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AMAZON RIVER INFLUENCE ON THE SEASONAL DISPLACEMENT OF THE SALT WEDGE IN THE TOCANTINS RIVER ESTUARY, BRAZIL, 1983-1985

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RESUMO — *O estuário amazônico é formado pelas descargas dos rios Amazonas e Tocantins. Tendo em vista que a ilha de Marajó separa parcialmente a foz desses dois rios, considera-se que a baía de Marajó seja apenas a foz do rio Tocantins e de outros pequenos rios ao seu redor. Com o objetivo de estudar a sazonalidade da invasão das águas estuarinas na baía de Marajó, realizou-se uma série de viagens em pequenos barcos ao longo do rio Pará e baía de Marajó, entre agosto de 1983 e abril de 1985, em que foram obtidos dados de temperatura e condutividade/salinidade da água. O período de coleta coincidiu com a maior seca do rio Amazonas registrada desde 1968, em 1983, e com o fechamento das comportas de Tucuruí, em 1984. As medidas de temperatura variaram entre 24 e 34,5 °C e não mostraram nenhum padrão relacionado com a sazonalidade da vazão dos rios. A condutividade oscilou de 20 a 16.200 µmhos•cm^{-1} e permitiu identificar o trecho do estuário que estava sob a influência das águas dos rios Amazonas ou Tocantins ou de águas estuarinas. Os dados mostraram haver uma complexa dinâmica de deslocamento de massas de água ao longo do ano nessa região. Durante o tempo chuvoso, no primeiro semestre do ano, a elevada descarga do rio Tocantins parece represar as águas do rio Amazonas na altura do Estreito de Breves e afastar as águas salobras para fora da baía de Marajó. Durante o verão, no segundo semestre do ano, quando a descarga do Tocantins é mínima, as águas do rio Amazonas penetram pelo Estreito de Breves e entram em contato com as águas salobras, que invadem a baía de Marajó. Aparentemente, a extensão da invasão de água salobra na baía de Marajó durante o verão parece estar mais relacionada com a descarga do rio Amazonas durante o período de seca do que a descarga do rio Tocantins durante o mesmo período.*

PALAVRAS-CHAVE: Rio Amazonas, Rio Tocantins, Estuário, Salinidade, Condutividade.

ABSTRACT — *The Amazon's estuary is formed by the final water courses of Amazon and Tocantins Rivers. Marajó Island partially separates the mouth bays of both rivers, and the entire discharge of the Tocantins flows into Marajó Bay. In order to study the mixing of fresh and ocean water within Marajó Bay, a series of 18 collecting trips was conducted from August, 1983, until April, 1985. Conductivity and temperature were monitored at monthly and bimonthly*

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intervals. Mean water temperatures ranged from 24 to 34.5°C, but this oscillation was not related to seasonality nor mixing of water masses. The conductivity values obtained ranged from 20 to 16,200 µmhos•cm⁻¹, and we believe conductivity is a useful indicator for separating waters from the Amazon, the Tocantins and the ocean. The conductivity results indicate a complex system of fresh water discharge dynamics. During the rainy season, which falls in the first half of the year, Tocantins River discharge is high; its water masses push the Amazon River waters up the Straights of Breves (Estreitos de Breves) and force ocean water out of Marajó Bay. This situation is inverted during the summer, or dry season, when the rate of the Tocantins discharge is low and the Amazon and ocean waters will meet in Marajó Bay. The extent of salt water intrusion into Marajó Bay seems to be related more to the Amazon River discharge than to the diminished water discharge of the Tocantins River.

KEY WORDS: Amazon River, Tocantins River, Estuary, Salinity, Conductivity.

INTRODUCTION

The Amazon Basin is situated totally in the tropics, between 5°N and 17°S; it includes about one-third of the area of South America and supplies about one-fifth of the total river water flowing into the planet's oceans (Milliman & Meade 1983). The discharges of the Amazon and Tocantins rivers create on the north-eastern South American coast a large fresh and salt water mixing zone with an almost 1700-mile long stretch of low-lying, muddy, and mangrove-fringed coastline. This environment extends from the Orinoco Delta in Venezuela into the Brazilian State of Maranhão and gives rise to some species, genera and sub-families of endemic fishes (Myers 1960).

