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NOTE

On the offshore dispersal of the Amazon's Plume in the North Atlantic: Comments on the paper by A. Longhurst, "Seasonal cooling and blooming in tropical oceans"

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Abstract—Coastal Zone Color Scanner (CZCS) satellite images show extensive plumes of discolored water extending from South America into the western tropical Atlantic. The most conspicuous plumes originate at the mouths of the Amazon and Orinoco Rivers, and plumes originating at smaller rivers can also be seen from space. In a recent paper by Longhurst (1993), the plume associated with the Amazon River was attributed to phytoplankton blooms stimulated by nutrients supplied via eddy upwelling. We revisit the argument that this plume is of riverine origin, and offer evidence that material present near continental margins can be advected offshore and trace circulation patterns in the adjacent ocean.

ON THE OFFSHORE DISPERSAL OF THE AMAZON'S PLUME IN THE NORTH ATLANTIC

Coastal Zone Color Scanner (CZCS) satellite images show two major plumes of discolored water in the western tropical Atlantic (Fig. 1). Both plumes form during August through November every year, are over 100 km wide, and extend over 1000 km into the adjacent ocean. One plume originates at the Amazon River mouth near the equator, and the other at the Orinoco River mouth near 9°N (Anon, 1989). The Amazon plume flows around the North Brazil Current retroflection near 5–10°N, and is carried eastward in the meandering North Equatorial Countercurrent. The Orinoco plume flows into the Caribbean Sea and drifts northwestward across the Caribbean, reaching Puerto Rico around October.

In a recent paper, Longhurst (1993) brings attention to the importance of tropical oceans as highly productive regions, previously overlooked in efforts at estimating global oceanic primary production. He proposes conceptual models to explain very large blooms of phytoplankton seen for the first time in ocean color imagery from the CZCS. Among his

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proposals, Longhurst (1993) argues that the plume seen in the CZCS images off the Amazon delta, extending into the tropical Atlantic off northeastern South America, is caused by eddy upwelling (e.g. Woods, 1988). He particularly rejects the notion that the discoloration tracing the North Brazil Current retroflection and North Equatorial Countercurrent is due to the dispersal of Amazon water. He explains that eddy upwelling occurs around the retroflection and associated anticyclonic features sufficiently strongly to induce an algal bloom, leading to the patterns detected in the images.

The physical, biological and chemical dynamics of the plumes seen in the western Atlantic are important for several reasons. The discoloration associated with the plumes, retroflection, and western countercurrent is very large (surface area exceeding 2×10^5 km^2) and quite distinct from the surrounding water. This discoloration is an important tracer for the fate of over 15% of the world's annual riverine input to the ocean, and it represents a potential source of nutrients and organic material to an otherwise oligotrophic interior tropical Atlantic Ocean and Caribbean Sea. Therefore, better understanding of its cause is important. Both the offshore advection of Amazon water and eddy upwelling could play a role in the discoloration of the water. Thus, the fundamental question is how much to do each contribute and which process dominates. This note discusses the two hypothetical causes using the CZCS images for evidence and concludes that advection of Amazon water is the dominant process.

Longhurst (1993) presents two main arguments in support of the hypothesis that upwelling is the cause of the "bloom" in the retroflection and western countercurrent. The first argument concerns a conceptual model of nutrient limitation in the immediate vicinity of the Amazon Delta, and the second uses an analogy with the Somali Current regime in the Indian Ocean.

In the first argument, he recalls that Amazon River water moving north along the continental shelf passes through three zones, including sequentially a light-limited zone, a zone of active plant growth, and an outer zone where algal growth is nutrient limited and which still lies inshore of the 100 m isobath (DeMaster *et al.*, 1991; Curtin and Legeckis, 1986). Longhurst then assumes that there is a lack of nutrients available further downstream, and therefore concludes that another explanation besides the Amazon River must be sought for the "bloom" seen in CZCS images of the retroflection region and countercurrent. In this argument, Longhurst explicitly assumes that the discoloration detected by the CZCS is primarily due to a vigorous bloom in this region.

