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Review

What nutrient sources support anomalous growth and the recent sargassum mass stranding on Caribbean beaches? A review

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ABSTRACT

Since 2011, tropical beaches from Africa to Brazil, Central America, and the Caribbean have been inundated by tons of sargassum seaweed from a new equatorial source of pelagic sargassum in the Atlantic. In recent years the extraordinary accumulations of sargassum make this a nuisance algal bloom for tropical coasts. In 2018 satellite data indicated floating mats of sargassum that extended throughout the Caribbean to the northeast coast of Brazil with the highest percent coverage over the water yet recorded. A literature review suggests that Atlantic equatorial recirculation of seaweed mats combined with nutrients from several possible sources may be stimulating the growth and accumulations of sargassum. In the western equatorial recirculation area, new nutrient sources may include Amazon River floods and hurricanes; in the eastern equatorial recirculation area, nutrient sources that could sustain the sargassum blooms include coastal upwelling and Congo River freshwater and nutrients.

1. Introduction – a new nuisance algal bloom

Sargassum seaweed has long been recognized as an important floating macroalga ecosystem with accompanying fish, encrusting organisms and crustaceans. This brown macroalga forms floating mats in the Sargasso Sea and is mainly composed of two species: *Sargassum natans* and *Sargassum fluitans* (Lapointe et al., 2014; Doyle and Franks, 2015; Lapointe, 1995; Lapointe, 1986; Parr, 1939). Small bladders filled with gas, or pneumatocysts, enable the algae to float until the mat becomes so encrusted with other organisms that it sinks after a year or so (Brooks et al., 2018; Gower and King, 2011). Analysis of satellite images from 2002 to 2008 revealed that the floating sargassum mats originated in the northwestern Gulf of Mexico each spring, probably fueled by nutrients from the Mississippi River plume and were exported to the Sargasso Sea during the summer months (Gower and King, 2011). In an average year the Mississippi River discharges nearly 1.6 million metric tons (mt) of nitrogen to the Gulf of Mexico, of which 0.95 million mt is nitrate and 0.58 million mt is organic nitrogen (Goolsby, 2000). This nutrient input could easily fuel the estimated one million tons wet weight of sargassum exported to the Sargasso Sea each year (Gower and King, 2011).

After 2011, various news reports indicated new Atlantic equatorial nuisance sargassum weed accumulations in Caribbean areas where they had previously never been reported (Oviatt et al., 2016). Processed satellite images to visualize sargassum distribution between 2000 and 2010 show minimal sargassum, with occasional mats appearing off the mouth of the Amazon River between August and October and moving northward with the Brazil current (Wang and Hu, 2016). Beginning in 2011, tons of stranded seaweed disrupted the ecology of shallow waters, boating activities and the large tourism industry of the Caribbean and required extensive removal efforts (Louime et al., 2017; Hinds et al., 2016; Rodríguez-Martínez et al., 2016; Hu et al., 2016). These new occurrences intensified with huge drifts of sargassum weed building up to 3 m high on beaches from Grenada to St Vincent, to Barbados to Mexico, costing the tourism industry tens of millions of dollars in cleanup costs. In Mexico the federal government assigned $3.2 million to sargassum removal in 2015 but the amount of seaweed still exceeded the capacity to remove it (Rodríguez-Martínez et al., 2016). One news report for French St Martin reported that 3 backhoes and 5 dump trucks were required for 21 days to clean a single resort beach and with the loss of tourists, the collective cost to the company rose to $1,000,000 (Higgins, 2016). Similarly, coastal areas and beaches along the African coasts of Sierra Leone, Nigeria and Ghana were blanketed by sargassum for the first time in 2011, disrupting fishing

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activities and small boat navigation (Smetacek and Zingone, 2013). During 2014–15, large amounts of sargassum stranded in the coastal areas of northern Brazil and offshore islands from 0° S to 3° S, causing disruptions to the local environments (Sissini et al., 2017).

Large, stranded mats of sargassum may take months to years to decay. The stranded sargassum on the coast of Mexico has caused eutrophication, leaving long lasting and severe effects. For example, seagrass meadows were replaced by *Halimeda* spp. and other algae (Tussenbroek et al., 2017). Near shore corals died after sargassum stranding caused low-oxygen events. The shallow ecosystems of corals and seagrass meadows are not expected to recover for decades (Tussenbroek et al., 2017). The regenerated nutrients from stranded mats greatly exceeded the annual supply of ground water nutrients to the coast. A year after the stranding, water transparency in parts of coastal Mexico was still below normal levels with ongoing eutrophication (Tussenbroek et al., 2017).

The sargassum implicated in the recent Caribbean and Central America beach stranding was a mixture of species and sub species in different proportions than the two species (*Sargassum natans* and *Sargassum fluitans*) dominating the Sargasso Sea (Schell et al., 2015). Amaral-Zettler et al. (2016) identified the equatorial *Sargassum* as *Sargassum natans (form VIII)* using new genetic techniques and distinguishing it from the two dominant Sargasso Sea species. This subspecies has apparently always been present but rare in the Sargasso Sea and initially dominated the tropical Atlantic recirculation area and Caribbean stranding events. The equatorial species was recorded as *S. natans*, during the 1930s by Taylor (1931, as cited in Szechy et al., 2012). Taylor first reported the occurrence of *S. natans* in Brazil and noted that it was outside the normal North Atlantic range. Szechy et al. (2012) reported floating rafts of *S. natans* off northern Brazil on July 11, 2011, as the Brazilian Navy investigated what they thought was an oil spill.

The question addressed in this review is: What physical factors have changed leading to new sources of nutrients that have recently eutrophied the equatorial Atlantic? Floating seaweed in this region and mass strandings on beaches in the Caribbean, Central America, western Africa and northern Brazil indicate seasonally eutrophic conditions during spring, summer and early fall months. Here we review several hypotheses for sources of nutrients that promote massive nuisance sargassum growth and biomass accumulations and examine the available literature and data for evidence to support those hypotheses. Major sources of nutrients for sargassum blooms may include rivers (Amazon, Congo, Orinoco), coastal upwelling (northwest Africa, southwest Africa, equatorial), precipitation and hurricanes.

2. The new Atlantic equatorial recirculation source area of sargassum

Several studies have described a new source of sargassum from the equatorial Atlantic although exact transport routes and timing are being intensively studied and improved communication connections between eastern and western Atlantic would help to understand sargassum occurrence. Annually, in early spring, mats of sargassum first appear off the coast of northern Brazil (Wang and Hu, 2017; Franks et al., 2016; Wang and Hu, 2016; Hu et al., 2016). Over the next 3 months sargassum mats off the equatorial Brazilian continental shelf are carried to the northwest in the North Brazil/Guiana Current along the coast to Venezuela where they are circulated in North Brazil current rings to the east of the Windward Islands (Fig. 1) (Putman et al., 2018). Model simulations of sargassum transport from the western equatorial Atlantic explain almost 90% of the annual variability in sargassum entering the Caribbean Sea (Putman et al., 2018). In late spring to fall of bloom years, mats strand on Caribbean beaches. Coles et al. (2013) present four plume schematics with the fast schematic showing an Amazon River plume generated at the river mouth in January–March and transported to the Caribbean in late spring and early summer, a time consistent with observed sargassum seaweed arrival (Fig. 2). The indirect schematics would deliver sargassum later in the year or direct the seaweed to the east where it might circulate and return to Brazil the following year. Two large phytoplankton blooms in the eastern Caribbean during 2009 and 2010 apparently originated from unusually large Amazon River plumes which provide evidence of river nutrient transport to the Windward Islands and may have been the start of flood plumes that initiated sargassum blooms in following years (Johns et al., 2014). Usually in June the Amazon plume joins the intensifying Equatorial Counter Current carrying seaweed mats to the African coast (Figs. 1, 2). Mats in the eastern Atlantic equatorial region may experience new growth with the availability of upwelled and river plume nutrients (Brooks et al., 2018). Mats in the African Equatorial Guinea coastal eddy circulate south to eventually join the South Equatorial Current for transport west to the Brazil coast for the following spring (Franks et al., 2016).

