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Tracing Amazon River water into the Caribbean Sea

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ABSTRACT

Monthly Amazon River discharge is correlated to historical monthly sea surface salinity (SSS) in the western tropical Atlantic Ocean and the Caribbean Sea. At Barbados a very high inverse correlation ($R^2 = 0.92$) exists if the discharge is lagged by two months, which corresponds to the travel time from the Amazon mouth to Barbados. Due to its proximity to Barbados, a small amount of the correlation can also be attributed to the Orinoco River. Between Barbados and the central Caribbean Sea (75W) the peak correlation of Amazon River discharge and SSS occurs at progressively longer lag times, representing the longer travel time. The correlation is highest at Barbados and diminishes with distance downstream. Downstream of the central Caribbean Sea (75W) no correlation is evident, as the Amazon water becomes too diluted to be clearly defined by available data. The results of the analysis are used to calculate surface current speeds of 0.34 ± 0.09 m/s from the Amazon mouth to Barbados and 0.10 ± 0.02 m/s from Barbados to the central Caribbean Sea (75W). Downstream of Barbados a subsurface maximum in correlation develops. The correlation is eroded more strongly at shallower depths due to more intense surface processes (e.g., evaporation and precipitation).

1. Introduction

The Amazon River discharges an average of 170,000 m^3/s of water into the western tropical Atlantic Ocean at the Equator (Fig. 1). From that point the Amazon water and associated constituents are transported by the ocean surface currents, with a gradual attenuation due to ocean mixing. The sea surface salinity (SSS) distribution clearly shows

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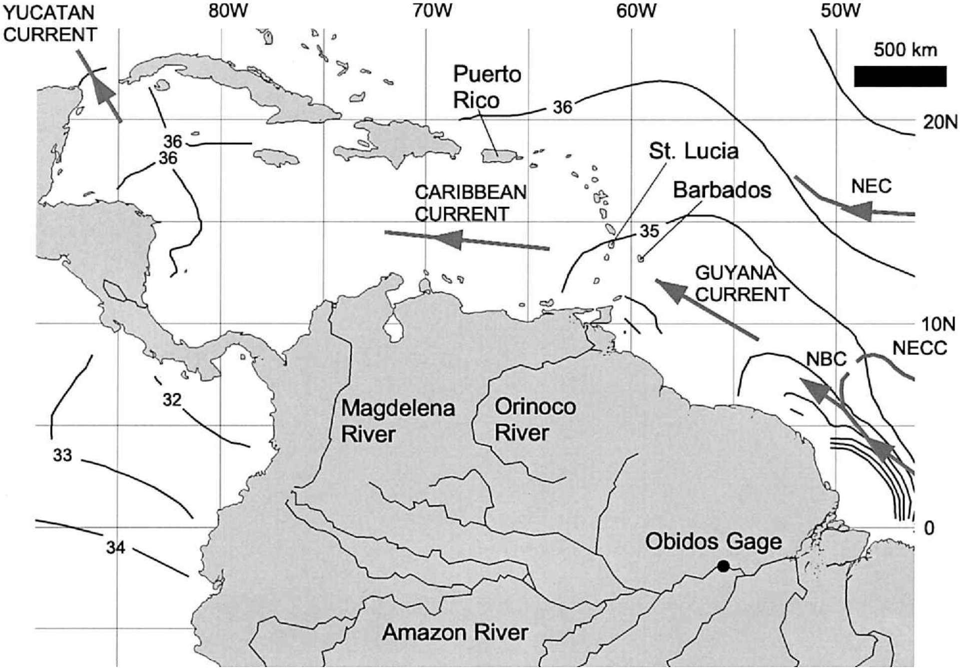

Figure 1. Mean annual sea surface salinity (SSS) and major ocean surface currents in the vicinity of the Amazon River mouth and Caribbean Sea [NBC = North Brazil Current, NEC = North Equatorial Current, NECC = North Equatorial Countercurrent].

the influence of the Amazon, as a low salinity plume stretching passed Barbados and into the Caribbean Sea. The Amazon water acts as a tracer of surface currents in the western tropical Atlantic Ocean and Caribbean Sea.