The two rivers, Amazon and Tocantins, are partially separated by Marajó Island. North of the island lies what is considered the "true" Amazon River mouth, while south of the island, Pará River and Marajó Bay are considered the mouth of the Tocantins and some others smaller rivers (Figure 1) (IBGE 1977; COPRAPHI 1984; Schwassmann et al. 1989). The combined estuarine opening of both rivers into the ocean is nearly 340 km wide. The transition between the lower course of the Amazon and its estuary may lie at the mouth of the Xingu River; from here on to where the mouth opens into the ocean there exists a complex system, like a great gulf, with a triangular area of 85,500 km^2 from river to river shore, not including the alluvial lands on both sides (Sioli 1966).

The seasonal fluctuation of river discharges cause a displacement of the salt wedge inside Marajó Bay on the southern side (Egler & Schwassmann 1962) and also on the shelf of the Amazon's mouth on the north side of Marajó Island (Gibbs 1970; Diegues 1972). Seawater never enters in the Amazon River mouth (Gibbs 1970), but brackish water was observed near the Tocantins mouthbay and 90 km upstream of Belém in the Guamá River (Schwassmann et al. 1989). The contact of Amazon and Tocantins waters occurs along the deep channels at the southwestern corner of Marajó Island, at least 200 km from the outer estuary. These channels are known as the Estreitos de Breves and their role has been a focal point of debate concerning possible inclusion of the Tocantins River in the Amazon River's basin

(Silvestre 1922; Pinto 1930; Roxo 1938). In the 1950's, the argument was laid to rest and the 1972 *Anuário Estatístico Nacional* considered as separate the basins of Amazon and Tocantins Rivers, with no significant influx of Amazon waters into the Pará River (IBGE 1977). Reis et al. (1977) also suggest some independence of the discharges of both rivers, but find some evidence for mixing of water masses based on concentrations of Deuterium and Oxygen-18 in the water.

In Amazonia the dry season is called "summer", while the wet, or rainy season is termed "winter". In the summer of 1983, Marajó Bay was strongly brackish and the population of the city of Belém drew brackish water from the faucets in their houses. This fact was due to the pumping of Guamá River water, that was mixed with brackish water from the bay, into the city water reservoir. As the last phase in the construction of the Tucuruí Hydroelectric Dam in the Tocantins River, it was planned to close all flood gates to fill the reservoir to capacity in 1984. Based on the previous year's experiences, it was expected that this total interruption of the Tocantins' flow would cause a large-scale intrusion of brackish water into Marajó Bay, salting the supply of drinking water for many cities near the estuary, including Belém. When the Tocantins River flow was completely blocked in November of 1984, no significant intrusion of the salt wedge into Marajó Bay was noted, in contrast to what had occurred in the previous year. This paper discusses the contribution of the Amazon River to the Tocantins estuary, and attempts to investigate current dynamics during 1983-84 in Marajó Bay.

METHODS

Eighteen sampling trips were made inside Marajó Bay from August, 1983 to April, 1985, on board of small fishing boats of about two ton displacement. During this time of 21 months, the intervals between successive trips was mostly monthly, but sometimes bimonthly, and only once there was a three-month lapse between trips. The data were obtained over 15 months, of which four months covered the winter (W), or rainy season (February to April); three were of the transition from winter to summer (TWS) (May to July); five covered the summer (S), or dry season (August to October); and the last three months were of the transition between summer and winter (TSW) season (November to January). These trips lasted from 1 to 20 days each and crossed the mouth of Pará and Tocantins Rivers between the Cape of Maguari, outside of Marajó Bay, and the Araras Islands, near the Estreitos de Breves (Figure 1). In this figure, a straight and angled line is drawn as a distance reference from the ocean, point zero lying near Espadarte Bank, at the transition of open seawater and closed bay-water. Sampled points were projected on this line and measured as distance from the ocean. Surface conductivities and temperatures were measured with a Fisher temperature-compensated conductivity/salinity bridge.

Discharges of Amazon and Tocantins River were inferred from measured water levels at Óbidos and Tucuruí, respectively. These stations are nearest to the mouths of both rivers where water level records had been kept over a series of years. The Departamento Nacional de Águas e Energia Elétrica (DNAEE) of the Ministério de Minas e Energia (MME) provided monthly minimum, maximum and mean water levels between January of 1983 and December of 1985. Table 1 shows characteristics of the drainage basin and distances of the Tucuruí and Óbidos sites.

