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Circulation in the Amazon River Estuary and Adjacent Atlantic Ocean[1]

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ABSTRACT

A preliminary survey of the water circulation in the Amazon estuary and adjacent ocean was conducted during both low-river and high-river discharge. Results indicate that, due to the river's large discharge, no salt-water wedge (35‰) enters the Amazon estuary during either low-river or high-river discharge. The zone of nearly vertical isohalines in the ocean near the river mouth represents an area of turbulent mixing. As the vertical mixing decreases seaward, a vertical stratification develops from about 60 km offshore during low-river discharge and from about 80 km offshore during high-river discharge. This stratification persists seaward across the continental shelf for 185 km during low-river discharge and for about 230 km during high-river discharge. During low-river discharge, an isolated freshwater lens was observed far off the French Guiana Coast.

Introduction. The Amazon River system is five times larger than the second-largest river in the world, the Congo (Gibbs 1967), and it supplies about one-fifth of the total river discharge into the world oceans. The tidal influence in the river extends at least 735 km upstream. In the ocean off the

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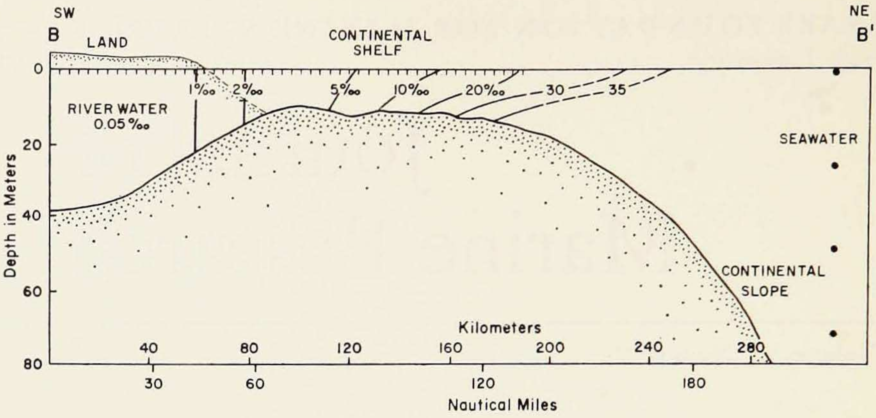

Figure 1. Cross-sectional salinity distribution during low-river discharge (August–September). Dots represent location of Bracui stations. Tick marks at water surface represent *in situ* salinometer profile positions from the ICOMI vessel.

Amazon estuary, the strong and shallow Guiana Current—an extension of the South Equatorial Current—flows in a northwestward direction parallel to the coast. The prevailing trade winds across most of the area produce waves that result in a steady longshore current flowing northwestwardly in the shallow water along the shore.

Since all of the material carried by the Amazon to the ocean passes into the estuary, this area provides an excellent location for the study of the amounts and types of suspended material carried by the river (Gibbs 1967). The large area of the Amazon estuary and the extensive area of the Atlantic Ocean affected by the river's discharge also offer a unique opportunity to investigate circulation patterns on a large scale. This study has been performed in part to determine whether the Amazon estuary is entered by salt water (35 ‰), since salt water does enter the estuaries of most large rivers of the world, and to observe oceanographic phenomena seaward.

Observations and Data. The oceanic observations were made by me in 1963 on the Equalant I cruise of the Chain (Woods Hole Oceanographic Institution) (Chain cruise 35), the Oregon (U.S. Bureau of Commercial Fisheries), and the Bertioga (Brazilian Navy). The work in the estuary and at the river mouth was carried out by me, in 1963 also, aboard a tugboat of the Companhia de Indústria e Comércio de Minas Gerais (ICOMI).

The data used in this study include: (i) those derived from analyses of the water samples (standard Mohr titration) obtained on the four cruises noted above, (ii) those obtained on the same four cruises, using specially constructed *in situ* salinity and temperature bridges having an accuracy of 0.5 ‰, and (iii) those on salinity and density in offshore areas obtained on cruises Equalant