3. Are Amazon floods a new source of nutrients for sargassum?

The western equatorial Atlantic is apparently the new, unexpected source of floating sargassum mats that strand in massive accumulations on Caribbean beaches (Johnson et al., 2013, Brooks et al., 2018, Putman et al., 2018, Wang et al., 2018, Wang and Hu, 2017, Hu et al., 2016, Franks et al., 2016, Gower et al., 2013, Hu et al., 2004). The Caribbean and western Atlantic equatorial surface waters have been historically oligotrophic, but in 2009 and 2010, large phytoplankton blooms in the northeastern Caribbean from Puerto Rico to Saba Bank, were attributed to nutrients from the Amazon River plume with satellite data indicating that such events had not happened in the past 30 years (Johns et al., 2014). Since 2011 the Amazon flood plume appears to have been the origin of massive blooms of sargassum which have resulted in tons of sargassum seaweed on Caribbean shorelines (Langin, 2018; Marechal et al., 2017). In July 2015 monthly mean sargassum biomass floating to the Caribbean from the western equatorial Atlantic was estimated at over 4 million tons (Wang et al., 2018).

During Amazon River flood years beach stranding of sargassum usually occurred (Table 1). The largest floods in Amazon River recorded history occurred during 2009, 2011, 2012, 2014, and 2015. The floods co-occurred with the western equatorial Atlantic increase of sargassum seaweed that stranded on Central American and Caribbean beaches and spread to Africa (Bowater, 2014). For example in 2012, some 500 villages, towns and cities were submerged by floodwaters at Iquitos, Peru, causing loss of life for dozens. This flood was 90 cm higher than the previous floods of 1938 and 1998 (Otoronogo Expeditions 2012). During Amazon non-flood years before 2011, and 2013, 2016 and 2017, sargassum blooms and subsequent impacts to coastal beaches were small or non-existent (Table 1). Satellite images indicate significant floating sargassum mats in 2016 (Wang et al., 2018) but the year 2016 has not been identified as a problem year for sargassum stranding on beaches (Milledge and Harvey, 2016).

Studies report that the Amazon basin has been experiencing significantly greater precipitation since the 1990s consistent with the warming phase of the Atlantic Multidecadal Oscillation (AMO) and global warming (Gloor et al., 2013). The AMO warming occurs during a roughly 75-year oscillation cycle when wind and current systems alternate with warming and cooling of the surface North Atlantic (Knight et al., 2006). Warm periods occurred during the oscillation cycle from the 1930s to the 1950s and the 1990s to present; cool periods have occurred during the 1900s to 1920s and 1960s to 1980s (Knight et al., 2006). The recent increasing rainfall and Amazon River floods can be correlated with increasing tropical Atlantic sea surface temperatures. The increase in sea surface temperature has likely caused an increase in water vapor input from the northeast equatorial trade winds to the northern Amazon basin. A previous Amazon River flood in 1938 may have occurred during the previous warming period of the AMO. A step increase of almost 1° C global warming occurred from the 1930s warm

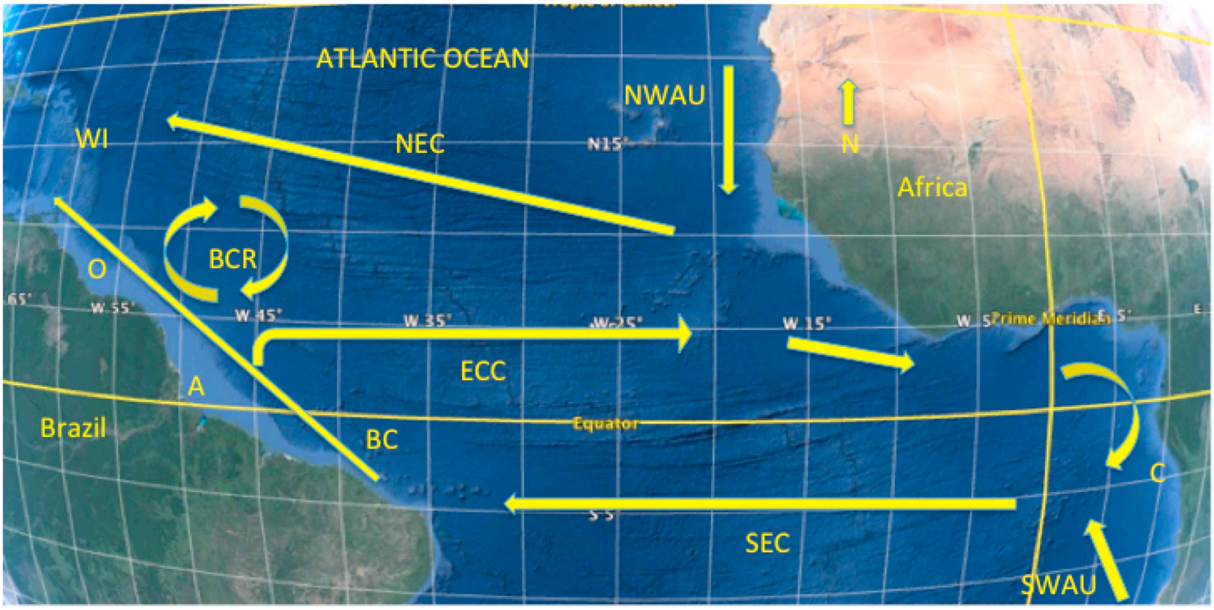

Fig. 1. Current boundaries of the equatorial Atlantic sargassum seaweed recirculation area. The arrows indicate dominant directional flow of the circulating currents. The northern boundary of the recirculation area is the North Equatorial Current (NEC); the southern boundary is the South Equatorial Current (SEC). The recirculation is due to the Brazil Current Rings (BCR) of the Brazil Current (BC) and the seasonal Equatorial Counter Current (ECC) moving from the eastern boundary of the recirculation area to the coastal African current at the western boundary. Major nutrient sources include Rivers (Amazon (A) at the equator and Orinoco (O) on the west, Congo (C) 6°S in the east), Upwelling (North West Africa (NWAU), South West Africa (SWAU), equatorial), and Hurricanes. Windward Islands (WI) lie to the northwest. (Map from Google Earth accessed December 2018).

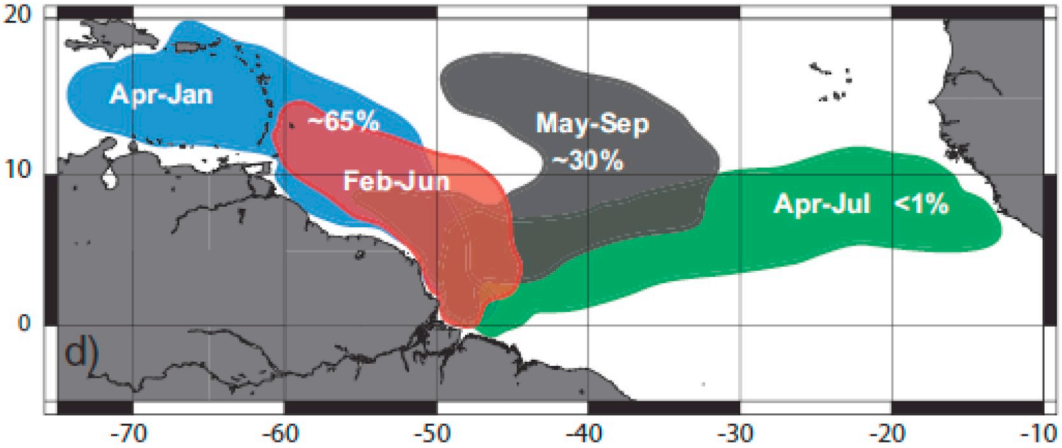

Fig. 2. Float drifters transport pathways with months of initiation noted and percentage of drifters that follow each pathway. (Used with permission of Coles et al., 2013, Fig. 6d, AGU publisher.)

period to the current warm period, an increase consistent with the greater flooding and greater storm intensity during recent years (Gloor et al., 2013).