RESULTS

A total of 218 stations was sampled in 18 trips from August of 1983 to April of 1985 in Marajó Bay and Pará River, along the 350 km distance of our plotted center line (Figure 1). Mean range of all monthly trips was 90.5 km (Table 2) and the area around 110 km distance was most frequently sampled. Only three trips were longer than 200 km, they occurred during July (TWS) of 1984 and January (TSW) and February (W) of 1985. Figure 2 shows the sampling points as to month and distance from the estuary, where the circle's diameter is proportional to the natural logarithm of conductivity in μmho•cm^{-1}. This figure shows the oscillating of conductivity along the distance line during the annual cycle. In the summer the conductivity was very high, especially in September of 1983 when it reached 16,200 μmho•cm^{-1} near 53 km. In winter the conductivity was low, around 45 μmho•cm^{-1} all over Marajó Bay. From 200 km inside the estuary, the water was not influenced by the ocean at any time of the year, and upstream of 150 km no brackish water was detected.

Measured temperatures ranged from 24 to 34.5°C and this variation was not related to season but was influenced by water depth and time of day of measurements.

The stretch along the inner Marajó Bay and Para River to the point of contact with the Amazon River, between Belém (130 km) and the Estreitos de Breves (350 km), was visited in three periods: July of 1984, and January and February of 1985. Figure 3 shows measured conductivities in each trip at the respective distance from the ocean. The difference of conductivity means between the three samples was small but clear and significant ($P<0.05$), with high conductivities in January of 1985 (TSW) of 54.2 μmho•cm^{-1} ($n=10$), and low conductivity waters in July of 1984 (TWS) 40.4 μmho•cm^{-1} ($n=6$), while the February 1985 (W) value of 46.3 μmho•cm^{-1} ($n=6$) falls between the other two. In January of 1985 we found conductivities of the Amazon River to be from 55 to 58 μmho•cm^{-1}, almost identical to conductivities measured in the Pará River, and it was not possible to detect a difference in the color of the two rivers. In July of 1984 and February of 1985, the color of Pará River waters changed from clay to brown-black, and conductivities were below 50 μmho•cm^{-1}. These data imply a significant influx of Amazon water into the Pará River through the Estreitos de Breves and eventual contact with ocean water during January of 1985.

Figure 4 shows water levels representative of discharges of Amazon and Tocantins River, measured at Óbidos and Tucuruí, respectively, from January,

Table 1. The basin characteristics of the hydrological stations of Tucuruí, Pará, on the Tocantins River, and Óbidos, Pará, on the Amazon River.

Hydrological Station	River	Drained Basin	Distance to Mouth	Distance to the Ocean
Óbidos	Amazon	4,168,746 km^2	770 km	770 km
Tucuruí	Tocantins	742,300 km^2	237 km	432 km

Table 2. The distance traveled during the the eighteen sampling trips, along the imaginary line between the mouth of Marajó Bay (Espadarte Bank) and Estreito de Breves (350 km), number of sampled points and the season, during 15 months between August, 1983, and April, 1985.

Months	Distance to the river mouth			Number of sample points	Seasons of the year
	Minimal	Maximal	Range		
1983					
August	76	108	32	7	TWS
September	53	53	0	1	TWS
October	76	110	34	6	TWS
December	53	95	42	6	TSW
1984					
March	50	50	0	7	W
April	78	130	52	21	W
May	1	105	104	31	TWS
June	55	140	49	11	TWS
July	61	310	249	37	TWS
August	195	325	40	2	S
October	85	140	55	20	S
December	80	180	100	30	TSW
1985					
January	130	350	220	15	TSW
February	50	350	300	17	W
April	16	95	79	7	W

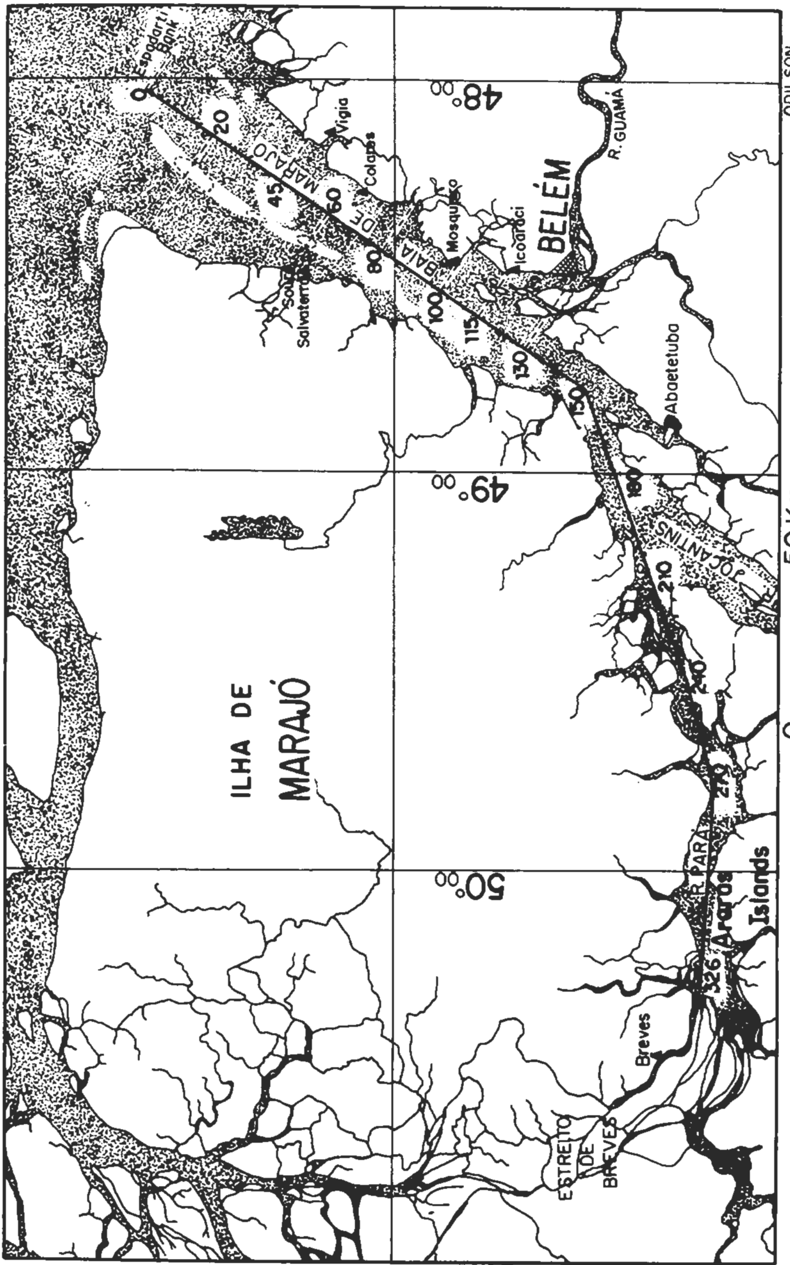

Figure 1 - Map of Marajó Bay, Tocantins River mouth and the lower Amazon River, showing the center line of 350 km length along which measurements were made in Marajó Bay and the Pará River.

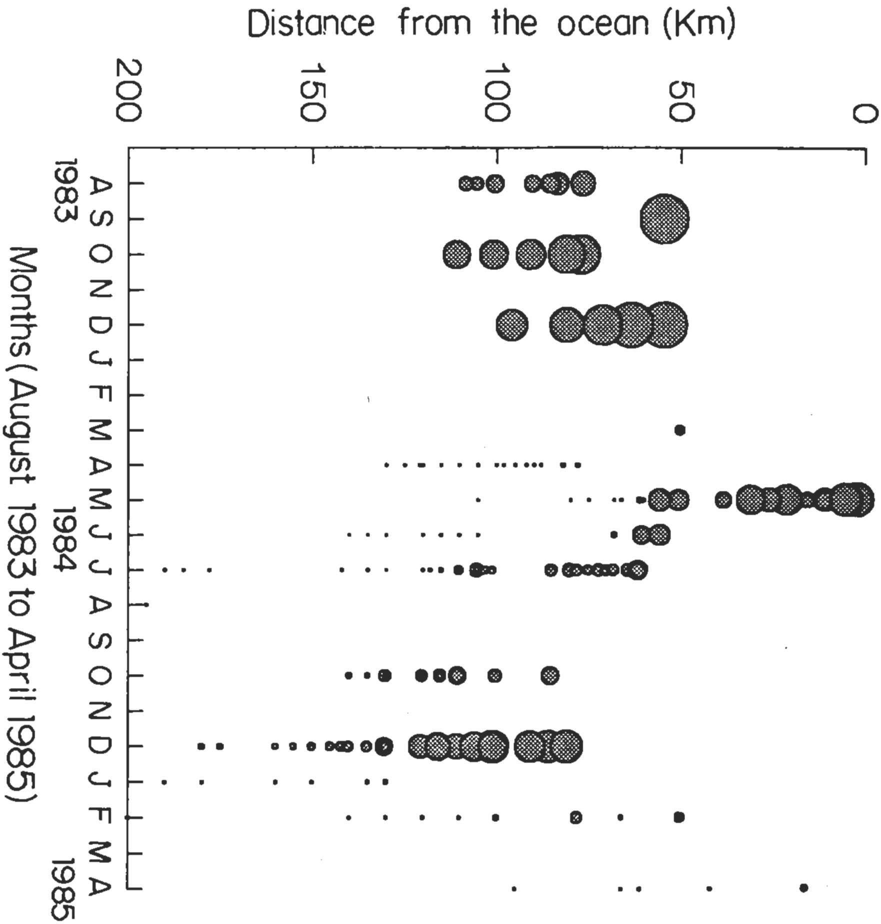

Figure 2 - Measured conductivities in relation to months and distance from the estuary. Circle diameters are proportional to the natural logarithm of conductivity in μmho•cm^{-1}.

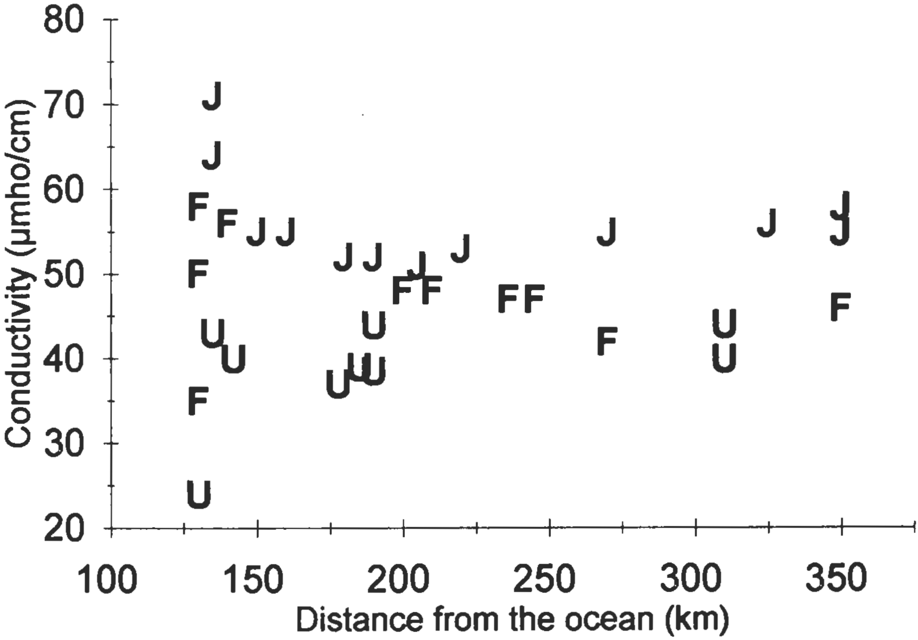

Figure 3 - Conductivities measured across Marajó Bay and the Pará River during July 1984 (U), and January 1985 (J) and February 1985 (F). The vertical broken line at 150 km delimits the extent of salt water intrusion, and the horizontal broken line at 50 μmho•cm^{-1} separates the waters of the Amazon and Tocantins Rivers.

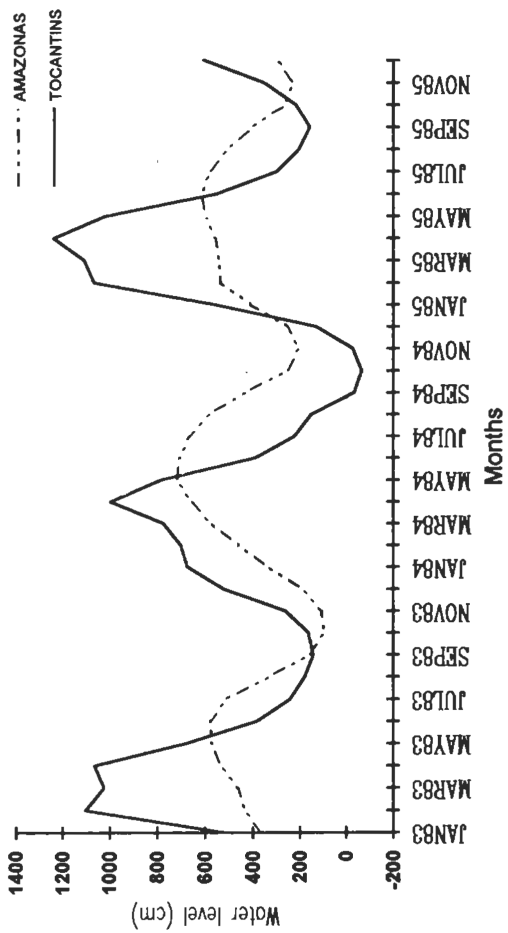

Figure 4 - Mean monthly water levels of the Amazon River (measurements taken at Óbidos), and Tocantins River (measurements taken at Tucuruí) from January 1983 to December 1985.

1983, to December, 1985. High water level of the Amazon River occurs in May and June, and of the Tocantins River from March to May. Comparing the relative water levels of the two rivers with our conductivity values in Figure 2, one can assume that the beginning of low conductivity values in Marajó Bay in March of 1984 may be related to discharge of Tocantins River mainly, independent of Amazon River, while the strong intrusion of salt water in Marajó Bay in 1983 and very small intrusion in 1984 do not correlate at all with the low discharge values of the Tocantins River. There is a good correlation, however, with Amazon River discharges that were low in 1983 and high in 1984, suggesting a variable but substantial annually cyclic invasion of Amazon water in the Tocantins estuary during the summer season which helps to maintain low conductivity levels in Marajó Bay.

DISCUSSION

The Amazon estuary is the largest mixing place of fresh and salt water of the planet Earth. Many studies have been conducted in the outer estuary (see Nittrouer & DeMaster 1986), but little work was dedicated to the inner estuary of Amazon and Tocantins River (Huber 1903; Egler & Schwassmann 1962; Sioli 1966).

Egler & Schwassmann (1962) and Schwassmann et al. (1989) described the displacement of the salinity wedge and of the zone of high diatom production in Marajó Bay, but did not discuss limnological changes of the inner area of Marajó Bay and Pará River. Reis et al. (1977) studied the concentration of isotopes of oxygen (O-18) and hydrogen (Deuterium) in waters from the North and South side of Marajó Island, Amazon River and Marajó Bay, respectively. They show differences in concentration of these isotopes from these places, and suggest some independence of the discharges of the two basins. The last mentioned authors also compare the fresh water of the Amazon River with the fresh and brackish water of Marajó Bay, including the season of marine intrusion. Considering only the data obtained in winter with only fresh water present, the means of the samples are not different ($P > 0,05$) and it is not possible to support two independent discharges.

The fortuitous events occurring in 1983 and 1984, that permitted us to reevaluate the flow dynamics, were the following two situations: low discharge of Amazon River in 1983, and complete obstruction of the Tocantins River in 1984. Considering the differences of the conductivities of the two rivers, it is possible to make a model of flow dynamics in Marajó Bay and Pará River. High Tocantins discharge during the winter normally dams the Amazon waters in the Estreito de Breves, and also pushes the salt wedge out of Marajó Bay. During the summer, the discharges of the Tocantins River and other small rivers are reduced and permit penetration of Amazon water through the Estreito de Breves into the Pará River, and also allow some intrusion of the salt wedge into Marajó Bay. The contact of these two water masses, Amazon and intruding marine water, occurs in the inner part of Marajó Bay. In the summer of 1983, Amazon River discharge was abnormally low and permitted an extensive intrusion of the salt wedge, which salted the drinking water of the city of Belém. At that time we measured very high conductivities in Marajó Bay. The important contribution of the Amazon's discharge to the flow in Marajó Bay during the summer was especially evident in 1984, when, although the flow of the Tocantins River was completely obstructed, no marine intrusion was noted.

The displacement of the wedge, or dividing zone, of Amazon and Tocantins waters is well known to fresh-water shrimp fishermen who live along the Pará River, the Estreito de Breves and the mouth of the Tocantins River. The migration of *Macrobrachium amazonicum* populations in the Tocantins River occurs at the begining of falling water levels, in May-June (Odinetz-Collart 1987). The shrimp fishermen of the Pará River follow the shrimp migration from the Tocantins mouth to the Xingu River entrance into the Amazon River, and the fishermen recognize the time and place to fish by color difference of the waters from the Amazon and Tocantins.

The dynamic flux of Tocantins and Amazon discharges needs further study, but a significant intrusion of Amazon waters into Marajó Bay has to be accepted. Better knowledge of this complex system will help to explain the migration, in the Lower Amazon River and estuary, of fresh water shrimp and many species of fish, especially the young of the big catfish *Brachyplatystoma*, of great importance to the commercial fishery and regional economy.

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