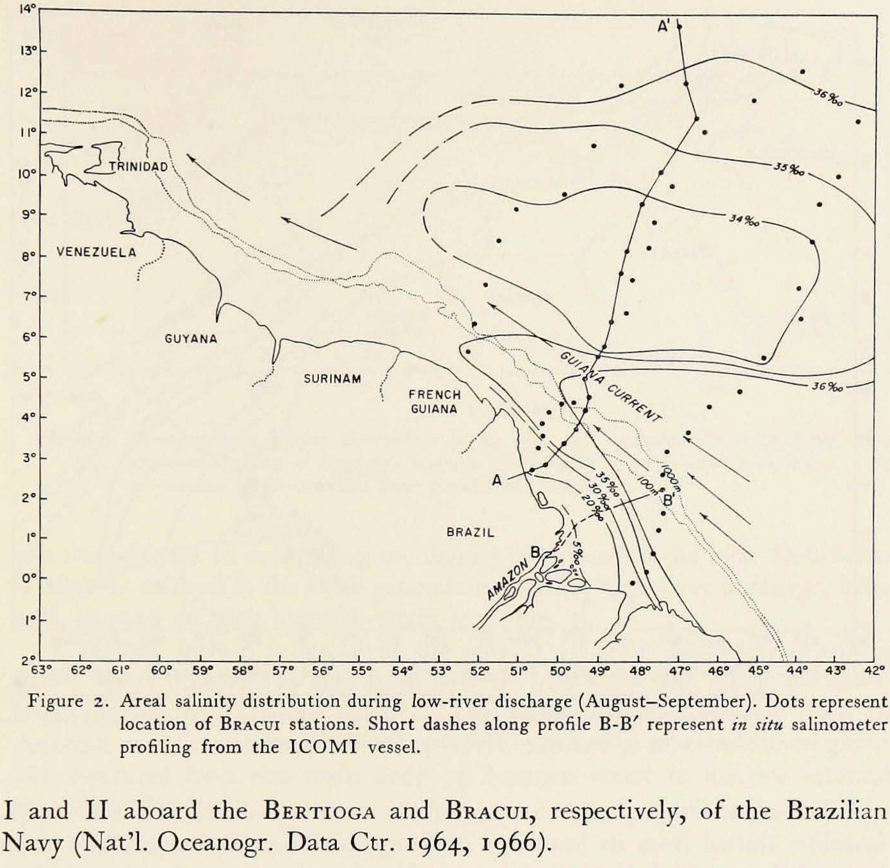

Figure 2. Areal salinity distribution during low-river discharge (August–September). Dots represent location of BRACUI stations. Short dashes along profile B-B′ represent *in situ* salinometer profiling from the ICOMI vessel.

I and II aboard the BERTIOGA and BRACUI, respectively, of the Brazilian Navy (Nat'l. Oceanogr. Data Ctr. 1964, 1966).

Results. Since the Amazon estuary has, in many places, a depth of 40 m or more, one might expect to find in it a salt wedge having its maximum extent at the highest spring tide during minimum river discharge. However, detailed profiling, using an *in situ* salinometer at approximately 4-km intervals, from Macapá, Brazil, outward into the ocean has revealed that no salt water (35 ‰) enters the estuary, even at its deepest portions. The actual extent of salt-water intrusion under the fresh-water layer is seen in Fig. 1, a cross-section of B-B′ on Fig. 2, extending from the estuary across the continental shelf. The surface 35 ‰ isohaline was 185 km offshore during the highest spring tide, i.e., at its position nearest to the river mouth. Under this fresh-water layer, seawater extended shoreward to 120 km offshore. The zone of thorough mixing near the river mouth is indicated by the nearly vertical isohalines.

The maximum influence of the Amazon River on the ocean is seen in Figs. 3 and 4. Although the entire pattern has been shifted seaward, the overall

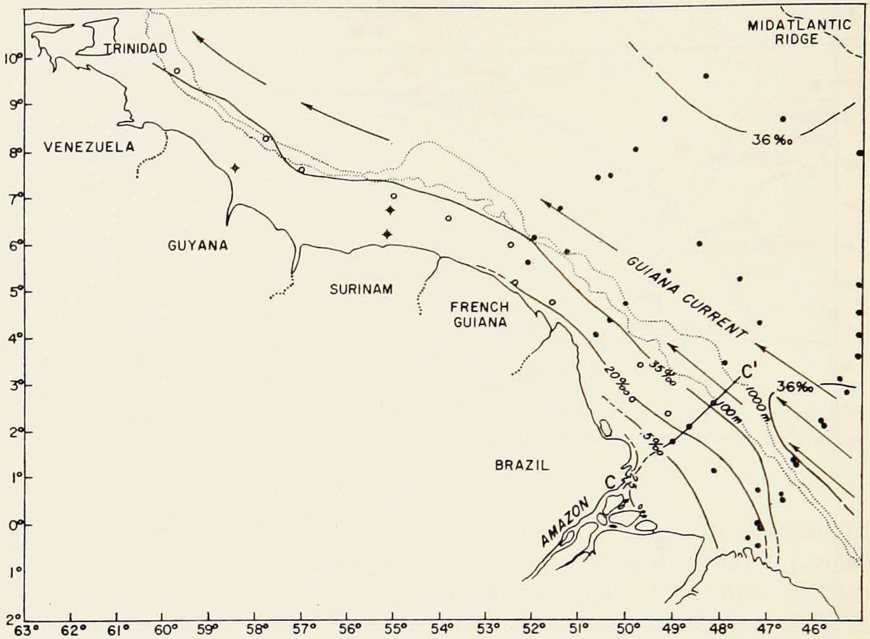

Figure 3. Areal salinity distribution during high-river discharge (February–April). Dots represent location of Bertioga stations. Circles represent location of M. V. Oregon stations. Dots with crosses represent location of Chain stations. Short dashes along profile C-C′ represent *in situ* salinometer profiling from the ICOMI vessel.

circulation pattern is similar to that of the low-river discharge. The 35‰ isohaline shifted from its low-river discharge position 185 km seaward from the mouth to a high-river discharge position 230 km from the mouth. The zone of very thorough mixing near the mouth is indicated by the nearly vertical isohalines.

The seaward decrease of thorough vertical mixing was accompanied by the development of vertical stratification from about 60 km offshore during low-river discharge and from about 80 km offshore during high-river discharge (Figs. 1, 4). Areal variations in salinity, other than those due to the seasonal influence of the river, also occurred. For example, tidal influences caused the isohalines to migrate back and forth over a limited distance.

An interesting feature of the Amazon's influence on the ocean, observed from data taken at offshore oceanographic stations during low-river discharge, is a large lens (1400 km × 620 km) of brackish water (<35‰) situated seaward of the French Guiana continental shelf (Fig. 2). The extent, stability, and isolation of this lens from the fresher waters shoreward of the Guiana Current can readily be seen in cross-sections showing salinity and density (Fig. 5). The similarity between these cross-sections indicates that temperature

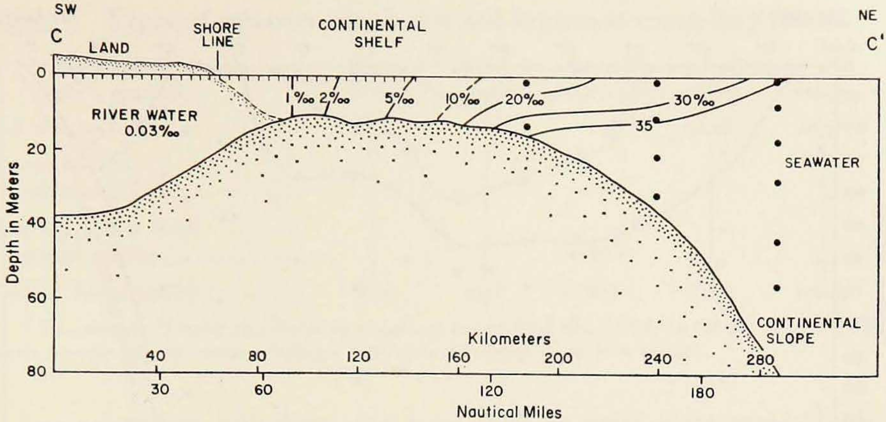

Figure 4. Cross-sectional salinity distribution during high-river discharge (February–April). Dots represent location of BERTIOGA stations. Tick marks at water surface represent *in situ* salinometer profile positions from the ICOMI vessel.

was insignificant in controlling the density variations in the lens. Data taken at offshore stations in the same general area during high-river discharge, however, showed no such brackish-water lens (Fig. 3).

A further feature is found in the smaller (> 1-km diameter) masses of turbid water observed by me, from both air and shipboard, along the shoreward edge of the Guiana Current. These masses extended seaward from the Amazon water mass along the shore, moved outward as lobes, and then gradually separated from the main body of Amazon water to migrate seaward, expanding slowly.

Discussion. Since the estuaries of most of the other large rivers of the world are entered by salt water (35 ‰) while that of the Amazon is not, recognition of the various types of circulation that exist at estuarine river mouths is essential for an understanding of the factors that determine the extent to which an estuary will be entered by a salt wedge.

Fresh water entering the sea has a lower density than seawater and will therefore flow seaward over the salt water. Circulation patterns that develop in estuaries can be classified as follows: (i) salt wedge, (ii) two-layer flow with entrainment, (iii) two-layer flow with vertical mixing, and (iv) vertical homogeneity. The type of circulation that develops between the fresh water and the salt water appears to depend primarily upon (i) river discharge, (ii) tidal current, (iii) estuary width, and (iv) estuary depth. Summarized in Table I from the data of Pritchard (1967) are the relationships between these factors and the various types of estuarine circulation, indicating the conditions favorable for the various circulation patterns. For more detailed information, see Bowden (1967), Pritchard (1967), and Hansen (1967).

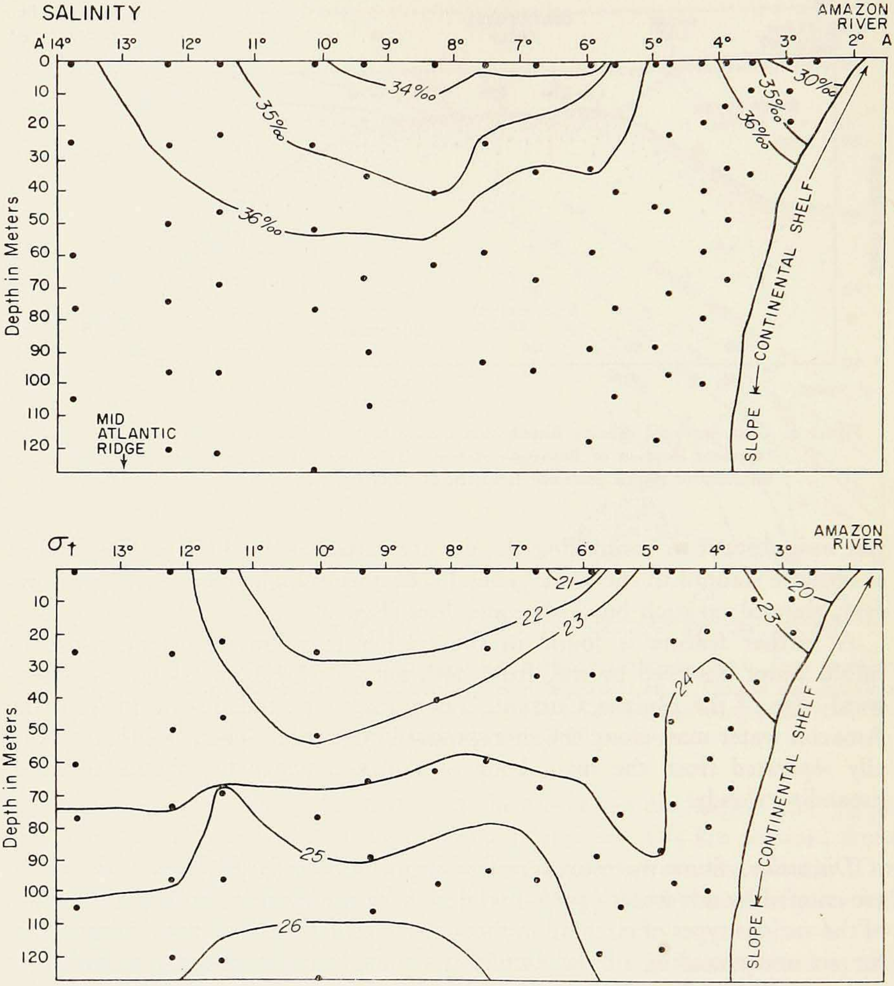

Figure 5. Top: Cross-sectional salinity distribution through low-salinity lens during low-river discharge. Dots represent location of Bracui stations.
Bottom: Cross-sectional σ_t distribution through low-salinity lens during low-river discharge. Dots represent location of Bracui stations.

As seen in Table I, the large discharge of the river and the great depth of the Amazon River estuary favor a salt-wedge type of circulation pattern while the river's high tidal currents and large estuary width favor a vertically homogeneous type of circulation pattern. However, neither of these circulation patterns develops within the Amazon estuary because of the river's immense discharge—so great that river water occupies the entire estuary at all times (Figs. 1, 4).

Table I. Types of estuarine circulation and important controlling factors.

Type of circulation pattern	River discharge	Tidal currents	Ratio: tide/river*	Estuary width	Estuary depth
Salt wedge	high ↑	low ↓	1	small ↓	large ↑
Two-layer flow with entrainment	│	│	∾10	│	│
Two-layer flow with vertical mixing	│	│	∾100	│	│
Vertical homogeneity	low	high	> 1000	large	small

* The amount of water that flows up an estuary during flood tide relative to the discharge of fresh water flowing into the estuary during a tidal cycle through a given cross section.

In a comparison with three other large estuarine rivers of the world (Table II), it is seen that only the Amazon estuary has no salt-water intrusion. The presence of seawater in the Congo and Columbia estuaries may be related partially to the fact that each has a deep-channel connection with the open ocean. The Amazon and Mississippi mouths have shallower portions—or "bars"—seaward of their estuaries. The sill, or bar, at the mouth of the Mississippi is within the bounds of the river's mouth while the bar at the Amazon entrance—unusually great (500–700 km) compared with most such bars—is located on the continental shelf. Again, apparently the river's great discharge (with the resulting fluid drag and entrainment) is sufficiently large to prevent salt-water intrusion into the estuary (Figs. 1, 4).

Seaward of the Amazon's estuary, the zone of highly turbulent mixing indicated by the vertical isohalines (Figs. 1, 4) corresponds to a somewhat constricted area (relative to areas further out on the continental shelf) where

Table II. Comparison of the estuarine circulation type and related factors for major rivers of the world.

Estuarine rivers	Mean discharge at mouth ($10^3 m^3/sec$)	Estuary: max. tidal range (m)	Estuary: width (km)	Estuary: depth (m)	Estuary: depth at entrance "bar" (m)	Estuary: distance of salt-water penetration (km)	Type of circulation
Amazon [β]	175.0	5	10–20	20–45	12	0	α
Congo [γ]	38.0	1.8	1.5–10	10–100	ζ	40	salt wedge
Mississippi [δ]	15.8	0.8	1–2	4–10	2–3	100	salt wedge
Columbia [ε]	2.3	4	3–9	20	ζ	40	salt wedge

α Two-layer flow with entrainment and vertical mixing.
β From Gibbs (1967).
γ From Spronck (1941).
δ From Scruton (1956).
ε From Hansen (1965).
ζ The Congo and Columbia rivers do not have a bar at their entrance.

Table III. Amazon River and oceanic circulation data.

	Discharge ($10^3 m^3$/sec)	Salinity ‰	Velocity (m/sec)	Length (α) (10^3m)	Area (β) ($10^3 m^2$)
LOW-RIVER DISCHARGE					
Top layer	332.7	20.0	0.12	514.0	2,692
Bottom layer	249.3	26.7	0.09	514.0	2,692
Amazon River	83.5	0.05	0.3	12.5	270
HIGH-RIVER DISCHARGE					
Top layer	758.0	20.0	0.07	723.0	10,341
Bottom layer	490.6	30.9	0.05	723.0	10,341
Amazon River	267.4	0.03	0.9	12.5	310

(α) Length of 20‰ isohaline in 10^3m.
(β) Cross-sectional area in $10^3 m^2$ at the 20‰ isohaline, assuming that division between top and bottom layer is at 50% of depth.

strong tidal currents meet the outflow. Well known locally as a zone of extremely rough choppy seas, this area abounds in visual evidence of great turbulence that seems to gradually decrease seaward. Until distinct stratification develops (Figs. 1, 4), some vertical mixing between the layers continues together with the upward movement of the seawater as it is entrained in the seaward-moving fresher layer. The greater amount of mixing shoreward may be due to the fact that the velocity at the interface between the layers is probably greater shoreward (Keulegan 1949).

An understanding of the near-shore circulation pattern off the mouth of the Amazon River is enhanced by calculating the discharges and velocities at the 20‰ isohaline, the position of which was determined from observations given in Figs. 2 and 3 and from aerial observations of the turbid zone, which appears to parallel the 20‰ isohaline. The discharges (Table III) were calculated for the upper and lower layers during periods of maximum and minimum discharge, using the mean values of several oceanographic profiles as well as the Amazon discharge reported by Gibbs (1967).

Fig. 6, incorporating data from Table III, is a diagrammatic cross-section of the low-discharge circulation. (Similar results would be obtained for high-discharge circulation.) Using Bowden's (1967) approach, the seaward discharge of the top layer at the 20‰ isohaline is represented by D_T, its salinity by S_T, the landward discharge of the bottom layer by D_B, its salinity by S_B, and the Amazon River discharge by D_R. If conditions for the continuity of water and of salt are stated respectively as

$$D_T - D_B = D_R; \quad D_T S_T = D_B S_B,$$

then these equations can be combined as

$$D_T = \frac{S_B D_R}{S_B - S_T}; \quad \text{and} \quad D_B = \frac{S_T D_R}{S_B - S_T}.$$

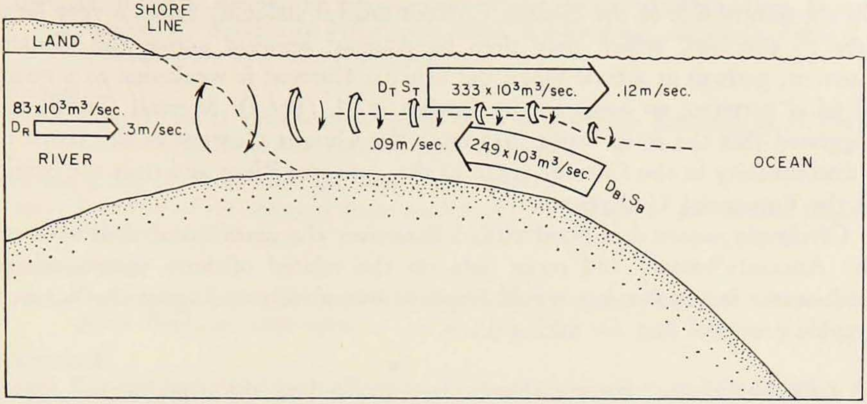

Figure 6. Diagrammatic cross-section of circulation pattern.

The discharge of the seaward-flowing top layer at the 20‰ isohaline is increased to about four times that of the Amazon River discharge and at this point is composed of three parts of the landward-flowing bottom current of seawater for each part of fresh water. In Fig. 6, the broad arrows indicate the entrainment of bottom water in the upper layer, with the zone of high turbulence near the mouth represented by long upward-directed and downward-directed arrows. Observe in Figs. 2 and 3 that the 20‰ isohaline, located about 125 km from land, is over the outer portion of the continental shelf, is a line 514 to 723 km in length, and is not in a channel as is the river. The seaward decrease in velocity, in spite of the great increase in discharge in the top layer, is due to the magnitude of this cross-sectional area.

The apparent absence during high-river discharge (Fig. 3) of a low-salinity lens similar to the large lens of brackish water observed seaward of the French Guiana continental shelf (Fig. 2) indicates that this phenomenon is not a permanent feature of this area. Either the low-salinity lens did not occur or, if it did, it was beyond the sampling stations. In 1964 and 1965, Ryther et al. (1967) identified large surface masses of low-salinity water at approximately the same locale during both low-river discharge (October–December 1964) and high-river discharge (May–June 1965). The data represented in Figs. 2 and 3 do, therefore, seem to clarify the question raised by Ryther et al. (1967: 77) as to "whether there is a permanent eddy or whether such features are produced continually and are short lived."

A possible source of these large lenses might be the smaller masses of water that separate from the Amazon water mass along the shore and then migrate seaward across the Guiana Current. Their observed expansion may be due to mixing with seawater. While none of these smaller lenses was as large as that based on the data in Fig. 2, it is possible that they coalesced after crossing the Guiana Current. It is possible also that the fresh water accumulates on the shoreward side of the Guiana Current until it suddenly forms a very large lobe (> 500 km), which may then be released seaward across the Guiana Current, perhaps at a time when the Guiana Current is weakened as a result of wind patterns, as suggested by Ryther et al. (1967). Metcalf (1968) has suggested that the fresh water may cross the Guiana Current as the result of a discontinuity in the Current north of the Amazon River and near the origin of the Equatorial Undercurrent.

Obviously, more data on stratified flow over the continental shelf area off the Amazon estuary and more data on the related offshore waters where fresh-water lenses develop would improve our understanding of the oceanographic processes that are taking place.

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