Undercurrent: the equatorial upwelling seems to be in most cases associated with the Equatorial Undercurrent. Many investigators have described such phenomena (Cromwell et al., 1954; Austin, 1960; Montgomery and Stroup, 1962; Wyrzki, 1966; Knauss, 1960, 1966; Pak and Zaneveld, 1973).
Fig. 8. A simple frontogenesis model in a meridional section across the equator showing effects of the Equatorial Undercurrent by isotherms with dashed lines.

A simple model of a meridional section illustrating the effects of the Undercurrent in generating a sharp temperature gradient in the surface layer, a front, is presented in Fig. 8. Undisturbed ocean is indicated by solid isotherms with the thermocline located at about 50 m depth. A slight meridional temperature gradient is assumed in the surface layer above the thermocline to account for the sources of the warm water on the north side and cold water from the Peru Current on the south side, although this gradient is not essential in the model. The Undercurrent is introduced into the undisturbed ocean and its upwelling effects are shown by the dotted curves. The upwelling effectively brings up cold water into the sea surface so that upper parts of the thermocline reach the sea surface. A front is formed accordingly. The temperature gradient in the surface layer of the undisturbed ocean results in a larger temperature gradient at the front on the northern side of the upwelling ridge as compared to the southern side.

We are convinced that equatorial upwelling occurs on the west side of the Galapagos Islands and the band of cold water along the equator is mostly derived from the equatorial upwelling. The equatorial front separates this cold water from the tropical surface water on the north side.

c. The equatorial front on the east side of the Galapagos Islands

Evidence of extension of the Equatorial Undercurrent to the east side of the Galapagos Islands was reported by several investigators: Knauss (1966) through direct current measurements; White (1969) through acceleration potential and thermostad distribution; Stevenson and Taft (1971) by a drogue trace at the salinity maximum relative to a reference drogue deployed at 320 m depth; Pak and Zaneveld (1973) by distribution of properties of water. Vertical distributions of temperature, salinity (Figs. 3 and 4) and nitrate and oxygen (Fig. 9) reveal several characteristic features of the Undercurrent: ridges and troughs in isopleths of temperature, salinity, nitrate and oxygen; salinity maxima under the thermocline ridges; and a thick layer of 13C water. Except for the ridges at the thermocline the characteristic features listed above are present in deep water, in the layer approximately from 50 to 250 m depths. Equatorial upwelling is apparent by the ridges in the thermocline layer. Similar forms of isotherm ridges are also found in the Eastpacific Atlas (Figs. 14-T-v24, 14-T-v26 in Vol. 1; Figs. 14-T-v8, 14-T-v10 in Vol. 5).

Fig. 9. Vertical distributions of oxygen and nitrate in the meridional section at 88°–15°W.
Stevenson and Taft (1971) presented convincing evidence of the equatorial front's association with the high-salinity core and the high salinity core's association with the Undercurrent. Although there is some doubt whether the high-salinity core is associated with the core of the Undercurrent because of the strong mixing as Wyrtki (1966) suggested, the high-salinity core under the front may still be in the Undercurrent. Such association between the equatorial front and the Undercurrent strongly supports the relationship of the cold water on the south side of the front to equatorial upwelling. Similar evidence was also observed by Enfield (personal communication, 1973) during 29 August–11 September, 1973: “We made five crossings of the equatorial front between 85W and the coast with hydrocasts (500 m) every 20–30 mi and BT’s every 10–15 mi... The subsurface salinity maximum (about 75 m) associated with the Undercurrent always manifested itself beneath the front in some way...”

If the Peru Current transports coastal upwelled water to the equatorial front, contribution of this water to the front will be greatest in the region east of the Galapagos Islands. We would like to have quantitative estimates of the two separate contributions of cold water, Peru Current and equatorial upwelling, but they are not available at this time. Little is known about the seasonal fluctuations of the Equatorial Undercurrent. According to Wyrtki (1974), the Undercurrent may be strong in March–May and weak in October–December. Observations of the Undercurrent in this region have been made during the time when the Undercurrent is hypothesized to be weak. Knauss (1966) observed during September–December, 1961, Stevenson and Taft (1972) in June 1969, and Pak and Zaneveld (1973) during October–December, 1971. We are inclined to believe that the Undercurrent extends to the east of the Galapagos Islands during most of the year since it was observed there during periods when it is believed to be weak. The Peru Coastal Current, on the other hand, undergoes a large seasonal variation in its speed and temperature (Wooster, 1961; Wyrtki, 1966). Considering such seasonal variations of the Peru Current, its contribution to the equatorial front is also expected to show a corresponding seasonal variation. On the basis of this indication, we may tentatively conclude that equatorial upwelling provides a steady contribution while the Peru Current gives a seasonal contribution to the equatorial front in the region between the Peruvian Coast and Galapagos Islands.

The maximum concentration of suspended particles observed along the front is consistent with the upwelling south of the front. The upwelling caused by the Undercurrent supplies the plant nutrients into the surface water as shown by the nitrate distribution in Figs. 5 and 9, and a high biological productivity follows. It is generally known that the suspended particles in the small size ranges are of mineral origin and the large size ranges are of biological origin. The maximum mean size along the front supports the previous interpretation of the maximum particle concentration along the front associated with a high biological productivity.

4. Discussion

The equatorial front to the west of 85W is probably in a quasistationary condition as Wooster (1969) suggested. Considering the seasonal variation of the Peru Current and the distance of transport, contribution by the Peru Current to the front on the west side of the Galapagos Islands seems to be secondary compared to the equatorial upwelling.

If equatorial upwelling is to be the primary source of the cold water of the equatorial front, another front separating the upwelled water and surface water of the South Equatorial Current is expected to be observed on the south side of the equator. Although the upwelled water is shown to be a tongue of cold water along the equator in the sea surface temperature maps of the Equatorial Pacific Ocean (Sverdrup et al., 1942; Bennett, 1963; Reid, 1969; Love, 1972a, b; U.S. Department of Commerce, 1973), such a secondary front has not been reported. This is probably due to a smaller contrast in water properties between the upwelled water and the surface water to the south of it. An effect of southerly winds over the southern border of the upwelled water is longitudinal divergence, which is unfavorable to formation of a front.

Evidence of the Equatorial Undercurrent extending to 55, 82W was observed during the East Pacific Expedition (Love, 1972b) in temperature (Fig. 47-T-v4), oxygen (Fig. 47.02-v4) and phosphate (Fig. 47-p-v4). The isotherms are spread with a ridge at the thermocline and a trough under the ridge. The isotherm trough is associated with high oxygen concentration and low phosphate concentrations. This is a typical feature of the Undercurrent. The surface front at this location shows a large horizontal temperature gradient—0.067°C mi⁻¹.

The El Niño phenomenon is apparently associated with the equatorial front and is related to an abnormal position and an abnormal intensity of the front. Since a front is a dynamic boundary of two water types involved, movements of the front are necessarily associated with corresponding movements of the water types. If El Niño depends on the extent of southward penetration of warm water, an abnormal displacement of the front toward the west in the region of the eastern terminus of the front seems to provide a favorable condition for such penetration. El Niño must also require a source of warm water in addition to a flow condition which will drive the water south. More observations of the front off the Ecuador-Peru Coast are necessary to verify the role of the Undercurrent in controlling the front, and the role of the front in controlling El Niño.
In summary, the following conclusion may be drawn:

1) Equatorial upwelling associated with wind-induced divergence and the Equatorial Undercurrent appears to be the major source of the cold water of the equatorial front to the west of the Galapagos Islands.

2) The Undercurrent extends on the east side of the Galapagos Islands beyond 85°30’W (Pak and Zaneveld, 1973). The Undercurrent is also associated with upwelling on the east side of the Galapagos Islands.

3) A well-defined equatorial front is observed to be associated with the equatorial upwelling on the east side of the Galapagos Islands.

4) It is suggested that, in addition to the Peru Current, upwelling associated with the Undercurrent may be a major source of the cold water of the equatorial front in the region east of the Galapagos Islands between 3N and 3S.

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REFERENCES