Could extraordinary events like the Amazon floods between 2011 and 2015 supply new nutrients to support 4 million metric tons of sargassum (Wang et al., 2018)? Some authors do not find evidence for this correlation (Wang and Hu, 2016). Others find that Amazon flood nutrients have supported phytoplankton blooms in the northeastern Caribbean (Johns et al., 2014). Generally it has been revealed that the Amazon River has low dissolved inorganic nitrogen, mainly as nitrate whose concentrations dilute during floods and also dilute rapidly at the mouth of the Amazon River at ordinary flow levels (Ward et al., 2016; Martinelli et al., 2010; Devol et al., 1995; Santos et al., 2008a; Martinelli et al., 2006). Median Amazon River concentrations were 9 µM for NO_3, 13 µM for DON and 22 µM for TDN during 1984 to 2001 (Martinelli et al., 2010). Data collected during November 2014 and July 2015 after years of boreal spring floods indicate TDN of 15 to 20 µM at the mouth of the Amazon (Ward et al., 2016). Because the Amazon basin has a low relief, river flows generally do not increase much over 50% during large flooding events (Fig. 3). El Niño non-flood years 2010 and 2016 had lower flows than non-flood years of 2013, 2017 and 2018 (Fig. 3) (Eltahir et al., 2004). Wang et al. (2018) report a nitrogen dry weight percent sargassum of 1.07% or 0.107% nitrogen wet weight sargassum. Using the recent values for nitrogen concentration (15 µM) and flow values for all rivers (Amazon, Xingu, Tapajos) at the Amazon mouth (205,000 $m^3 s^{-1}$), flow in July (a non-flood month) of 2015 could have supported ~30 million tons wet weight of sargassum compared to the 4 million tons estimated by Wang et al. (2018). For perspective, Martinelli et al. (2006) have estimated 3 million metric tons (3.3 million tons) of total nitrogen including about 1 million metric tons of DIN annually exported to the coast by the Amazon River based on pre-1999 data sources compared to ~1 million metric tons N per year for the calculation above.

While the Ward et al. (2016) value (15 to 20 µM TDN) approximates

Table 1
Years of *Sargassum* beaching and the available nutrient sources.

Year	Amazon river flood nutrients	Hurricane nutrients prior year	Eastern Atlantic equatorial nutrients[a] prior year	Excessive *Sargassum* beaching
2009	Yes	No		No, Phytoplankton Bloom
2010	No, El Niño	No		No
2011	Yes	Yes		Yes
2012	Yes	Yes		Yes
2013	No	Yes	Yes, Congo Flood	No
2014	Yes	No		Yes
2015	Yes	Yes		Yes
2016	No, El Niño	Yes		No reports
2017	No	No	Yes, SEC	No reports
2018	No	Yes		Yes
2019	? El Niño	No		? No

[a] SEC - South Equatorial Current and upwelling wind along coastal Africa.

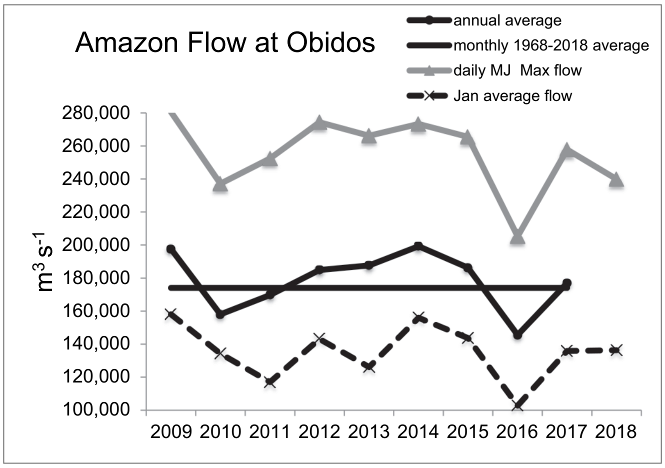

Fig. 3. Amazon flow levels during the flood periods from 2009 to present at Óbidos, Brazil. MJ is May–June.
(Brazil River Agency: Agencia Nacional de Aguas: http://www3.ana.gov.br/portal/ANA/portal-ingles/information, accessed Dec. 2018.)

the required nitrogen to support observed sargassum biomass it is not clear why the non-flood year 2013, with roughly equivalent flow and nitrogen concentrations should not also support large sargassum biomass (Fig. 3). It is also not clear how such a large sargassum biomass could accumulate in the western equatorial Atlantic without a large input of nutrients from a source like the Amazon River, just as the Mississippi River apparently supplies nutrients to sargassum species in the Gulf of Mexico (Brooks et al., 2018; Gower and King, 2011).

An explanation for making new flood nutrients available may lie in the physical timing of flood events and the location of the Intertropical Convergence Zone. The mats that arrive off the coast of Brazil in February apparently predict the summer Caribbean large-scale seaweed beach strandings (Wang and Hu, 2017). The Amazon River flowing at Obidos, Brazil, in early January, would reach the continental shelf in late February (Korosov et al., 2015). January flows are higher in flood years compared to non-flood years and may push out earlier than in non-flood years to the shelf edge to encounter floating mats (Fig. 3). During January, February and March the Intertropical Convergence Zone brings high precipitation to the western Atlantic equatorial region at the mouth of the Amazon depositing Saharan dust containing iron and nutrients (Wang and Hu, 2016; Swap et al., 1992; Schlosser et al., 2014; Paerl et al., 1999). The reduced salinity may retain the nutrients in the surface waters where it is available for seaweed growth. From November to early spring the equatorial counter current does not run eastward creating a quiet area of no currents where sargassum mats may accumulate and grow (see Wang and Hu, 2016). The mats may be left over from the previous year's bloom and re-growing (Wang and Hu, 2016) or new mats from the eastern equatorial Atlantic portion of the recirculation area (Brooks et al., 2018; Franks et al., 2016). Mats moving from the east have not been observed as satellite coverage has only been applied in the western equatorial Atlantic. Higher plume flows and the Brazil Current in later spring sweep the mats to the Caribbean (Putman et al., 2018) (Figs. 2, 3). Concurrent data on flow, salinity and nutrient concentrations at the mouth of the Amazon River have not been available to test these hypotheses.

In addition to nitrogen inputs from Amazon River flow, a large pool of dissolved organic nitrogen forms at the mouth of the Amazon River, perhaps derived from sediment organic matter (Gensac et al., 2016). Santos et al. (2008b) report minimum, maximum and median concentrations of DON at sites on the Amazon continental shelf of 39, 168 and 85 μM, respectively, during a decreasing discharge period. The data were collected long before the development of sargassum blooms, in August 2001, from 41 stations located on the inner shelf at the mouth of the Amazon from latitude −1 to 4.5° and longitude −48 to −51°. Presumably these concentrations of DON would be higher in flood years when more organic materials are deposited than in non-flood years although no measurements were taken to confirm this supposition.

Several researchers have performed experiments indicating that dissolved organic nitrogen substrates were readily taken up by macroalgae and *Sargassum* sp., in particular (Vonk et al., 2008; Van Engeland et al., 2011). Hanisak and Samuel (1987) found high growth rates for pelagic species *S. fluitans* and *S. natans* as well as benthic *Sargassum* species under favorable light, temperature and nutrient conditions. Both pelagic species attained rates of 0.11 doublings per day and performed best at higher light, salinity and temperature conditions than benthic species required. Vonk et al. (2008) found that benthic *Sargassum* sp. uptake rates of dissolved organic nitrogen substrates, including urea, exceeded the rates of all other macroalgae and seagrass blades. DON is likely a utilizable source of nitrogen in nutrient limited waters for sargassum just as it is for phytoplankton (Bronk et al., 2007; Glibert et al., 2006; Seitzinger et al., 2002). Urea has been identified as a major agricultural fertilizer for sugar cane and corn and as a new contributor to coastal eutrophication (Glibert et al., 2006). Glibert et al. (2006) showed that Brazil was a major user of urea fertilizer from 1999 to 2000, using from 500,001 to 15,000,000 metric tons/y. Urea was identified two decades ago at the mouth of the Amazon, but at low concentrations of ~1 μM (Demaster and Pope, 1996). Concentrations which may now be higher, have not been reported.

4. Could Atlantic hurricanes be a factor for sargassum distribution and growth?

So far, the research community has not examined hurricanes, as a source of a new dominant sargassum subspecies and of nutrients for sargassum growth. These powerful and intensifying storms can change circulation and ranges of species, upwell deep water column nutrients, destroy biological communities and be a long lasting source of nutrients to surface water sargassum. The following speculations are correlative only, but suggestive.

Hurricanes may have led to the inoculation of *Sargassum natans (form VIII)* seaweed into the Central West Atlantic. Before 2010 only phytoplankton bloomed in Amazon flood plume waters (Johns et al., 2014). The 2010 hurricane season had 12 storms and was the first of 3 very active hurricane years between 2010 and 2012 (https://en.wikipedia.org/wiki/2010_Atlantic_hurricane_season). Hurricane Tomas, a low latitude storm originating off the coast of west Africa and moving to Brazil and the Amazon River mouth, swept through the Windward Islands in late October 2010 with highest wind speeds of 155 km h^{-1} (Fig. 4). The storm brought heavy rainfall and strong wind gusts across the Windward Islands, Venezuela and northern Guyana before developing into a

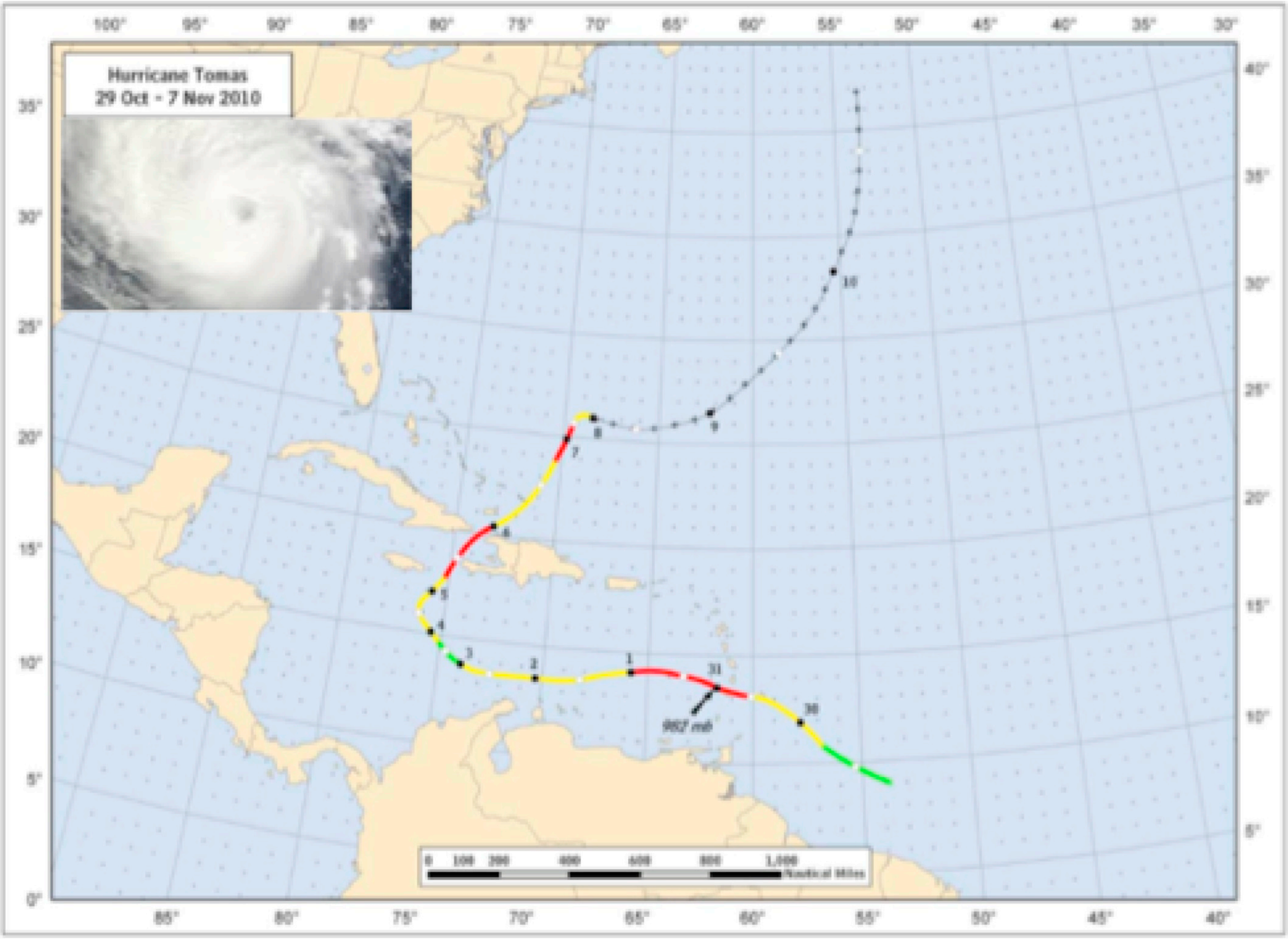

Fig. 4. The track of Hurricane Tomas (red is hurricane intensity) October 29 to November 7, 2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
(Map modified from Pasch and Kimberlain, 2011.)

hurricane. Could this hurricane have injected *Sargassum natans (form VIII)* seaweed into the Brazil and Equatorial Counter Currents to initiate the first bloom in 2011? Could such a hurricane shift pools of coastal nutrients, for example, from the mouth of the Amazon River, to sargassum mats?

In any year several tropical storms and hurricanes pass through the western tropical Atlantic. The storms, mixing water to depths of tens of meters, bring cold, nutrient rich water to the surface (Gierach and Subrahmanyam, 2008). When 2017 Hurricanes Irma and Maria passed through on September 7 and 20, surface water temperatures dropped by about 1 °C in the coastal waters of St John USVI (National Park Service Monitoring Data, J. Miller, 2019 pers. comm.). Hurricane circulation may transport upwelled nutrients and materials remineralizing nutrients into the area east of the Windward Islands, where they may recirculate for 6 months in Brazil Current Rings (Putman et al., 2018) (Fig. 1). The quiet region and concentrated nutrients would support sargassum accumulation, growth and blooms in the western equatorial Atlantic in the following spring (Putman et al., 2018).

Large sargassum beaching years have usually been preceded by strong hurricane seasons (Table 1). Satellite data indicate large percent coverage of sargassum and hurricanes in the previous fall in 2011, 2012, 2015 (Wang and Hu, 2016) and 2018 (University of South Florida: optics.marine.usf.edu, Langin, 2018). Both 2013 and 2016 were minimal years in terms of hurricanes compared to other years when one or more major hurricanes impacted the area (https://www.nhc.noaa.gov/data/tcr/, accessed November 2018). The lack of sargassum in 2013 has been attributed to strong eastward flow of the north Brazil current retroflection to the Equatorial Counter Current in 2012 (Putman et al., 2018) although 2013 and 2016 were also years of no Amazon River floods (Table 1).

Two category 5 hurricanes (Irma, Maria) and several smaller storms in the western tropical Atlantic in the season of 2017 comprised a suite of extreme events for the Caribbean due in part to above average sea surface temperatures (Fig. 5, Camp et al., 2018). The 2017 hurricane season was one of the most active since reliable records began in 1966 with 6 major hurricanes and with the third highest accumulated cyclone energy on record (Camp et al., 2018). The Amazon River did not flood in 2018 but this year had the highest sargassum percent coverage and beach stranding yet recorded (Langin, 2018). The hurricanes mixed tropical waters to depth and caused tons of terrestrial vegetation to be exported to the ocean (Fig. 6a). Settled and suspended particulate matter formed a mat of regenerating nutrients for several months after the storms (Fig. 6b). Levels of benthic macroalgae were the highest ever recorded at these sites for months after the passage of the storms (Fig. 6b). News reports from Barbados indicated that the storms caused home septic systems to malfunction due to hydraulic loading of soils. The storms flooded waste water systems and released nutrients from several islands. All these sources of nutrients possibly contributed to sargassum growth in the spring and summer of 2018. News reports indicate high nitrate loads in Puerto Rico streams a year after Hurricane

Fig. 5. Hurricanes Irma and Jose September 6, 2017.
From earthobservatory.nasa.gov.

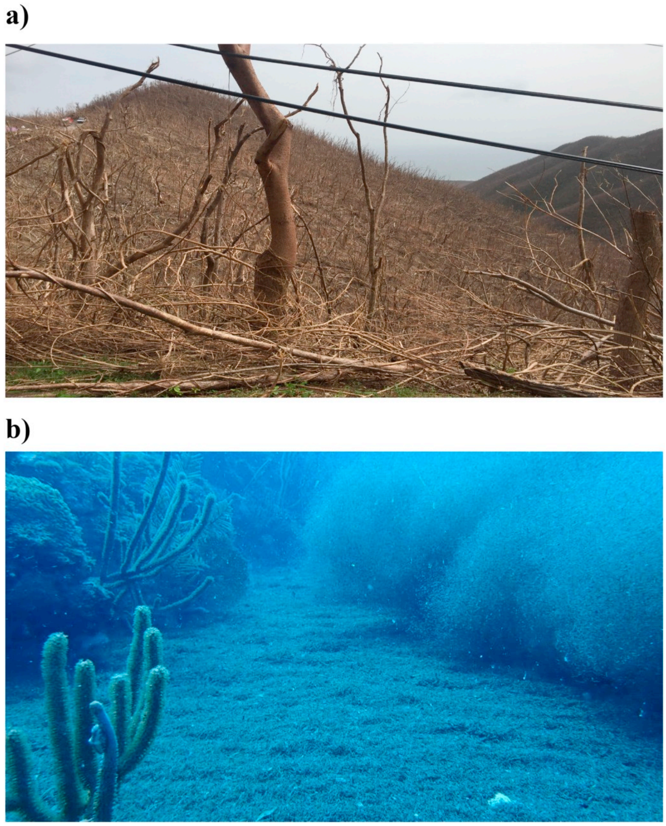

Fig. 6. Hurricanes in 2017 stripped vegetation from Caribbean Islands a. and this exported organic material formed an easily suspended and settled layer about 10 cm deep over the bottom b.
(J. Miller, US National Park Service, US Virgin Islands, public domain.)

Maria which could lead to lasting coastal eutrophication (https://www.forbes.com/sites/marshallshepherd/2018/12/10/the-startling-thing-hurricanes-are-doing-to-puerto-rico-watersheds/#56e090fb6604). Wynne (2017) has reported that recirculating currents in the northern Caribbean may be trapping nutrients and allowing them to accumulate around the Windward Islands contributing to coastal eutrophication in island areas.

A further source of nutrients could have been the August 2018 Orinoco River floods that may have prolonged the summer beaching of sargassum seaweed (https://www.caracaschronicles.com/2018/08/27/orinoco-river-floods-ciudad-bolivar-refugees-have-nowhere-to-go/, Accessed August 2018). The Orinoco River has an average discharge of 36,000 $m^3 s^{-1}$ and concentrations of dissolved inorganic nitrogen of 8.1 μM and of dissolved inorganic phosphorus of 0.3 μM, with a total nitrogen export of 0.54×10^6 metric tons per year (Lewis and Saunders, 1989). During a summer flood period significant nutrients could be exported to Caribbean waters (Johns et al., 2014).

5. Nutrient sources in the eastern equatorial Atlantic

Nutrient injections in the eastern Atlantic recirculation area could provide new growth to floating sargassum mats for the trip back across the Atlantic to Brazil staging grounds (Fig. 1). Three sources of nutrients in the eastern equatorial Atlantic recirculation area include the Canary Current and the Benguela Current that carry nutrients from coastal African upwelling areas, and the Congo River plume at 6°S (Fig. 1, da Cunha and Buitenhuis, 2013). Upwelling systems in the eastern Atlantic recirculation area are the most important sources of nutrients, followed by seasonal upwelling events in the Gulf of Guinea. In the Gulf of Guinea, upwelling and freshwater conditions create a stable mixed layer that traps nutrients in a water column of longer residence time to which the Congo River also contributes nutrients (da Cunha and Buitenhuis, 2013).

Alternating floods, in the west and east equatorial Atlantic may have acted to sustain sargassum mats past a one-year life cycle in 2013 (Table 1). Typically, Congo River floods occur before or after Amazon River floods in a seesaw fashion (Elatahir et al. 2004). A flood in the Amazon correlates with decreased rainfall in the Congo and vice versa; El Niño floods in the central Pacific correlate with drought in Amazon and Congo watersheds (Eltahir et al., 2004). Thus, the Amazon flood of 2012, was followed by the 2013 Congo River flood (Spencer et al., 2016; Becker et al., 2014). The Congo River flow is small compared to the Amazon River and averages 38–41,000 $m^3 s^{-1}$ with dissolved inorganic nitrogen levels of 14 μM to 37 μM in high and low water, respectively (Descy et al., 2017; Spencer et al., 2016; Tshimanga et al., 2016). Thus the Congo flood of 2013 may have enhanced the growth of sargassum during the cross Atlantic transport of sargassum to the Brazil Current and the Caribbean beach strandings of 2014 (Wang and Hu, 2017).

Processes within the equatorial Atlantic that might lead to new nutrient injections include wind induced coastal upwelling in the northeast Canary and southeast Benguela currents, north and south equatorial currents and enhanced eddy circulation (Wang and Hu, 2016). However, there is no evidence that these processes have been enhanced during the period of sargassum blooms. Trade wind intensities during the negative North Atlantic Oscillation tend to be lighter than during the positive NAO period from 1970s to 2000 (George and Saunders, 2001). A positive NAO leads to stronger trade winds, enhanced wind-induced latent heat flux, tropical north Atlantic sea surface temperature cooling, and lower tropical north Atlantic atmospheric moisture content (George and Saunders, 2001). Thus wind intensities and eddy intensities are currently weaker than in the decades of the positive NAO. Unusual event years such as 2017 discussed below, can happen at any time but on average upwelling and eddy circulation nutrient sources would be expected to have not changed or in fact, would be less now than those sources were in the late 1900s before sargassum blooms occurred.

Nutrients associated with Benguela upwelling in 2017 may have contributed to the growth of sargassum before transport west to Brazil in early spring 2018 (Table 1). Benguela upwelling winds in 2017 were 65% and 77% more intense than in 2016 and 2018 (Fig. 7a, b). The stronger winds of 2017 would have resulted in nutrient upwelling from a deeper mixed water layer than the other two years in this location. The upwelled nutrients may have been concentrated in the stable shallow freshwater Congo River plume. These nutrients may have sustained and contributed to the largest sargassum seaweed bloom yet during the non-Amazon flood year of 2018. Strong upwelling winds do not appear to be present during the period of sargassum blooms in the Northeast equatorial current (Fig. 7b).

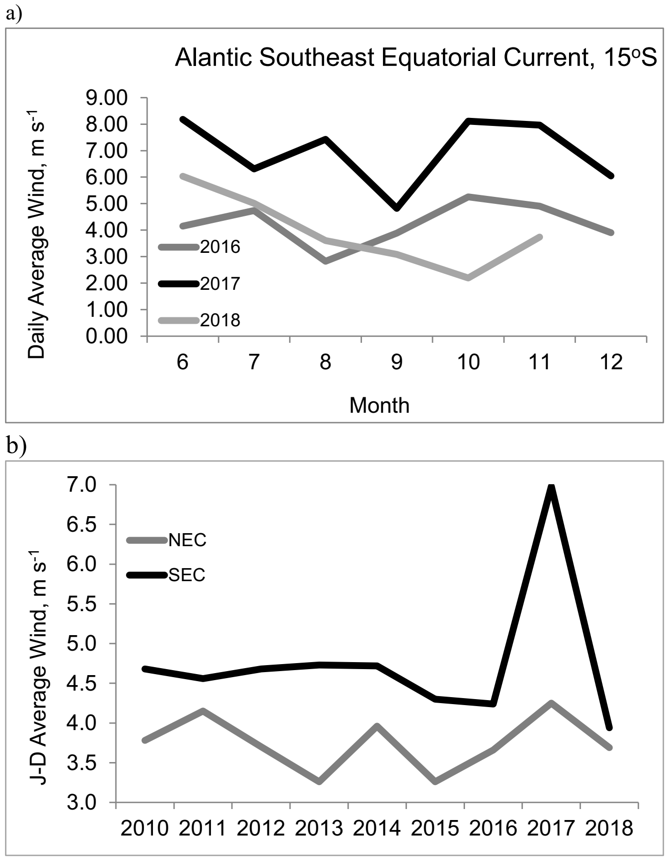

Fig. 7. Upwelling winds: a. Daily meridional wind speed at 15° South in the Southeast Equatorial Current (SEC) 15°S, 10°E; b. average meridional wind speed June to December (J-D) in the 15°S, 10°E Southeast and 15°N, 342°E Northeast Equatorial Currents (NEC).
(Data from NCEP/NCAR NOAA reanalysis: Kalnay et al., 1996, accessed Dec. 2018, Data set ID: esrlNcepRe.)

6. Summary: nutrient sources of the equatorial Atlantic

Several potential equatorial sources of nutrients have been identified that require new studies to confirm their potential contribution to stimulating sargassum growth. The major eastern nutrient sources for 2 of the 5 sargassum bloom years include African coastal upwelling and the Congo River (Table 1). Nutrients in the eastern equatorial Atlantic may sustain seaweed mats for a new life cycle and trip back across the Atlantic to support a bloom in the following year (Fig. 7). In the western equatorial Atlantic, new nutrients from Amazon River floods and hurricanes may have initiated seaweed blooms during 5 of the years between 2009 and 2019 (Table 1). The extraordinary biomass of floating sargassum since 2011 is correlated with Amazon flood years and hurricane years where hurricanes occur in the year previous to the bloom. The extreme intensity of flood events and hurricanes may be due to climate warming combined with the warm cycle of the AMO (Gloor et al., 2013; Camp et al., 2018; Webster et al., 2005). Sargassum can bloom without hurricanes as in 2014 when no hurricanes occurred in the previous year (Table 1). If the Amazon River is the major source of nutrients initiating sargassum blooms, sargassum growth might be expected to decline as the warm phase of the north AMO has declined (Vogan, n.d) and Amazon floods have decreased. Instead satellite data show the largest seaweed percent coverage to date occurred during the 2018 non-Amazon flood year but after the extraordinary Caribbean hurricane season of 2017, posing the possibility that hurricanes, without an Amazon flood, may promote sargassum blooms (University of South Florida, n.d).

With no hurricanes and no Amazon flooding, sargassum may fail to bloom although blooms seem to occur in the absence of identified eastern equatorial nutrients (Table 1). The case example for this scenario is the year 2016 when satellite images predicted a significant sargassum bloom (Wang and Hu 2018). However, no significant hurricanes occurred in 2015 in the western Atlantic and because it was an El Nino year, no Amazon flooding occurred in 2016 (Table 1). Significant sargassum beach stranding was not reported in 2016 (Milledge and Harvey, 2016). Could the 2016 satellite images show sargassum left over from 2015 that failed to re-bloom and later sank (e.g. Wang and Hu, 2016)? If major new nutrient sources fail in a given year, little or no sargassum may bloom such as, in the pre-2011, 2013, 2016, 2017 and potentially 2019 (no 2018 hurricanes, El Niño correlates with no Amazon flooding) seasons (Table 1).

The Caribbean Regional Fisheries Mechanism (CRFM) has estimated the sargassum clean-up costs for the Caribbean in 2018 at $210 million causing severe impacts on regional economies and indicating the need for more information on the massive sargassum beaching events. Future research, focusing on obtaining data to investigate Amazon floods and hurricanes as possible new sources of nutrients subsidizing sargassum blooms in the western Atlantic region and subsequent sargassum deposition on tropical coastlines, could benefit preparedness planning and mitigation strategies.

Declaration of Competing Interest

None.

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Author contributions

Candace Oviatt reviewed the literature, analyzed the data, evaluated the hypotheses and drafted the manuscript. Kristin Huizena retrieved the data on Amazon River flow, rainfall, equatorial wind speed and Congo River flow. Caroline Rogers formulated the idea for the manuscript, edited the drafts, supplied photographs for illustration and guided the internal submission process. W. Jeff Miller edited the drafts, took photographs for illustration and provided field observations for the manuscript.

References

Amaral-Zettler, L., Dragone, N., Schell, J., Slikas, B., Murphy, L., Morrall, C., Zettler, E., 2016. Comparative mitochondrial and chloroplast genomics of a genetically distinct form of sargassum contributing to recent “Golden Tides” in the Western Atlantic. Ecology and Evolution 7, 516–525. https://doi.org/10.1002/ece3.2630.

Becker, M., da Silva, J.S., Calmant, S., Robinet, V., Linguet, L., Seyler, F., 2014. Water level fluctuations in the Congo basin derived from ENVISAT satellite altimetry. Remote Sens. 6, 9340–9358. https://doi.org/10.3390/rs6109340.

Bowater, D., 2014. Record Floods in Brazil Bring Chaos to Amazon. Towns. Amazonas, Brazil. http://www.bbc.com/news/world-latin-america-28123680, Accessed date: 16 February 2019.

Bronk, D.A., See, J.H., Bradley, P., Killberg, L., 2007. DON as a source of bioavailable nitrogen for phytoplankton. Biogeosciences 4, 283–296.

Brooks, M., Coles, V.J., Hood, R.R., Gower, J.F.R., 2018. Factors controlling the seasonal distribution of pelagic sargassum. Mar. Ecol. Prog. Ser. 599, 1–18.

Camp, J., Scaife, A.A., Heming, J., 2018. Predictability of the 2017 North Atlantic hurricane season. Atmos. Sci. Lett. 19https://doi.org/10.1002/asl.813. 7p.

Coles, V.J., Brooks, M.T., Hopkins, J., Stukel, M.R., Yager, P.L., Hood, R.R., 2013. The pathways and properties of the Amazon River plume in the tropical North Atlantic Ocean. Journal of Geophysical Research: Oceans 118, 6894–6913. https://doi.org/10.1002/2013JC008981.

da Cunha, L.C., Buitenhuis, E.T., 2013. Riverine influence on the tropical Atlantic Ocean biogeochemistry. Biogeosciences 10, 6357–6373. https://doi.org/10.5194/bg-10-6357-2013.

Demaster, D.J., Pope, R.H., 1996. Nutrient dynamics in Amazon shelf water: results from AMASSEDS. Cont. Shelf Res. 16 (4), 263–289.

Descy, J.P., Darchambeau, F., Lambert, T., Stoyneva-Gaertner, M.P., Bouillon, S., Borges, A., 2017. Phytoplankton dynamics in the Congo River. Freshw. Biol. 62, 87–101. https://doi.org/10.1111/fwb.12851.

Devol, A., Forsberg, B., Richey, J., Pimentel, T., 1995. Seasonal variation in chemical distributions in the Amazon (Solimões) River: a multiyear time series. Global Biogeochemical Cycle 9 (3), 307–328.

Doyle, E., Franks, J., 2015. *Sargassum* Fact Sheet. Gulf and Caribbean Fisheries Institute (3p).

Eltahir, E.A.B., Loux, B., Yamana, T.K., Bomblies, A., 2004. A see-saw oscillation between the Amazon and Congo basins. Geophys. Res. Lett. 3, L23201. https://doi.org/10.1029/2004GL021160.

Franks, J.S., Johnson, D.R., Ko, D.S., 2016. Pelagic sargassum in the tropical North Atlantic. Gulf and Caribbean Research 27 (1), SC6–SC11. https://doi.org/10.18785/gcr.2701.08.

Gensac, E., Martinez, J.-M., Vantrepotte, V., Anthony, E.J., 2016. Seasonal and interannual dynamics of suspended sediment at the mouth of the Amazon River: the role of continental and oceanic forcing, and implications for coastal geomorphology and mud bank formation. Cont. Shelf Res. 118, 49–62. https://doi.org/10.1016/j.csr.2016.02.009.

George, S.E., Saunders, M.A., 2001. North Atlantic Oscillation impact on tropical north Atlantic winter atmospheric variability. Geophys. Res. Lett. 28 (6), 1015–1018.

Gierach, M.M., Subrahmanyam, B., 2008. Biophysical responses of the upper ocean to major Gulf of Mexico hurricanes in 2005. J. Geophys. Res. 113, C04029. https://doi.org/10.1029/2007JC004419.

Glibert, P., Harrison, J., Heil, C., Seitzinger, S., 2006. Escalating worldwide use of urea – a global change contributing to coastal eutrophication. Biogeochemistry 77, 441–463. Ó Springer 2006. https://doi.org/10.1007/s10533-005-3070-5.

Gloor, M., Brienen, R., Galbraith, D., Feldpausch, T., Schöngart, J., Guyot, J., Espinoza, J., Lloyd, J., Phillips, O., 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophys. Res. Lett. 40, 1729–1733. https://doi.org/10.1002/grl.50377.

Goolsby, D.A., 2000. Mississippi Basin nitrogen flux believed to cause gulf hypoxia. EOS Trans. Am. Geophys. Union 81, 325–327.

Gower, J., King, S., 2011. Distribution of floating sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. Int. J. Remote Sens. 32, 1917–1929.

Gower, J., Young, E., King, S., 2013. Satellite images suggest a new sargassum source region in 2011. Remote Sensing Letters 4 (8), 764–773. https://doi.org/10.1080/2150704X.2013.796433.

Hanisak, M.D., Samuel, M.A., 1987. Growth rates in culture of several species of sargassum from Florida, USA. In: Ragan, M.A., Bird, C.J. (Eds.), Twelfth International Seaweed Symposium. Hydrobiologia, vol. 151/152. Dr. W. Junk Publisher, Dordrecht, pp. 399–404 printed in the Netherlands.

Higgins, M., 2016. Where's the beach? Under the seaweed. https://www.nytimes.com/.../caribbean-beaches-dig-out-from-massive-seaweed-invasion, Accessed date: September 2018.

Hinds, C., Oxenford, H., Cumberbatch, J., Fardin, F., Doyle, E., Cashman, A., 2016. Golden Tides: Management Best Practices for Influxes of sargassum in the Caribbean With a Focus on Clean up. Centre for Resource Management and Environmental Studies (CERMES), The University of the West Indies, Cave Hill Campus, Barbados (17 pp).

Hu, C., Montgomery, D., Schmitt, R., Muller-Karger, F., 2004. The dispersal of the Amazon and Orinoco River water in the tropical Atlantic and Caribbean Sea: observation from space and S-PALACE floats. Deep-Sea Research II 51, 1151–1171.

Hu, C., Murch, B., Barnes, B., Wang, M., Marechal, J., Franks, J., Johnson, D., Lapointe, B., Goodwin, D., Schell, J., Siuda, A., 2016. *Sargassum* watch warns of incoming seaweed. EOS 97. https://doi.org/10.1029/2016EO058355.

Johns, E.M., Muhling, B.A., Perez, R.C., Muller-Karger, F.E., Melo, N., Smith, R.H., Lamkin, J.T., Gerard, T.L., Malca, E., 2014. Amazon River water in the northeastern Caribbean Sea and its effect on larval reef fish assemblages during April 2009. Fish. Oceanogr. 23, 472–494.

Johnson, E.R., Ko, D.S., Franks, J.S., Moreno, P., Sanchez-Rubio, G., 2013. The sargassum invasion of the eastern Caribbean and dynamics of the equatorial North Atlantic. In: Proceedings of the 65th Gulf and Caribbean Fisheries Institute. Nov. 5–9, 2012 Santa Marta, Colombia, pp. 102–103.

Kalnay, et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin American Meteorological Society 77, 437–470.

Knight, J., Folland, C., Scaife, A., 2006. Climate impacts of the Atlantic multi-decadal oscillation. Geophys. Res. Lett. 33 (4p), L17706. https://doi.org/10.1029/2006GLO26242.

Korosov, N., Counillon, F., Johannessen, J.A., 2015. Monitoring the spreading of the Amazon freshwater plume by MODIS, SMOS, Aquarius, and TOPAZ. Journal of Geophysical Research: Oceans 120, 268–283. https://doi.org/10.1002/2014JC010155.

Langin, K., 2018. Seaweed masses assault Caribbean Islands. Science 360 (6394), 1157.

Lapointe, B.E., 1986. Phosphorus-limited photosynthesis and growth of *Sargassum natans* and *Sargassum fluitans* (Phaeophyceae) in the western North Atlantic. Deep-Sea Res. 33, 391–399.

Lapointe, B.E., 1995. A comparison of nutrient-limited productivity in *Sargassum natans* from neritic vs oceanic waters of the western North Atlantic Ocean. Limnol. Oceanogr. 40, 625–633.

Lapointe, B.E., West, L.E., Sutton, T.T., Hu, C., 2014. Ryther revisited: nutrient excretions by fishes enhance productivity of pelagic *Sargassum* in the western North Atlantic Ocean. J. Exp. Mar. Biol. Ecol. 458, 46–56.

Lewis Jr., W., Saunders III., J., 1989. Concentration and transport of dissolved and suspended substances in the Orinoco River. Biogeochemistry 7, 203–240.

Louime, C., Fortune, J., Gervais, G., 2017. *Sargassum* invasion of coastal environments: a growing concern. American Journal of Environmental Science 13 (1), 58–64. https://doi.org/10.3844/ajessp.2017.58.64.

Marechal, J., Hellio, C., Hu, C., 2017. A simple, fast, and reliable method to predict *Sargassum* washing ashore in the Lesser Antilles. Remote Sensing Applications: Society and Environment 5, 54–63.

Martinelli, L., Howarth, R., Cuevas, E., Filoso, S., Austin, A., Donoso, L., Huszar, V., Keeney, D., Lara, L., Llerena, C., McIssac, G., Medina, E., Ortiz-Zayas, J., Scavia, D., Schindler, D., Sota, D., Townsend, A., 2006. Sources of reactive nitrogen affecting ecosystems in Latin America and the Caribbean: current trends and future perspectives. Biogeochemistry 79, 3–24. https://doi.org/10.1007/s10533-006-9000-3.

Martinelli, L., Coletta, L., Ravagnani, E., Camargo, P., Ometto, J., Filoso, S., Victoria, R., 2010. Dissolved nitrogen in rivers: comparing pristine and impacted regions of Brazil. Brazil Journal of Biology 70 (3), 709–722 supplement.

Milledge, J.J., Harvey, P.J., 2016. Golden tides: problem or golden opportunity? The valorization of *Sargassum* from beach inundations. Journal of Marine Science And Engineering 4, 60.. 19p. https://doi.org/10.3390/jmse4030060. www.pnas.org.cgi doi: 10.1073pnas.0606377103.

Otorongo Expeditions, 2012. http://otorongoexpeditions.com/author/otoexadmin/, Accessed date: 16 February 2019.

Oviatt, C., Rogers, C., Miller, W., 2016. What is the source of *Sargassum* seaweed on Caribbean beaches. Reef Encounter 31 (1), 45–49.

Paerl, H.W., Willey, J.D., Go, M., Peierls, B.L., Pinckney, J.L., Fogel, M.L., 1999. Rainfall stimulation of primary production in the western Atlantic Ocean waters: roles of different nitrogen sources and co-limiting nutrients. Mar. Ecol. Prog. Ser. 176, 205–214.

Parr, A.E., 1939. Quantitative observations on the pelagic *Sargassum* vegetation of the western North Atlantic. Bulletin Bingham Oceanographic Collection 6 (1), 94.

Pasch, R. J., T. B. Kimberlain. 2011. Tropical cyclone report hurricane Tomas (AL212010), October 29–November 7, 2010. NOAA National Hurricane Center. 20p. Https:/www.nhc.noaa.gov/data/tcr/AL212010_Thomas.pdf

Putman, N., Goni, G., Gramer, L., Hu, C., Johns, E., Trinanes, J., Wang, M., 2018. Simulating transport pathways of pelagic *Sargassum* from the Equatorial Atlantic into the Caribbean Sea. Prog. Oceanogr. 165, 205–214.

Rodríguez-Martínez, R.E., van Tussenbroek, B.I., Jordán-Dahlgren, E., 2016. Afluencia masiva de sargazo pelágico a la costa del Caribe Mexicano (2014–2015). In: García-Mendoza, E., Quijano-Scheggia, S.I., Olivos-Ortiz, A., Núñez-Vázquez, S.J. y (Eds.), Florecimientos Algales Nocivos en México. CICESE, Ensenada, México, pp. 352–365 (Translated from Spanish).

Santos, M., Medeiros, C., Muniz, K., Feitosa, F.A.N., Schwamborn, R., Macêdo, S.J., 2008a. Influence of the Amazon and Pará Rivers on water composition and phytoplankton biomass on the adjacent shelf. J. Coast. Res. 585–593. https://doi.org/10.2112/05-0538.1.

Santos, M., Muniz, K., Barros-Neto, B., Araujo, M., 2008b. Nutrient and phytoplankton biomass in the Amazon River shelf waters. Anais da Academia Brasileira de Cincias 80 (4), 703–717 (Annals of the Brazilian Academy of Sciences).

Schell, J.M., Goodwin, D.S., Siuda, A.N.S., 2015. Recent sargassum inundation events in the Caribbean: shipboard observations reveal dominance of a previously rare form. Oceanography 29 (3), 8–11.

Schlosser, C.J.H., Klar, K., Wake, B.D., Snow, J.T., Honey, D.J., Woodward, E.M.S., Lohan, M.C., Achterberg, E.P., Moore, C.M., 2014. Seasonal ITCZ migration dynamically controls the location of the (sub)tropical Atlantic biogeochemical divide. PNAS (Proceedings of the National Academy of Sciences of the United States of America) III (4), 1438–1442. www.pnas.org/cgi/doi/10.1073/pnas.1318670111.

Seitzinger, S.P., Sanders, R.W., Styles, R., 2002. Bioavailability of DON from natural and anthropogenic sources to estuarine plankton. Limnol. Oceanogr. 47 (2), 353–366.

Sissini, M.N., Szechy, M.Barreto.M., Lucena, M., Oliveira, M., Gower, J., Liu, G., Bastos, E., Milstein, D., Gusma, F., Martinelli-Filho, J., Alves-Lima, C., Colepicolo, P., Ameka, G., Johnson, K., Gouvea, L., Torrano-Silva, B., Nauer, F., Nunes, J., Barufi, J., Rig, L., Guez, R., Mello, T., Lotufo, L., Horta, P., 2017. The floating *Sargassum* (Phaeophyceae) of the South Atlantic Ocean – likely scenarios. Phycologia 56 (3), 321–328.

Smetacek, V., Zingone, A., 2013. Green and golden seaweed tides on the rise. Nature 504, 84–88. https://doi.org/10.1038/nature12860.

Spencer, R.G.M., Hernes, P.J., Dinga, B., Wabakanghanzi, J.N., Drake, T.W., Six, J., 2016. Origins, seasonality, and fluxes of organic matter in the Congo River. Glob. Biogeochem. Cycles 30, 1105–1121. https://doi.org/10.1002/2016GB005427.

Swap, R., Garstang, M., Greco, S., 1992. Saharan dust in the Amazon Basin. Tellus 44B, 133–149.

Szechy, M.T.M. de, Guedes, P.M., Baeta-Never, M.H., Oliveira, E.N., 2012. Verification of *Sargassum natans* (Linnaeus) Gaillon (Heterokontophyta: Phaeophyceae) from the Sargasso Sea off the coast of Brazil, western Atlantic Ocean. Check List 8 (4), 638–641.

Tshimanga, R.M., Tshitenge, J.M., Kabuya, P., Alsdorf, D., Mahe, G., Kibukusa, G., Lukanda, V., 2016. Ch. 4 a regional perceptive of flood forecasting and disaster management systems for the Congo River basin. In: Flood Forecasting. Elsevier, pp. 87–123. https://doi.org/10.1016/B978-0-12-801884-2.00004-9.

Tussenbroek, H.A., Rodriguez-Martinez, R., Espinoza-Avalos, J., Canizales-Flores, H., Gonzalez-Godoy, C., Barba-Santos, M., Vega-Zepeda, A., Collado-Vides, L., 2017. Severe impacts of brown tides caused by *Sargassum* spp. on near-shore Caribbean seagrass communities. Mar. Pollut. Bull. 122, 272–281.

University of South Florida: optics.marine.usf.edu, mengqui@mail.usf.edu, accessed August 2018.

Van Engeland, T., Bouma, T., Morris, E., