The influence of the meandering Guiana Current and Amazon River discharge on surface salinity near Barbados[1]

by Gary A. Borstad[2,3]

ABSTRACT

The seasonal surface salinity regime near Barbados, West Indies is explained in terms of the oceanography of the area. Because of its position relative to the complex and meandering Guiana Current along the northeast coast of South America, the island of Barbados receives mixtures of two fundamentally different surface water types. During the northern winter very blue, oligotrophic and saline water having little vertical structure in the upper 100 m arrives from the north and east. Beginning in January these waters are diluted by pulses of progressively more green, less saline and therefore less dense water arriving in shallow pools from the southeast via the Guiana Current. After August, a combination of decreasing Amazon River discharge and changing wind patterns over the region of the Amazon plume directs much of the brackish water eastward in the Equatorial Counter Current and surface salinities at Barbados and elsewhere in the western tropical Atlantic steadily increase. Interannual variations of Amazon River flow appear to account for approximately 64% of the variations of the annual minimum surface salinity at Barbados. The minimum surface salinity at Barbados is expected to decrease if the Amazon discharge (which has been recently shown to be affected by clearcutting in Amazonia) continues to increase.

1. Introduction

There has been considerable interest in the hydrography and plankton biology of the western tropical Atlantic for many years, by South American institutes working in support of coastal fisheries (Fukoka, 1971; Margalef, 1965; Cadee, 1975; Corredor, 1978 and others) and by others because this area is the ultimate source of all the water entering the Caribbean Sea (Lewis and Fish, 1969; Ryther *et al.*, 1967; Hulbert and Corwin, 1969; Steven, 1971; Mazeika, 1973; Froelich *et al.*, 1978).

The island of Barbados lies well off the South American coast and east of the Antilles Arc (Fig. 1), and because of this has been utilized extensively as a platform for the study of tropical plankton biology (Lewis and Fish, 1969; Steven

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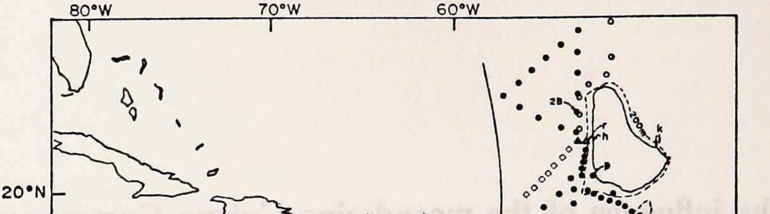


Figure 1. Location of Barbados with respect to the South American Continent and the place names mentioned in the text. Letters and symbols indicate location of stations for salinity data in Figure 2. This study: 8 km station (▲); 4 km station (△); May 21, 1975 (○); July 21-23, 1975 (●); January 21, 1976 (◇). Steven *et al.*, 1970 (2B); Partlo, 1975 (P); Kidd, 1978 (R,K,H); Hawkins, 1980 (H).

et al., 1970; Wells, 1976; Sander and Moore, 1978 and others). The island is small, with very little runoff and with a very narrow shelf. It is bathed by westward and northwestward surface currents of between 20 and 45 km/day (NODC data) and there is little island mass effect (Sander and Steven, 1973). For these reasons the general hydrography of the western tropical Atlantic will have profound effect on conditions in the planktonic realm around Barbados.

It is well known by those who study this area that there are large fluctuations of surface salinity and hence of density (also of silicate and to a lesser extent of other nutrients) caused by the massive outflow of the Amazon River (Ryther *et al.,* 1967; Steven and Brooks, 1972; Van Bennekom and Tijssen, 1978). This paper examines the temporal variations of surface salinity at Barbados which are closely related to the temporal variations of many plankton organisms there (Borstad, 1982). Both can be explained in terms of the temporal and spatial variations of the physical regime of the western tropical Atlantic, particularly along the South American continental shelf.