The major ocean current in the vicinity of the Amazon discharge is the North Brazil Current (NBC) (Fig. 1; Johns *et al.,* 1990; Didden and Schott, 1993; Fratantoni *et al.,* 1995; Richardson *et al.,* 1994; Mooers and Maul, 1998; Goni and Johns, 2001), which is part of the northward flowing western boundary current system. The NBC curls to the east and south near 6N in what is known as a retroflection to feed the North Equatorial Countercurrent (NECC). The retroflection is a seasonal phenomenon that has been observed to occur from about June through March. At other times the NBC continues along the coast to feed the Guyana Current. During the retroflection period the NBC frequently closes in on itself and pinches off an eddy that continues northwestward. The Guyana Current and NBC retroflection eddies represent a significant source of water for the Caribbean Sea. The main inflow to the Caribbean Sea occurs through several passages between the Antilles Islands (Gordon, 1967; Johns *et al.,* 2002). This flow feeds the Caribbean Current, which flows westward and northward exiting the Caribbean Sea through the Yucatan Channel.

Several researchers have studied the far-field distribution of Amazon River water.

Steven and Brooks (1972) found an inverse relation between SSS and silicate at Barbados and concluded that the low SSS water is from the Amazon. Froelich *et al.* (1978) also found an inverse relation between SSS and silicate at Puerto Rico. They showed that minimum SSS progresses downstream from Barbados to St. Lucia to Puerto Rico. Using a simple mixing model, they conclude that at least 60% of the freshwater in the eastern Caribbean Sea is from the Amazon. Borstad (1982) examined seasonal and interannual variability of salinity at Barbados and explained it with changes in current patterns and Amazon discharge rate. Dessier and Donguy (1993) statistically analyzed historical SSS data from the tropical Atlantic Ocean and Caribbean Sea and identified Amazon water in the Atlantic Ocean (5–10N, 30–40W; 1,800 km from the source) and West Indies (16–18N, 57–60W; 2,100 km from the source). They also noticed the occurrence of low SSS in the Caribbean Sea progressively farther downstream with time. Deuser *et al.* (1988) analyzed sediment trap data at Barbados and observed a correlation between SSS and deep-water particle flux. They concluded that the increased particle flux is due to increased productivity in water from the Amazon. Bowles and Fleischer (1985) analyzed sediment cores collected in the southeastern Caribbean Sea and identified the Amazon as a major source of that sediment. Moore *et al.* (1986) used ^{228}Ra, salinity and silica tracers to detect the presence of Amazon water in the surface waters of the Antilles and eastern Caribbean Sea. Kelly *et al.* (2000) also used ^{228}Ra to determine that the freshwater at Barbados is from the Amazon. Müller-Karger *et al.* (1988) used Coastal Zone Color Scanner (CZCS) satellite images and drifting buoys to trace the Amazon water. They showed that the fate of Amazon water is strongly influenced by the seasonal pattern of the NBC retroflection. Signorini *et al.* (1999) presented Sea-viewing Wide Field-of-View Sensor (SeaWiFS) images that also show the seasonal effect of the NBC retroflection on the Amazon plume.

The objective of the research presented in this paper is to trace the Amazon water using seasonal variability of freshwater (SSS anomaly). SSS alone is not an ideal tracer, because multiple sources and sinks, such as other rivers, evaporation (E) and precipitation (P), may mask the Amazon signal. However, the signal of the Amazon seasonal variability is specific enough to distinguish it from other sources. The seasonal signal in SSS is expected to correlate negatively with the Amazon discharge, when corrected for travel time and the affects of $E - P$ and other sources are accounted for. Although the seasonal variability of SSS downstream of the Amazon has been explained qualitatively using the Amazon discharge rate (e.g. Borstad, 1982), this has not been done quantitatively using a large database of historical SSS measurements (1919–1997) and covering a large area (0–5,000 km downstream of the Amazon discharge). A similar analysis was done by Salisbury *et al.* (2001) who correlated monthly Mississippi and Orinoco River flow rates to water radiance from SeaWiFS satellite images. However, they did not explicitly account for the travel time. If the travel time is not incorporated into the analysis, correlations are only meaningful within distances corresponding to a few months travel time from the source.

First the data sources are discussed. Then the analysis for one location, Barbados, is

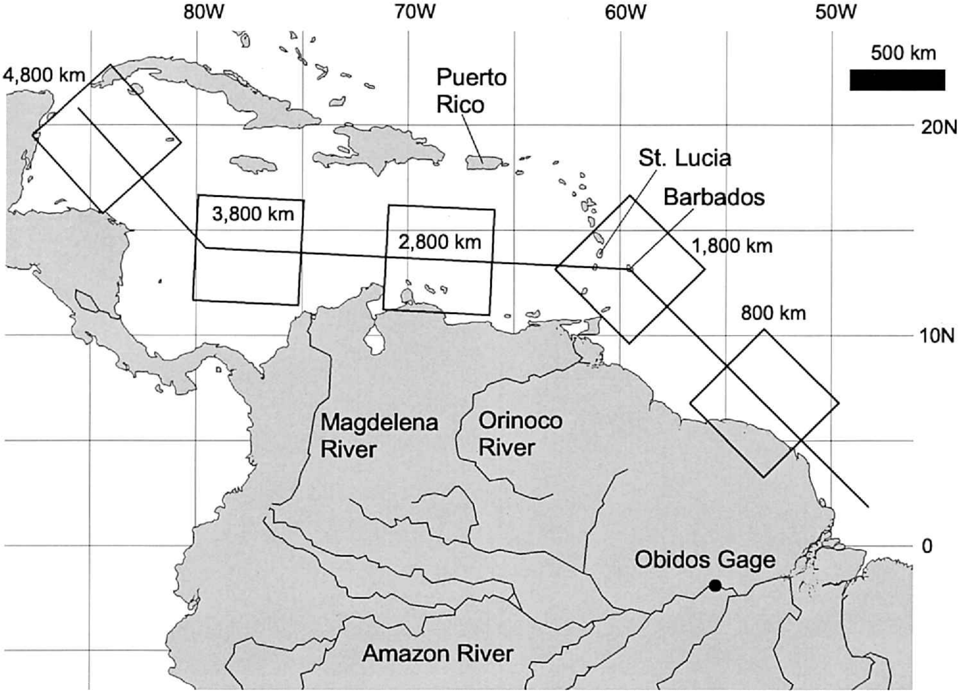

Figure 2. Amazon River streamline and boxes used to aggregate sea surface salinity (SSS) data (for clarity only 5 of the 46 boxes used are shown).

presented. Following that, the analysis is repeated for other locations along the Amazon streamline and with depth. Lastly the conclusions of the research are presented.

2. Data sources

The Amazon discharge record at Obidos (1928–1947, 1968–1998; Bodo, 2001; Fig. 1) is used in this study. Two major tributaries (Tapajos and Xingu rivers) enter the Amazon downstream of Obidos and the Para/Tocantins river discharges near the Amazon mouth. The annual discharge of each of these systems is about 5% of the Amazon. The seasonal pattern of the Tapajos and Xingu rivers is significantly different from that at Obidos, which causes the peak at the mouth to occur earlier in the year than at Obidos (Lentz and Limeburner, 1995). However, the difference is less than one month and is, therefore, neglected in this study. Historical SSS data were obtained from Conkright *et al.* (1998). The data span the period 1919–1997.

3. Salinity at Barbados

SSS data are grouped in a 5° × 5° latitude/longitude box at Barbados (Fig. 2). The horizontal size of the box is based on two criteria. The box should be (1) large enough to provide sufficient number of data so the results are not significantly affected by individual outliers, and (2) be small enough to be representative of a specific area. The SSS is defined as the average salinity within the upper 25 m of the water column, based on the vertical analysis presented later in this paper. Barbados is chosen as the center of the box because the island has been the subject of numerous previous Amazon tracer investigations (e.g., Steven and Brooks, 1972; Borstad, 1982; Kelly *et al.,* 2000) and it is just downstream of the complex NBC retroflection. The box is angled at 45° of the latitude/longitude grid, so as to be aligned along the approximate axis of the Guyana Current.

The monthly mean SSS and variability (Fig. 3a, ± 2 standard deviations) reveals a strong seasonal SSS signal. Within the year the mean SSS varies from 34.24 in June to 35.48 in January. The mean for April is abnormally low (open symbol). This is due to data collected during one sampling cruise in April 2–5, 1985. We suspect that the sampling was performed within a low salinity pool entrapped within an NBC eddy. These events have been observed previously (Borstad, 1982; Stansfield *et al.,* 1995; Kelly *et al.,* 2000). The data from that sampling cruise are omitted in the subsequent analysis (closed symbol).