Muller-Karger *et al.* (1988) discussed CZCS images and surface drifter trajectories of the western tropical Atlantic Ocean. Comparing these data with historical measurements of sea surface salinity (from Cochrane, 1969), they conclude that Amazon river water is advected offshore around the retroflection, and entrained into the countercurrent, which then carries this fresh water eastward. DeMaster *et al.* (1991) also discuss the offshore advection of Amazon water via the retroflection and say:

"The ^{228}Ra/^{226}Ra signature of Amazon estuarine waters may be traced hundreds of kilometers into the Atlantic Ocean (Moore *et al.*, 1986) . . . The influence of the Amazon upon the open Atlantic was unambiguous in July and September, 1989. Salinities 500–1700 km from the river mouth ranged from 30.5 to 34.5 . . . In July and September 1989, salinities of 31 to 32 . . . and excess ^{224}Ra activities . . . were measured in the region of the North Brazil Current retroflection (8°N, 380 km offshore). This implies that waters in the core of the retroflection were <5 days removed from the ^{224}Ra source (i.e., the deltaic muds on the Amazon Shelf). To move the waters this distance requires a sustained current of >80 cm/sec. This observation agrees with the drogue tracks during the August 1989 hydrography leg (Limeburner *et al.*, 1990)."

Other analyses of historical salinity data show that nearly 70% of the Amazon plume water is carried eastward in the North Brazil Current Retroflection between August and October (Lentz, 1995). Three drifters deployed off the Amazon's delta by Limeburner *et al.* (1995) trace possible trajectories of the fresh water as it moves offshore. Dessier and Donguy (1994) find a belt of low surface salinities (<36 p.s.u.) between 5 and 10°N in historical merchant ship data which extends "all the way from South America to Africa between June and December", and conclude that the Amazon contributes to this feature. The seasonal advection of fresh water from the west, at least as far as 25–30°W between 5 and 10°N, is also documented in the hydrographic data of the Programme "Francais Ocean et Climat Atlantique equatoriaL" (Focal, 1986) and of the Soviet "Short-Term Climate Variability Program" (Razrezy, 1993).

An analogous situation is found to the northwest. The Orinoco's discharge flows into the Caribbean Sea, and disperses in the Ekman drift generated by the trade winds (Muller-Karger *et al.*, 1989). The low salinity layer of Orinoco water containing high silicate concentrations is apparent in transects across the Caribbean basin (e.g. Froelich *et al.*, 1978; Morrison and Nowlin, 1982). It is visible in satellite imagery during September–November every year, at the same time that a large fraction of the Amazon's discharge is diverted into the countercurrent (Fig. 1). A simple mass balance study demonstrates that the fresh water present in the Caribbean at this time is primarily of Orinoco origin (Muller-Karger *et al.*, 1989); if the Amazon's discharge were included as well, the size of the plume in the eastern Caribbean would be much larger.

Field data show that the discoloration of the water in the Atlantic and Caribbean plumes is due to the presence of both phytoplankton and large amounts of colored dissolved organic matter (Gelbstoff), even at distances upwards of 1000 km from the continent. Therefore, the CZCS imagery for regions such as the Amazon and Orinoco plumes needs to be interpreted with caution. The CZCS data generally available (as used by ourselves and Longhurst, 1993) have been processed to "pigment" concentration according to a simple algorithm, derived in waters where ocean color was primarily a function of chlorophyll concentration (Gordon *et al.*, 1983). However, in these plumes, the presence of large amount of Gelbstoff has a severe impact on the algorithm. Gelbstoff strongly absorbs blue light, leading to gross overstimates of the amount of chlorophyll in the Amazon and Orinoco plumes (*cf* Hochman *et al.*, 1993). This overestimate is not due to fluorescence of dissolved humics (*cf* Longhurst, 1993).

Various expeditions have documented the presence of viable plants in the Amazon plume (Wood, 1966; Ketchum and Ryther, 1966; Hulburt and Corwin, 1969) and in the Orinoco plume (Yoshioka, 1985; Bidigare *et al.*, 1993), and of considerable amounts of Gelbstoff (Blough and Zafiriou, 1993). In fact, the taxonomic composition of the flora within fresh water lenses associated with the Amazon plume at distances greater than 500 km offshore has been classified as "neritic" (Hulburt and Corwin, 1969). The abundant diatomaceous flora which exists year-round near the Brazil–Guyana coast is carried far offshore as the plumes are dispersed into the tropical Atlantic and Caribbean Sea. Concentrations of both phytoplankton and Gelbstoff decrease rapidly with distance from the mouth of the river along the axis of the Orinoco and Amazon river plumes (e.g. Muller-Karger *et al.*, 1989). We expect that the discoloration in the distal ends of the plumes is primarily due to dissolved constituents. However, significant phytoplankton biomass was measured in the Orinoco plume off Puerto Rico by Yoshioka (1985), and we propose that a viable community remains in the Amazon's plume as it drifts eastward in the countercurrent.

How can plants be viable in these river plumes at such distances from the estuaries? The river-plume nutrient-limitation hypothesis advanced by Longhurst deserves careful consideration.

Nittrouer *et al.* (1986), DeMaster *et al.* (1983), and Gibbs (1970) show that, immediately off Brazil, the Amazon's discharge onto the shelf is contained in a plume flowing northward inshore of the 60 m isobath. As the Amazon's waters move north of 3°N, they are contained in a narrow (less than 50 km), swiftly-moving wedge against the coast. A sharp zonal salinity gradient is found directly off the Amazon's delta, approximately between the 20 m and the 60 m isobaths. Here, river-borne suspended matter settles out providing an ideal environment for plant growth, rich in nutrients and light (Milliman and Boyle, 1975; Gibbs, 1970). Maximum biogenic silica production takes place in this salinity gradient region (DeMaster *et al.*, 1983).

The nutrient content of pure Amazon discharge water is high (8.5 μM NO_3-N, 0.15 μM NO_2-N, 0.52 μM PO_4-P, 128 μM SiO_4-Si) and nitrogen is enriched in the Amazon estuary due to remineralization of terrigenous particulate matter (approximately 20 μM NO_3-N in waters of salinity <9 psu; Edmond *et al.*, 1981; Milliman and Boyle, 1975; Livingstone, 1963). A large decrease in NO_3 and PO_4 is observed between the 9 and 14 isohalines over a distance of about 20 km (Edmond *et al.*, 1981). Here, the dissolved inorganic nitrogen to phosphorus ratio decreases from about 15:1 to about 4:1. Dissolved inorganic nitrogen rapidly becomes undetectable south of 3–4°N.

Longhurst (1993) uses this scenario to argue for nutrient limitation. However, little deposition of biogenic silica occurs on the Amazon shelf (Edmond *et al.*, 1981). Biogenic particles are swept north in the rapid flow of the river plume. Nearly 100% of the dissolved silica supplied by the Amazon escapes the Amazon continental shelf, and no modern biogenic silica sediments are found on this shelf (DeMaster *et al.*, 1983). Chase and Sayles (1980) found that phosphorus is released from Amazonian suspended material over a period of days. Edmond *et al.* (1981) found that remineralization of the organic components in fluvial particles within the estuary is incomplete. Additional remineralization occurs over the shelf off NE Brazil and the Guyanas (e.g. 25–54% of the particulate nitrogen and 8–31% of the particulate phosphorus are remineralized in the plume away from the estuary). Therefore, decomposition of phytoplankton, other particles, and dissolved organic matter could provide a source of recycled nutrients for continuing growth within the plume, downstream of the Amazon shelf, casting reasonable doubt on Longhurst's assertion of nutrient limitation.

The historical data collected during *ATLANTIS II* Cruise 14 (October–November, 1964), and *CHAIN* Cruise 48 (May–June, 1965) (Ketchum and Ryther, 1966) further support the concept of vigorous recycling within the offshore extension of the Amazon plume. The *ATLANTIS II* data report shows that at surface salinities of 34.5–36.0 (0–20 m), ammonia concentrations were consistently high and frequently reached values in the 1–3 μM NH_4-N range even at distances >600 km offshore. In contrast, surface nitrate was consistently low at these locations (*ca* 0.06–0.15 μM NO_3-N). The source of this recycled nitrogen is evident: zooplankton observations showed that animal biomass within the Amazon plume was at least three times the biomass observed in adjacent oceanic waters (Calef and Grice, 1967).

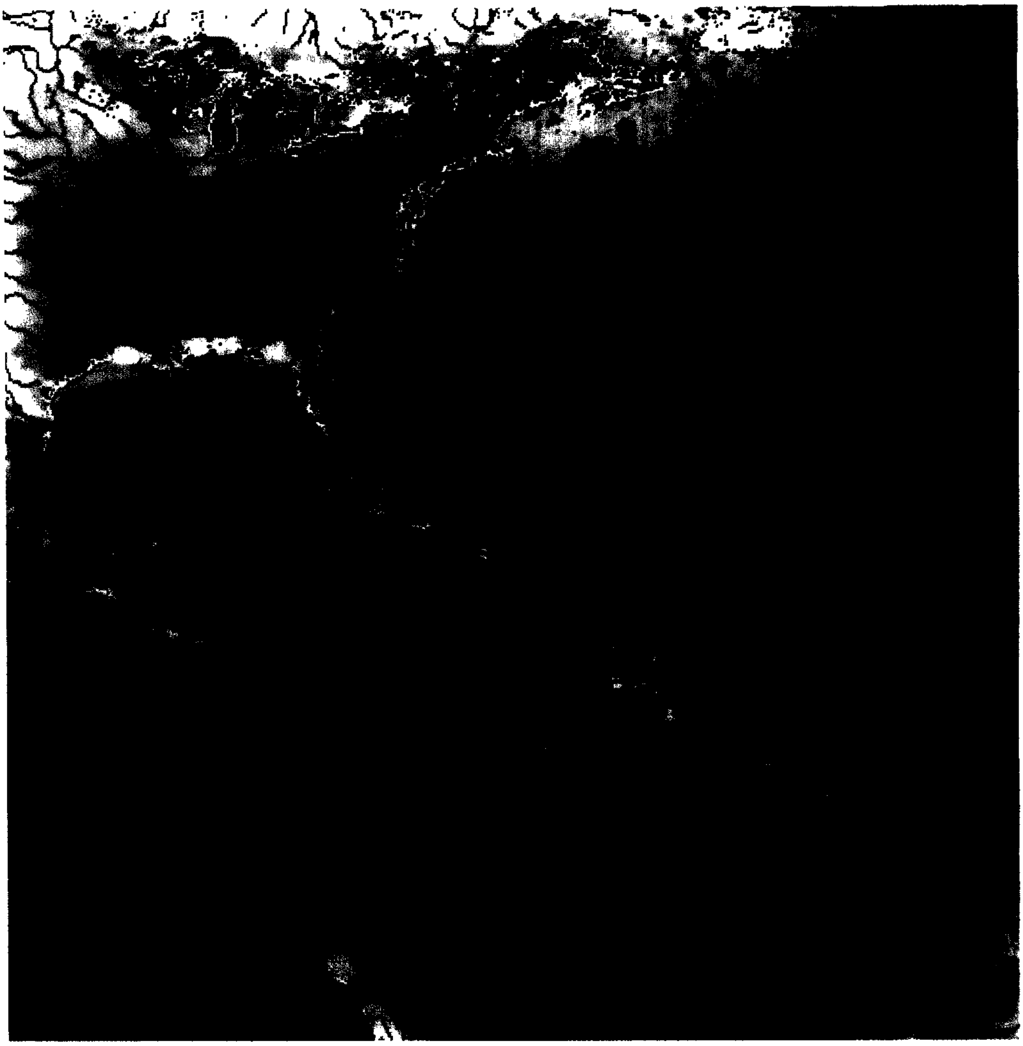

Fig. 1. Oceanic and land vegetation composite of the western North Atlantic and the American continent. The oceanic pigment image is a mean of Coastal Zone Color Scanner (CZCS) images collected over this region in October 1979. The Amazon and Orinoco River Plumes are visible as orange–yellow–green plumes off northeastern South America. The oceanic image was computed from spatially degraded images (20 km pixel resolution) in order to circumvent computational and mass storage limitations. Purple and blue colors indicate clear waters and low pigment concentrations. Green, yellow, and red indicate increasingly higher turbidity and pigment concentration. The areas shaded in grey off the Amazon delta and along the NE South American coast have extremely high sediment loads. The image of the American continent is based on a climatology of the Normalized–Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA Polar Orbiting Satellites. Yellow colors show less vegetation, and green to dark green shows increasingly higher vegetation indices. Positions of rivers are sketched in without representing their volumetric discharge.

In his second argument, Longhurst suggests that the North Brazil Current retroflection is similar to the Somali Current retroflection, which has been described by Bruce (1979, 1984). Longhurst concludes that, since there are no major rivers along the Indian Ocean coastline near the location of this retroflection, the chlorophyll field associated with the Somali Current eddies must be due to eddy upwelling. Longhurst concludes by analogy that the patterns off South America do not require a river, and that an eddy should suffice as a nutrient supply mechanism.

Indeed, the inshore portion of the Somali Current is a well known region of coastal upwelling, forced by the strong southwest monsoon. Nevertheless, CZCS images of the Indian Ocean do not show a plume with proportions similar to the one seen in the Atlantic. Instead, high pigment values are concentrated in the northwestern Arabian Sea, north of the Somali Current, with only a thin wedge extending around the northern part of the large northern Somali basin eddy and then southward along the coast of Somalia. There is no offshore extension as seen seasonally in the Atlantic North Equatorial Countercurrent.

Rather than chlorophyll being produced *in situ* around the periphery of the northern Somali basin eddy, satellite data indicate that the discoloration is due to the entrainment of chlorophyll-rich waters from the continental margin, much as occurs off the west coast of South America. Cooler upwelled water is clearly detectable by infrared satellite imagery, primarily in the upwelling region along the Somali coast (e.g. Tran *et al.*, 1993).

Longhurst's assessment of the role of eddy upwelling in the North Brazil Current retroflection is based in part on analogy to patterns of vertical velocity observed in a numerical simulation of the northern Somali basin eddy. Brock *et al.* (1991), using a reduced gravity model of the Arbian Sea, show evidence of upwelling along the southern flank of the northward moving anticyclonic eddy. In such situations, most of the vertical motion along the periphery of isolated translation eddies is simply a kinematic consequence of their propagation. The strength of the vertical velocity depends on the propagation speed and the slope of the isopycnals (McGillicuddy *et al.*, 1995). Downwelling occurs along the leading edge (in the direction of propagation) of anticyclonic eddies, and upwelling occurs along the trailing edge. Given that the NBC retroflection generally propagates northward until an anticyclonic eddy pinches off (Richardson *et al.*, 1994; Johns *et al.*, 1990), one would predict that the northern flank of this feature would be an area of downwelling, not upwelling. Thus it seems difficult to attribute the discoloration of the northern border of the retroflection to a phytoplankton bloom stimulated by upwelling of the type modeled by Brock *et al.* (1991).

This is not to say that other vertical transport processes might not be active in the NBC retroflection. Woods (1988) used a primitive equation model to demonstrate the presence of strong upwelling patches in the anticyclonic flanks of a meandering jet. In coupled physical and biological simulations of the Gulf Stream, Flierl and Davis (1993) showed that such upwelling tends to enhance phytoplankton biomass along the crests of meanders. However, the amplitude of the biological response is small (10–20%) because upwelled fluid is rapidly advected into regions of downwelling further downstream. Determining whether or not this upwelling mechanism could stimulate the growth of enough phytoplankton biomass to account for the discoloration in the NBC retroflection will require further investigation.

If eddy upwelling was very strong, a clear signal in sea surface temperature would be expected off South America around the retroflection and along the North Equatorial Counter Current. However, this is not supported by the available observations. Off South

America, salinity, temperature, phosphate and nitrate sections conducted by Ryther *et al.* (1967), and Hulburt and Corwin (1969, their Fig. 7) show that there is upwelling near the coast of the Guyanas where the retroflection originates, but that this upwelling is narrow and confined to the continental margin. Further offshore, their sections show that upwelling on both sides of the countercurrent is confined to depths greater than 100 m (see also Ketchum and Ryther, 1966). This is supported by infrared satellite data (see data from Tran *et al.*, 1993), which show sporadic cooler surface temperatures only close to the continent near 6–8°N, where the retroflection originates. Historical data shows that the western tropical Atlantic features some of the warmest year-round temperatures in the Atlantic (Rual and Jarrige, 1984; Legeckis, 1986; Strong, 1986).

We conclude that two very different mechanisms cause the two patterns of discolored water off northern South America and off eastern Africa: coastal upwelling in the latter and Amazon River water in the former. Upwelling off South America is much weaker than off eastern Africa, but the discoloration in the shape of an eddy is much more apparent off South America. In both cases, the strength of the signal seen in the CZCS imagery is associated with offshore advection of material from the continental margin.

In order to further investigate causes of the Amazon plume we examined the CZCS "pigment" patterns in other ocean currents which are similar to the North Brazil Current retroflection. The few CZCS images available do not reveal major chlorophyll plumes associated with upwelling along the anticyclonic edge of the New Guinea Coastal Current, which retroflects around the Halmahera Eddy into the Pacific Countercurrent, or in the Loop Current which retroflects in the Gulf of Mexico (Muller-Karger *et al.*, 1991), or in the Agulhas Current which retroflects south of Africa. In each of these cases, there is evidence for entrainment of material either from the adjacent shelf or from an upwelling area near the continental margin. In the particular case of eddies shed by the Agulhas Current, the CZCS data also show clearly how waters with high pigment concentrations from the Benguela Upwelling region are entrained and advected offshore around the eddies (Weeks and Shillington, 1994). The high concentrations found toward the south of the Agulhas retroflection, along the front between the Agulhas Return Current and the cold subantarctic waters, mark the eastward extension of high concentrations observed west of the retroflection, namely along the northern wall of the Subtropical Convergence. The lack of plumes in other currents that retroflect suggests that upwelling along the edge of these associated eddies is probably less a factor than entrainment from a nearby source (e.g. the Amazon, Benguela upwelling, Somali upwelling) and advection of materials around the eddies.

A further problem with the eddy upwelling hypothesis concerns the Orinoco plume in the Caribbean Sea, which is not associated with a current retroflection. If neither a retroflection nor eddies exist, then eddy upwelling cannot be the cause of this plume. There are eddies year-round off northeastern South America (*cf* Johns *et al.*, 1990) which are traced by elevated pigment concentrations in CZCS images. Some of these eddies can be seen carrying pigments in large arcs extending from the Orinoco delta toward Barbados. The pigment in these eddies is traceable to either the Amazon's or Orinoco's discharge and again represents a signal that is heavily influenced by colored dissolved organic matter.

In summary, the eddy upwelling hypothesis used by Longhurst to explain the Amazon plume seems flawed for several reasons. The sources of the two major plumes of discolored water in the western tropical Atlantic coincide with the geographic location of the deltas of two major rivers, the Amazon and Orinoco. The two plumes are consistent with the advection of river water by nearby ocean currents. There is no downplume discontinuity between nearshore Amazon water and the offshore Amazon plume, which would be expected if there were a nutrient limited zone between the two and if eddy upwelling were the sole cause of the offshore bloom. There is no cool water in the Amazon plume (or in the Orinoco plume), which would be expected if upwelled water were the cause. Other currents similar to the North Brazil Current retroflection—the Somali Current, New Guinea Coastal Current, Loop Current and Agulhas Current—do not have major discolored plumes associated with them, other than those which may be due to entrainment of blooms associated with upwelling at the origin of the retroflections.

The arguments presented here for the most part use the CZCS imagery to infer processes affecting the dispersal of material in the ocean. The historical imagery is of limited value for a variety of reasons, discussed at length elsewhere (e.g. Muller-Karger *et al.*, 1989). Detailed *in situ* measurements in the western tropical Atlantic, combined with measurements from the new series of ocean color scanners (SeaWiFS, EOS Color) will be required to determine the dominant processes and the physical and biogeochemical consequences of the offshore dispersal of riverine waters. Only through a focused field and satellite-based observation program will we be able to unravel the relative importance of mechanisms causing the discoloration of waters over large areas of the tropical ocean, and converge on better estimates of the role of these regions in the global carbon cycle.

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