2. Materials and methods

Two stations off the west coast of Barbados at approximately 13°12′N, 59°42′W (8 km from shore in 400 m water) and 13°12′N, 59°40′W (4 km from shore in 200 m water) were visited at intervals of between one week and one month between July 1974 and May 1976 (Fig. 1). At each station a hydrocast was made to collect water for biological studies (Borstad, 1982) as well as salinity which was measured with an inductively coupled Autolab Industries Model 601, Mark III salinometer. Vertical temperature profiles were obtained using a Mark IV Thermoline recorder. Supplemental records included sea surface and air temperature, sea state, wind speed and general meteorological observations as well as Secchi transparency. After July 1975 observations of the color of the sea were made by comparing the apparent color of the Secchi disc as it disappeared to a series of colored K_2CrO_4 and $CuSO_4$ solutions according to Forel-Ule formulae given by Hutchinson (1957).

Independent studies of other locations around the island (Partlo, 1975; Kidd 1978; Hawkins, 1980) and a series of short cruises in May and July 1975 and January 1976 supplement the time series from the two stations described above, and provide some information on spatial variability of the surface layers.

3. Results

The water column was permanently stratified with an upper seasonal pycnocline, the top of which varied in depth from 15 m at some times during July and August, to 100 m or more in February. There was little variation in surface water temperature (25°C in March, to 28.5°C in September) and density in the uppermost layer was controlled by salinity. Figure 2 illustrates the seasonal progression of the surface layer (between 1 and 5 m) salinity at closely spaced intervals for several locations around the island. As there is very little runoff from the island of Barbados (Sander, 1971), inshore surface salinities closely follow those offshore. In Figure 2, lines join data from each station - the longer intervals between sampling at the 8 km station (▲) in 1976 gives a false impression of the variation of salinity. A better impression is arrived at by considering the entire suite of salinity data. Surface salinities decreased from a maximum of about 35.5 ppt during winter to a minimum in summer as a result of the passage of pools or cells of less saline water (from 15 to 35 m deep) superimposed on the generally freshening flow. During the first eight months of the year the envelope representing the range of ten years of earlier salinity data widens progressively: beginning in August-September, salinities increase steadily with a very narrow envelope (1974 being an exception).

The apparent color of the sea, as first subjectively observed from the deck of the vessel and later as measured with a Forel color scale, changed appreciably throughout the year and during the first half of the year, over short times and distances. The relationships between surface salinity, Forel color, Secchi trans-

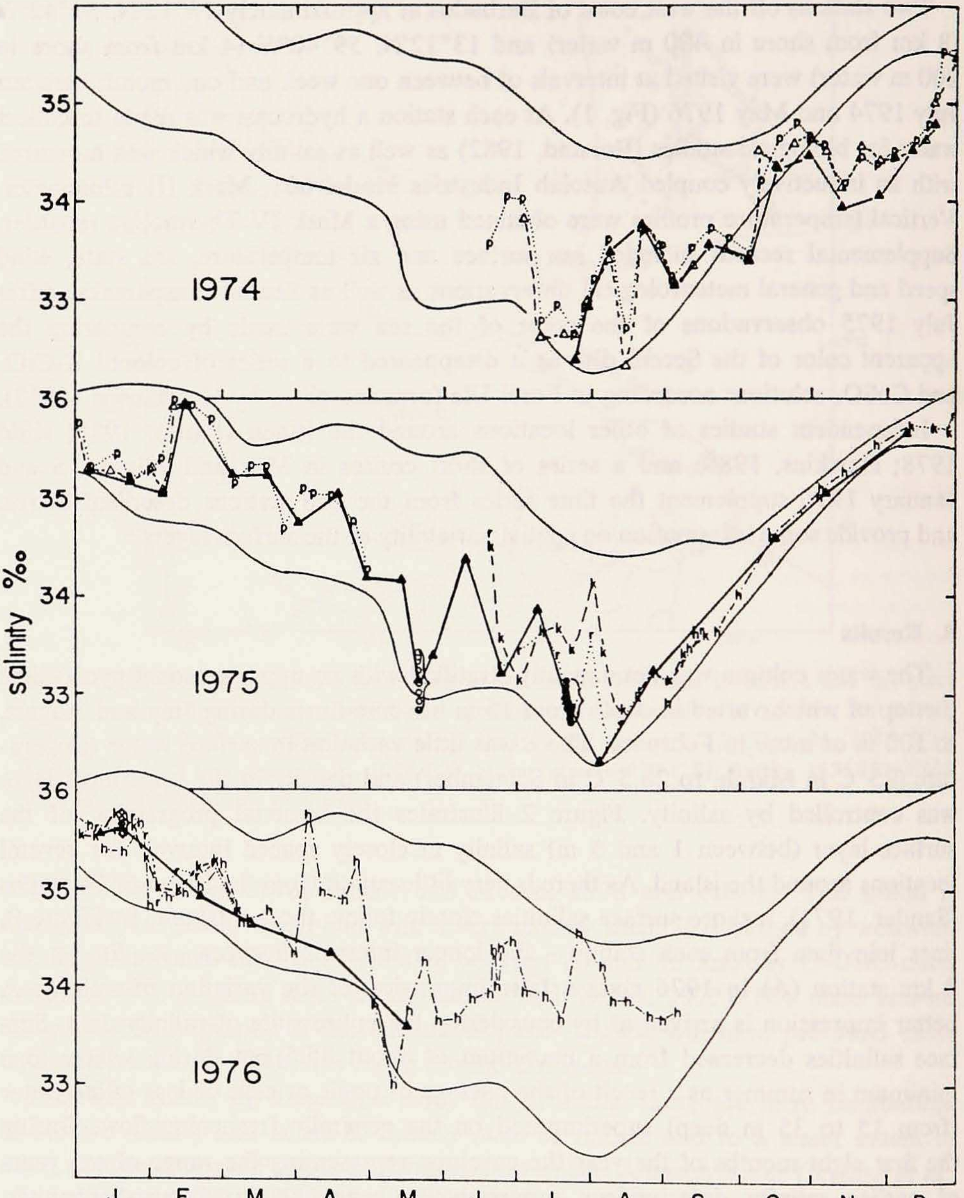


Figure 2. Seasonal progression of surface layer salinity (1-5 m) during 1974-1976 at several stations around Barbados (locations and references in Fig. 1). Envelope marks the range of available data from all previous work (Beers *et al.*, 1965; Steven *et al.*, 1970; Sander, 1971, NODC data) within 10 km of the island.

Table 1. Relationships between color, salinity, Secchi depth and chlorophyll concentration.

Regression equation	Number of pairs	Coefficient of determination
FOREL COLOR = 31.74 - 0.86 Salinity	n = 46	$r^2 = 0.53$
FOREL COLOR = 6.2 - 0.17 Secchi	n = 29	$r^2 = 0.41$
SECCHI DEPTH = 2.56 Salinity - 66.84	n = 29	$r^2 = 0.29$
FOREL COLOR = 2.84 - 1.49 Chlorophyll *a*	n = 46	$r^2 = 0.0025$

parency and 5 m chlorophyll *a* concentration are described in Table 1. The high salinity waters observed in winter were a deep oceanic blue, and more transparent. The coefficients of determination (r^2) indicate that 53% of the variations of Forel color and only 29% of Secchi transparency were associated with variations of surface salinity. There was no relationship between color and chlorophyll *a* content.

4. Discussion

The salinity data in Figure 2 confirm earlier reports of complex temporal fluctuations (Beers, *et al.*, 1965; Steven *et al.*, 1970) but more completely describe many smaller freshwater pools or eddies with rather sharp boundaries superimposed on the general freshening during the first part of the year. That the lower salinity waters appeared distinctly greener is almost certainly a result of the presence of dissolved organic compounds (humic and fulvic acids) of terrestrial origin in Amazon water (Williams, 1968). Such compounds absorb strongly at shorter wavelengths and where the concentration of chlorophyllous pigments is low, will noticeably affect the color of the water (Morel and Prieur, 1977), causing a change from blue to green and then to brown as their concentration increases.

The most important source of these low salinity surface waters at Barbados (and in the western tropical Atlantic) is now generally regarded as the Amazon River (Bohnecke, 1936; Steven and Brooks, 1972; Froelich *et al.*, 1978; Van Bennekom and Tijssen, 1978). Bohnecke's (1936) early Meteor Atlas depicted the seasonal westward spread to the Antilles of a very large tongue of low salinity surface water from the area of Cape Orange. Later studies of the area off the Amazon mouth (Gibbs, 1970; Cadee, 1975) and downstream (Van Bennekom and Tijssen, 1978) demonstrated that the low-density, turbid Amazon water is directed north along the Brazilian coast by the trade winds and becomes entrained in the fast flowing Guiana Current. Studies with widely spaced stations in the region of Cape Orange (Ryther *et al.*, 1967; Metcalf, 1968; Hulbert and Corwin, 1969) suggested that the Guiana Current, in which the Amazon plume is imbedded, did not flow uninterrupted along the South American coast. These authors described pools or lenses of low salinity surface water to the north of Cape Orange (See Fig. 1 for location) which had apparently broken off the main Guiana Current and were surrounded by blue, more saline waters having significantly different physical, chemical and biological character (both in numbers and composition of the plankton). They commented that these low salinity, high silicate lenses of Amazon River water retained a characteristic 'brownish-black' color in the region of Cape Orange.

More recently, direct visual observation of the western tropical Atlantic from spacecraft altitudes has indicated the very great extent of this discoloration. Figure 3 illustrates the approximate boundary of brownish-colored waters recorded by American astronauts conducting visual oceanographic observations during the APOLLO-SOYUZ Test Project in July 1975 (Borstad, 1979). The significance of the fact that the Guiana Current waters are discolored lies in the possibility of using the Coastal Zone Color Scanner on the satellite NIMBUS 7 (Gordon *et al.*, 1980) to study the dynamics of this area on a synoptic scale.

The most extensive and synoptic ship surveys of the Guiana Current have been those conducted by the Venezuelans (Fukuoka, 1971; Febres-Ortega, 1974) using a single vessel occupying stations approximately 100 km apart on systematic grids along the northeastern coast of South America. These surveys detected large apparently continuous meanders in the core of the current in July-August, 1968, April 1970 and April and November of 1972. The data from these surveys (as examples see Figs. 3 through 6) show that with appropriate station spacing, the tongue of low-salinity surface waters from the region of the Amazon River can be followed intact all along the South American coast. The distribution of these low-density waters corresponds with the circulation inferred from dynamic topography for each cruise. Further evidence that these meanders may carry brackish Amazon waters to the vicinity of Barbados is provided by the paths of two near-surface drogues tracked in May of 1970 and 1971 by the UNDP fisheries research vessel *Calamar* (Anon., 1971 a, b). The drogue tracks and isohalines in Figures 3-6, as well as those shown by Parr (1938), Mazeika (1973) and Mazeika *et al.* (1980) suggest that the possibility of direct transport of Orinoco water to Barbados is small. One cannot deny this possibility in light of the confused circulation in the area, however.

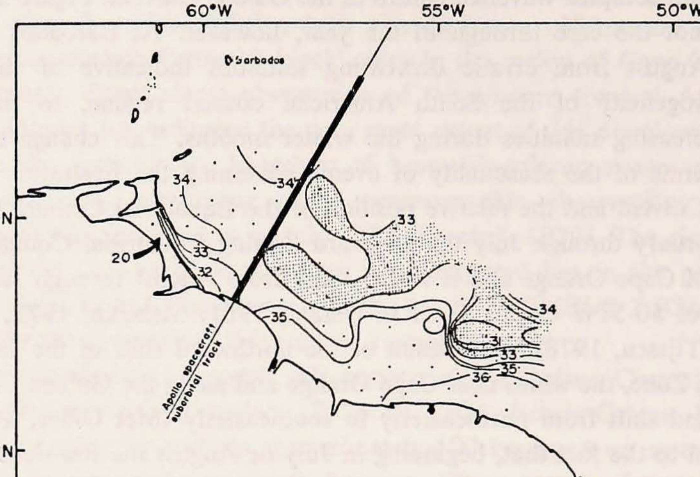
Febres-Ortega and Herrara (1976) has summarized the situation thusly: ". . .circulation of Atlantic water masses off the Guianas is highly variable, with large transient fluctuations associated to the occurrence of meanders. The origin of these meanders has been variously attributed to bathymetric influence, water piling up against the Lesser Antilles, and variations in the winds as well as in river runoff (Fukuoka, 1971; Mazeika, 1973; Febres-Ortega, 1974). It also seems likely that the meanders should be better developed when the water flux is highest. In any case, these meanders gradually sweep the eastern flank of the Antillean Arc, even though their motion is not as swift as that of the currents themselves."

Barbados is in a geographic position to receive the northernmost extensions of these meanders and it is readily apparent that the temporal fluctuations of surface salinity near the island in the first half of the year are a result of the sharp boundaries and complex wavelike nature of the Guiana Current. Figure 2 illustrates that this is not the case throughout the year, however. At Barbados there is a change in August from erratic decreasing salinities indicative of the extreme spatial heterogeneity of the South American coastal regime, to much more constant, increasing salinities during the winter months. This change can be explained in terms of the seasonality of events governing the freshwater supply to the Guiana Current and the relative position of the Equatorial Counter Current.

From February through July the eastward flowing Equatorial Counter Current begins east of Cape Orange and is weak - only from August through January is it strong west of 50-51W (Schumacher in Defant, 1961; Mazeika, 1973; Van Bennekom and Tijssen, 1978). As a result of the northward shift of the Intertropical Convergence Zone, the winds near Cape Orange and along the Guiana Coast weaken in July and shift from northeasterly to southeasterly (Met Office, 1948). This seems related to the fact that, beginning in July or August the low-density surface waters of the Amazon River plume seem to be directed (by Ekman transport?) further offshore to the north and east of Cape Orange where they contribute to the North Equatorial Counter Current (Cochrane, 1965, 1969). This seasonal change in direction of flow near Cape Orange coupled with the reduction of Amazon discharge after June, coincides with a strong decrease in the strength of the Guiana Current (Fuglister, 1951) and a sharply reduced supply of brackish water to the western tropical Atlantic and Caribbean. This combination of events allows a return to more homogeneous conditions. Metcalf (1968), Mazeika (1973) and Mazeika *et al.* (1980) have pointed out the existence of a slow southward flow of homogeneous North Equatorial surface waters of high salinity near 36-37 ppt during the fall and winter. In a companion paper (Borstad, 1982), I have shown that this seasonal change from a coastal-neritic influence to an oceanic-oligotrophic influence has considerable biological importance at Barbados.

Year-to-year variations. It is reasonable to expect that variations of the total annual outflow of the Amazon River might be felt at Barbados as variations in the summer freshening and variability as suggested by Kidd and Sander (1979). Figure 7 illustrates that interannual variations of Amazon flow at Obidos, Brazil can explain some 64% of the variations observed at Barbados of the minimum summer salinity. This is almost exactly the same percentage contribution to summer freshening in the western tropical Altantic by the Amazon River calculated by Froelich *et al.* (1978) using salinity-silicate relationships for the western tropical Atlantic and eastern Caribbean.

During the period 1968-1975, the minimum summer salinity at Barbados was decreasing and the maximum summer discharge of the Amazon River was increasing. The magnitude of the Amazon discharge increase in recent years can be



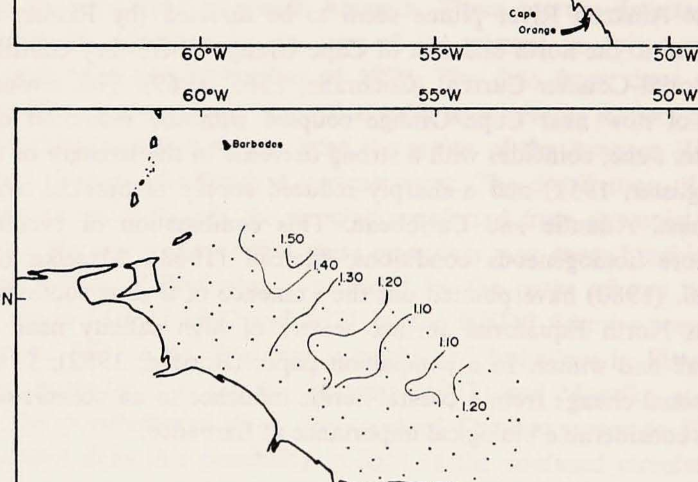
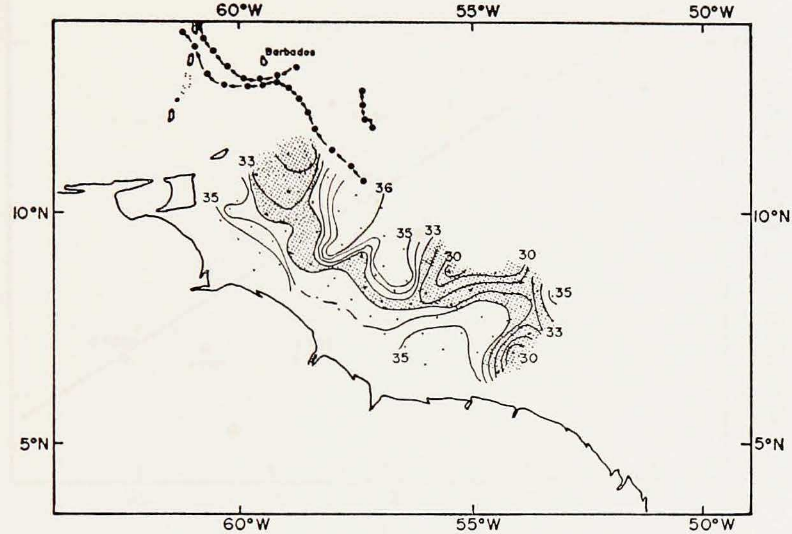


Figure 3. Surface salinity off the Guiana Coast during July 7 to August 17, 1968 (after Urosa and Rao, 1974). Oblique line marks suborbital track for revolution 104 of the APOLLO 5 spacecraft July 23, 1975 when visual observations of the brown discoloration of the Guiana Current were made from spacecraft altitudes. Wide line indicates extent of discoloration.

Figure 4. Dynamical topography relative to 800 db, July 7 to August 17, 1968 along the Guiana Coast (from Fukuoka, 1971).



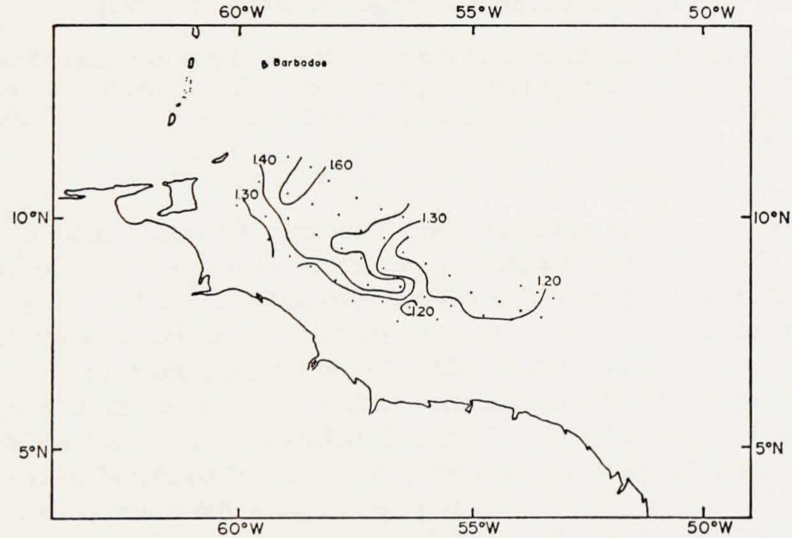


Figure 5. Surface salinity off the Guiana Coast during April 7 to 23, 1970 (R.V. *Lasalle*, NODC cruise #SD930010). Small arrows join the noon positions of two parachute drogues tracked by R. V. *Calamar*, May 5-18, 1970 and May 21-30, 1971 (the more northerly of the two tracks) (Anon., 1971a, 1971b).

Figure 6. Dynamical topography relative to 800 db, April 7 to 23, 1970 along the Guiana coast (from Fukuoka 1971).

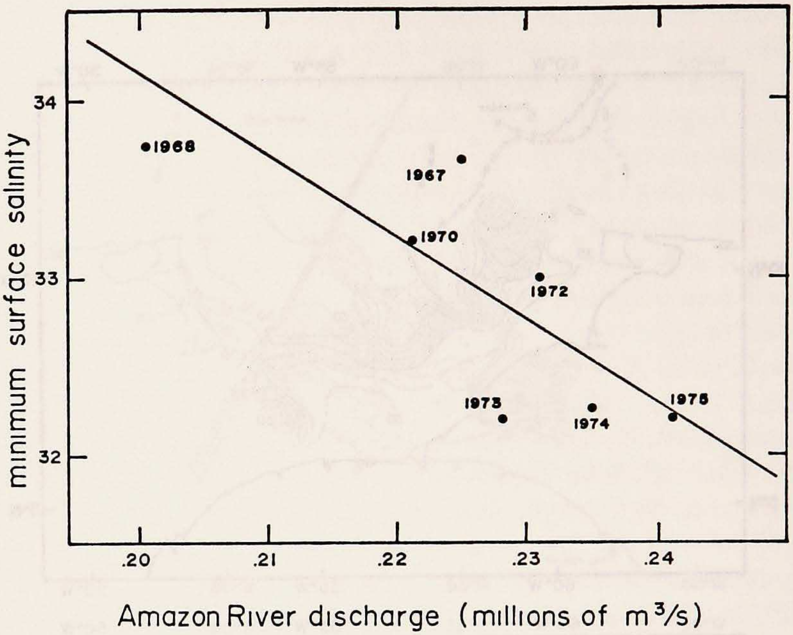


Figure 7. Relationship between minimum summer surface salinity at Barbados and the maximum monthly mean discharge of the Amazon River at Obidos, Brazil calculated from gauge height and discharge rating data. S‰ = 43.52-.0468 × Discharge (Discharge in $10^6 m^3 s^{-1}$).

assessed by examination of Figure 8, which illustrates the annual mean, maximum (usually May or June) and minimum (November) discharge at the Obidos river gauge station for the period 1928 through 1946 and 1968-1975.[4] The maximum, mean and minimum discharge in the more recent period has increased substantially over those during the 1930's and 1940's. Rating tables and gauge heights supplied by Dr. Joaquim Guedes de Amorim Coelho of the Brazilian Departamento Nacional de Aguas e Energia Eletrica (DNAEE) were used to calculate river discharge for both periods. It may be possible to equate these alterations in Amazon discharge to the massive forest clearing operations in Amazonia, as Gentry and Lopez-Parodi (1980) have done. They also have shown a consistent increase in the Amazon flow (at a gauge situated at Iquitos, Peru) in the absence of significant changes in rainfall and pointed out that perhaps a quarter of the forest cover of Amazonia has been destroyed in recent years. If there is a causal relationship

4. Annual discharge at the river mouth calculated by Oltman, (1968) and quoted by Gibbs (1967, 1970) for the period 1928-1946 (175,000 m^3s^{-1}) takes into account an estimated 18,000 m^3s^{-1} contribution by rivers downstream of Obidos. Also, this estimate which was based on only three complete measurements of the discharge made in 1963, is higher than the estimate given here because the stage-discharge relationship developed by the DNAEE between 1967 and 1975 (n=40) is significantly different than Oltmans.

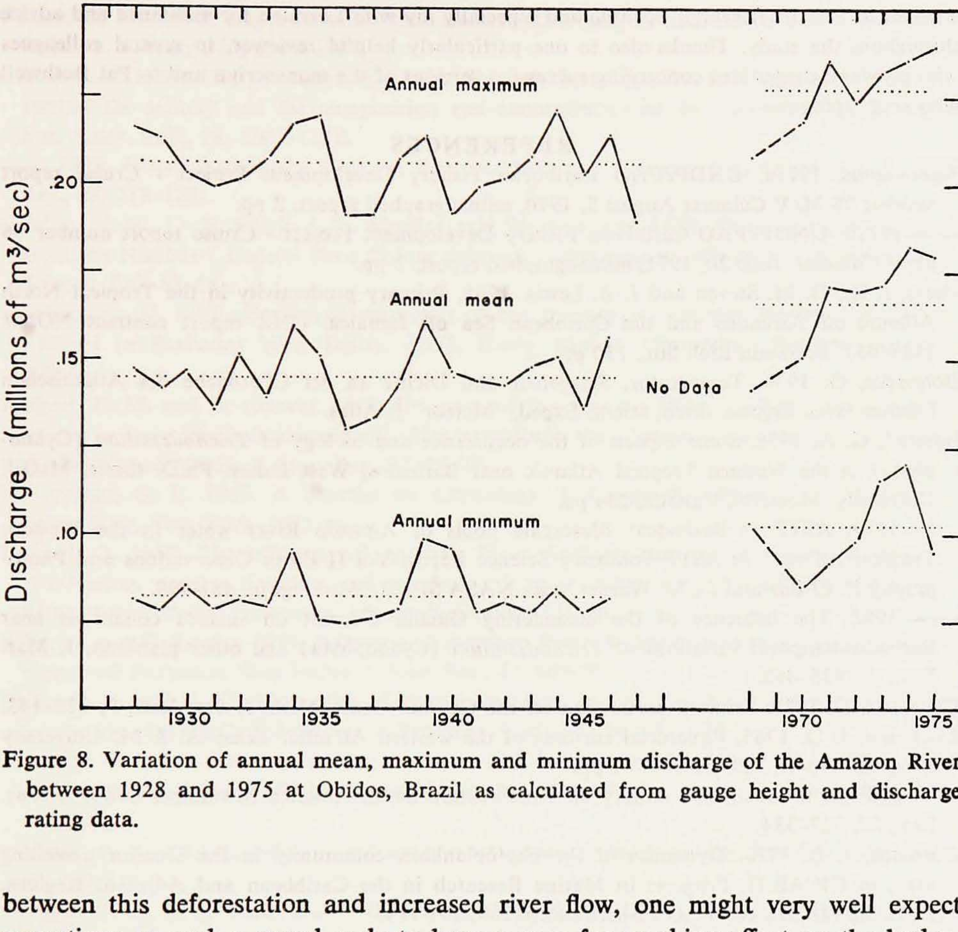


Figure 8. Variation of annual mean, maximum and minimum discharge of the Amazon River between 1928 and 1975 at Obidos, Brazil as calculated from gauge height and discharge rating data.

between this deforestation and increased river flow, one might very well expect operations on such a grand scale to have a very far reaching effect on the hydroclimate of much of the western tropical Atlantic. They should therefore be monitored closely.

In summary it can be said that the waters around Barbados and in the eastern Caribbean are very heterogeneous, with very different origins and past histories. In these regions surface salinity is an important water mass characteristic, indicating the presence of coastal and river derived contributions. It is imperative that these facts be kept in mind in biological oceanographic or fisheries-related studies in these regions. A companion paper (Borstad, 1982) describes the link between surface salinity and the biology of the planktonic regime at Barbados.

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