Although previous tracer studies have established the Amazon as the major *source* of freshwater at Barbados (e.g., Steven and Brooks, 1972; Borstad, 1982; Kelly *et al.,* 2000), the *seasonal variability* of SSS can be effected by factors other than the Amazon discharge rate. This includes seasonal changes in current pattern (e.g., NBC retroflection; Müller-Karger *et al.,* 1988), near field processes (e.g., winds; Lentz and Limeburner, 1995), $E - P$, and other rivers (i.e. Orinoco River; Müller-Karger *et al.,* 1989). The effect of near field processes and changes in current pattern are discussed further in the next section. The effect of atmospheric exchange on SSS is investigated (Fig. 3b; based on Schmitt *et al.,* 1989). The seasonal pattern of $E - P$ agrees qualitatively with that of SSS at Barbados, with low $E - P$ corresponding to low SSS. However, $E - P$ is always positive, which can only cause an increase in SSS. Dessier and Donguy (1993) also concluded that the effect of precipitation on SSS in the eastern Caribbean Sea is minor. Clearly a nonlocal freshwater source is needed to close the SSS budget.

The monthly Amazon discharge (Fig. 3c, open circles) varies from 112,000 m^3/s in November to 229,000 m^3/s in May and June. In general, the seasonal pattern agrees with that of SSS at Barbados. However, a two month shift is apparent, which is due to the travel time of Amazon water from its mouth to Barbados. To account for the travel time, the Amazon discharge is lagged by two month (Fig. 3c, filled circles). This is in agreement with Steven and Brooks (1972) who estimated the travel time to be 70–80 days (2.5 month). The analysis assumes a relatively steady flow pattern from the Amazon mouth to Barbados. Although, the NBC current pattern is known to change within the year (e.g., Müller-Karger *et al.,* 1988) historical SSS data indicated that a significant fraction of the Amazon water is carried northwestward toward the Caribbean Sea even during periods of NBC retroflection (Dessier and Donguy, 1993; Lentz, 1995).

The Orinoco River discharges close to Barbados (Fig. 1) and has a seasonal pattern almost inverse to SSS at Barbados (Fig. 3c, open squares). This suggests the Orinoco could

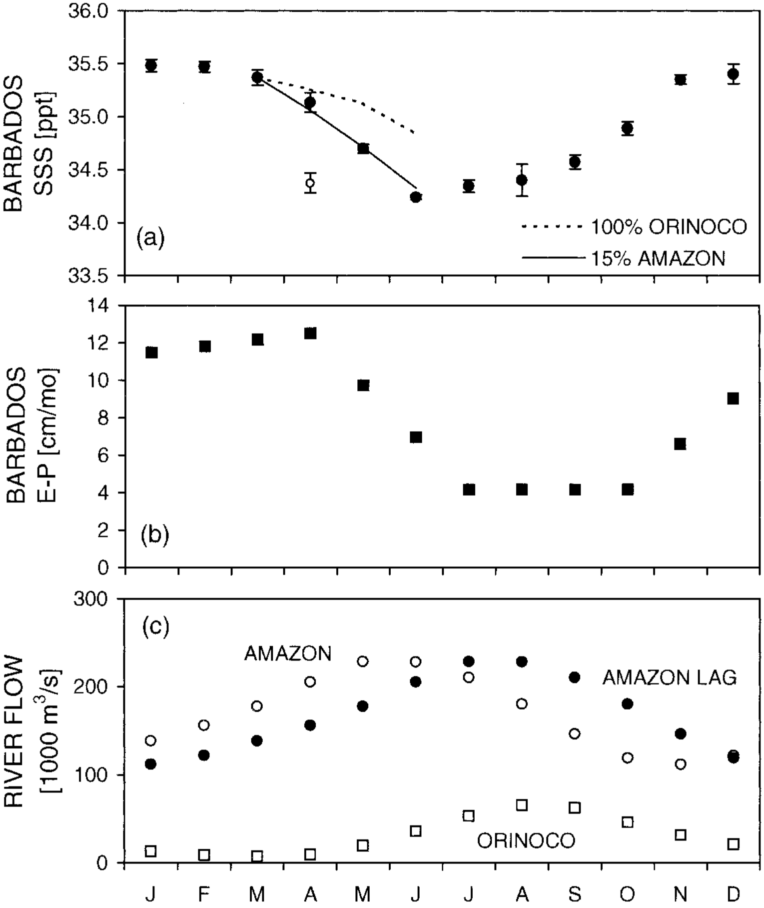

Figure 3. (a) Monthly sea surface salinity (SSS) at Barbados. The SSS for April is abnormally low (open symbol), which is due to one sampling event. That data are omitted (closed symbol). Lines correspond to box dilution model for Amazon and Orinoco rivers. (b) Monthly evaporation minus precipitation ($E - P$) at Barbados. (c) Amazon and Orinoco river flow rates. The Amazon flow rate is lagged by two month (filled circle) to account for the travel time from the Amazon mouth to Barbados.

drive the SSS signal at Barbados. However, the Orinoco peak flow does not occur until August when SSS at Barbados is starting to increase again. This phase discrepancy increases if any lag due to travel time is taken into account. Further, a simple dilution model applied to the 5° × 5° × 25 m box for the time of significant SSS decrease (March–June) shows that the Orinoco does not have the required freshwater flow (Fig. 3a). Only 15% of the two-month lagged Amazon is required to account for the SSS decrease. Since the seasonal pattern of the Orinoco is similar to the two-month lagged Amazon it is difficult to distinguish their relative contribution to SSS at Barbados and downstream.

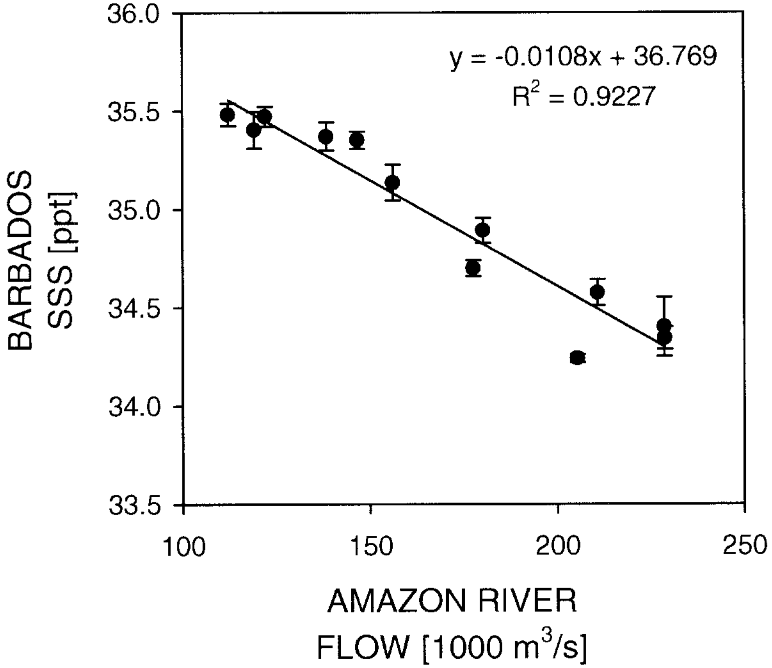

Figure 4. Monthly sea surface salinity (SSS) at Barbados versus 2 month lagged monthly Amazon River flow rate.

However, the seasonal patterns and magnitudes of the two rivers do suggest that the seasonal SSS signal at Barbados is mostly due to the Amazon. This is consistent with the results of radionuclide tracer studies (e.g., Kelly *et al.,* 2000).

The two-month lagged Amazon discharge reveals a linear inverse relationship to SSS at Barbados (Fig. 4). The coefficient of determination (R^2) is 0.92, indicating that 92% of the variability in the monthly SSS is explained by linear regression with Amazon discharge. The R^2 for the Orinoco (no lag) is 0.58.

4. Salinity along the Amazon streamline

The analysis for one location (Barbados) is now repeated for other locations along the Amazon streamline. The box is moved in 1° steps 5,000 km along the approximate streamline as defined by mean surface current pattern (Wüst, 1964) from the Amazon mouth through the Caribbean Sea to the Yucatan Channel (Fig. 2). There is no appreciable seasonal pattern in monthly SSS upstream of the Amazon (36.03 ± 0.13; box center: °0, 40W), so the SSS anomaly signal within the study area is a reflection of the Amazon pulse of freshwater. The size and shape of the box is kept constant, but the rotation angle is adjusted to coincide with that of the streamline. For each location the correlation of SSS and Amazon seasonal discharge is quantified as for Barbados (R^2). However, since the

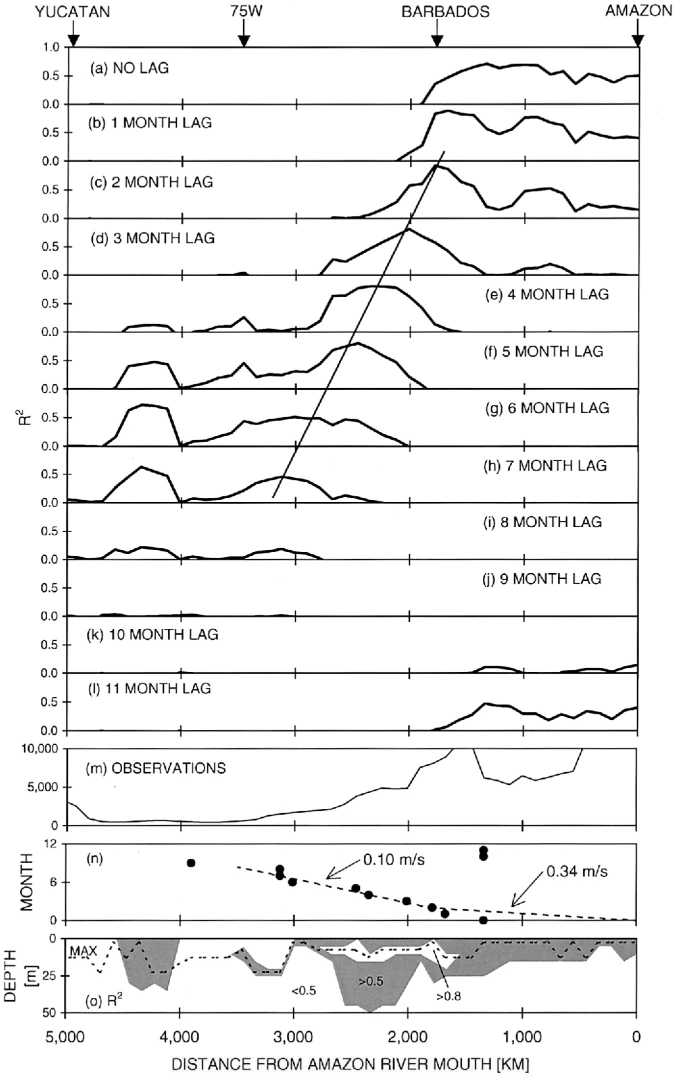

Figure 5. (a)–(l) Coefficient of determination (R^2) for monthly sea surface salinity (SSS) and Amazon River flow rate. The analysis is performed for different locations along the streamline and different lag times. (m) Number of observations per box. (n) Lag time for maximum correlation and calculated current speeds. (o) Depth of maximum correlation (dotted line) and 0.5 and 0.8 R^2 contours.

travel time along the streamline varies, the analysis is done for all twelve possible lag times (no lag, one-month lag . . . eleven-month lag). The coefficient of determination (R^2) varies along the streamline for the different lag times (Fig. 5). For clarity, only the R^2 values for negative or inverse correlations of Amazon discharge to SSS are plotted.

The highest correlation occurs when the lag time equals the travel time. For a two-month lag (Fig. 5c), for example, the correlation is highest at Barbados (~1,800 km from the Amazon mouth). As expected downstream of Barbados the peak correlation occurs progressively at longer travel times. The correlation also decreases with distance from the Amazon mouth indicating that progressively less of the SSS variability is explained by the Amazon discharge, due to the attenuating affects of ocean mixing.

Our results are in agreement with those of other researchers who looked at specific locations within the Caribbean Sea. Froelich *et al.* (1978), for example, observed minimum SSS at Puerto Rico during late October and early November. This is five months after the Amazon peak discharge (May–June). In this study the highest correlation between SSS at Puerto Rico (~2,600 km) and Amazon flow is calculated for a five-month lag (Fig. 5f).

For locations closer to the Amazon mouth (0–1,500 km) a downstream progression of the peak is not as apparent as for Barbados. However, the correlation is highest for lag times close to zero (eleven-month lag to one-month lag), indicating a relatively short travel time. The results indicate that the surface current pattern in the near field is not steady and continuous. This is in agreement with previous studies that found that the near field structure of the Amazon plume is influenced by wind forces and the complex transients associated with the NBC (Lentz, 1995; Lentz and Limeburner, 1995; Johns *et al.,* 1990; Didden and Schott, 1993; Fratantoni *et al.,* 1995; Richardson *et al.,* 1994; Goni and Johns, 2001). Lentz (1995) has examined near-field (4S–10N) historical SSS data and found that the seasonal pattern of the Amazon discharge, winds and NBC pattern effect the size and shape of the Amazon plume. In the NBC retroflection region (6N), the current pattern exhibits a strong seasonal cycle.

It appears that by the time the Amazon water crosses the central Caribbean Sea (75W; 3,500 km from the river mouth) the correlation has diminished. Further downstream (4,300 km) there is a peak in correlation. Since the peak is relatively isolated it cannot be attributed to the Amazon. Also note the low number of observations in that area (Fig. 5m). In the western Caribbean Sea heavier precipitation has also been found to effect SSS (Dessier and Donguy, 1993).

The location of the peak correlation can be used to calculate the travel time of Amazon water and thus the speed of the surface current. Figure 5n shows the lag time at which the maximum correlation occurs. For this analysis only results from the region where the influence of the Amazon flow is apparent (0–4,000 km) are included. From the Amazon mouth to Barbados the travel time is two months, corresponding to a velocity of 0.34 ± 0.09 m/s. From Barbados (1,800 km) to the central Caribbean Sea (75W; 3,500 km) the calculated velocity is 0.10 ± 0.02 m/s.

The current speed estimates from this study can be compared to those of other researchers. Mean alongshore currents over the shelf in the near-field area of the Amazon plume were estimated to be 0.40 m/s (Curtin, 1986), 0.36 and 0.72 m/s (2 stations; Lentz, 1995), 0.34, 0.72 and 0.64 m/s (based on 9 drifters; Limeburner *et al.,* 1995) and 0.46 and 0.83 m/s (2 stations; Johns *et al.,* 1998). The speed of retroflection eddies has been estimated to be 0.11–0.17 m/s (Johns *et al.,* 1990), 0.15 m/s (Didden and Schott, 1993), 0.09 m/s (Richardson *et al.,* 1994), and 0.08–0.16 m/s (Fratantoni *et al.,* 1995). These previous estimates indicate that the velocity is about 0.54 m/s from the Amazon mouth (Equator) to the retroflection region (6N) and 0.12 m/s from there to Barbados (13N). The distance weighted average of those values is 0.31 m/s, which is effectively the same as the 0.34 ± 0.09 m/s estimated in this study. However, the above estimate is based on the speed of retroflection eddies. During the continuous NBC flow pattern Müller-Karger *et al.* (1988) estimated the surface current speed based on drifter buoys to be larger (about 0.90 m/s). Mooers and Maul (1998) present average surface currents for the eastern Caribbean Sea (Grenada and Venezuela basins; 2,000–3,000 km from the Amazon source) varying from about 0.05 to 0.30 m/s. Carton and Chao (1999) estimate the westward propagation speed of eddies within the Caribbean Sea, based on TOPEX/POSEIDON altimetry data and model results, at 0.12 m/s. Fratantoni (2001) calculated a mean speed of the Caribbean Current, based on drifter data, of 0.31 m/s. The estimate from this study (0.10 ± 0.02 m/s) falls within the range of Mooers and Maul (1998), is very close to the estimated eddy propagation velocity (Carton and Chao, 1999), but is lower than the value of Fratantoni (2001). Overall, the travel time estimates from this study appear reasonable.

5. Depth penetration of the Amazon signal

The depth penetration of the Amazon signal, an effect of vertical mixing, is analyzed by examining the correlation between salinity and lagged Amazon discharge at various depths. For this analysis the data are grouped in 5 m depth intervals. Upstream of Barbados (900 km from Amazon, Fig. 6c) the correlation is confined to the top 15 m. At Barbados (1,800 km from Amazon, Fig. 6b) the correlation depth extends to 30 m and downstream (2,600 km from Amazon, Fig. 6a) it extends to 45 m. Downstream of Barbados the maximum correlation is below the top interval. This feature is not very pronounced and could be coincidental. Along the Amazon streamline the correlation extends to progressively larger depths from the mouth to the western Caribbean Sea (2,500 km) (Fig. 5o). Also, the depth of maximum correlation (Fig. 5o, dotted line) occurs mostly below the surface beyond about 1,500 km from the mouth, indicating that a subsurface maximum does develop. It is plausible that the correlation erodes more strongly at the surface due to the local effects of evaporation and precipitation, with the Amazon signal preserved in the sub-surface layer.

6. Conclusions

The seasonal discharge of the Amazon River is highly correlated with sea surface salinity (SSS) at Barbados if the Amazon discharge is lagged by two months, the two-month lag representing the travel time of water from the Amazon mouth to Barbados. Between Barbados and the central Caribbean Sea (75W) along the axis of the Caribbean Current the peak correlation occurs at progressively longer lag times, representing the

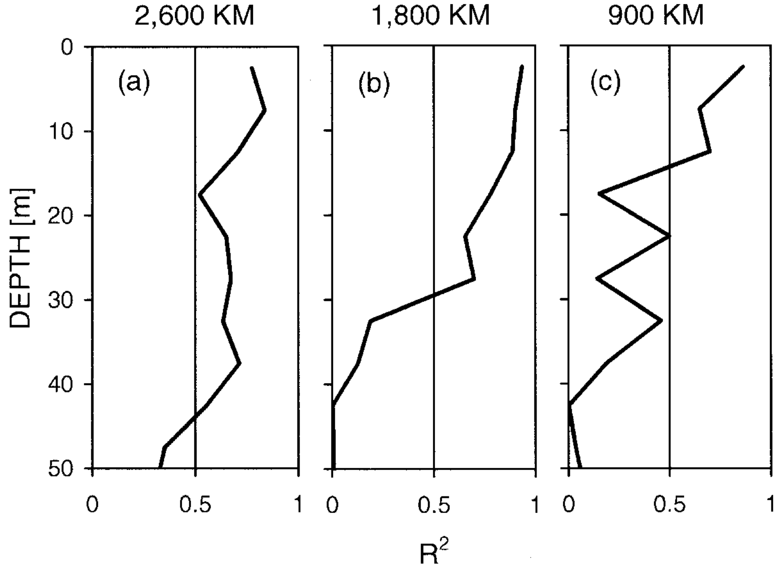

Figure 6. Coefficient of determination (R^2) for monthly salinity (SSS) and lagged Amazon River flow rate at 5 m depth intervals. (a) 2,600 km from Amazon (5 month lag). (b) 1,800 km from Amazon (Barbados, 2 month lag). (c) 900 km from Amazon (1 month lag).

longer travel time. The correlation is highest at Barbados and diminishes with distance downstream. The region upstream of Barbados does not show this progression, because of the complex transient current pattern within the North Brazil Current (NBC) retroflection. Downstream of the central Caribbean Sea (75W) no correlation between Amazon flow and SSS is evident, as the Amazon water becomes diluted or the data set is inadequate to properly resolve the Amazon signal. The progression of peak correlation is used to calculate surface current speeds of 0.34 ± 0.09 m/s from the Amazon mouth to Barbados and 0.10 ± 0.02 m/s from Barbados to the central Caribbean Sea (75W). These values are in general agreement with those of other researchers. The depth of the correlation increases with distance from the Amazon mouth due to vertical mixing. Farther downstream a subsurface maximum in correlation develops. The correlation is eroded most strongly at shallower depth, presumably due to surface processes (e.g., evaporation and precipitation).

Rivers are important variables in oceanography as their freshwater affects SSS and the buoyancy of the surface layer, and they represent a source of materials exotic to the ocean and important to biological activity. Despite this importance, tracing river water over large distances has not been a main focus of oceanographers' attention. There are a few studies that trace the Mississippi to southern Florida and along the southeast coast of the US (e.g., Ortner *et al.,* 1995), and there are a few tracing the Amazon (see references above), but surprisingly few in other areas. This is perhaps because of a lack of SSS data. Tracing those super rivers over great distances may become an important endeavor, once sufficient data are available. This may occur when surface salinity sensors are placed aboard satellites, such as proposed as part of the Aquarius satellite. Then our views of SSS, which are still of those smoothed atlas-like maps, derived from discrete data points far apart in space and time, will change, as did those of sea surface temperature since the advent of satellite IR data.

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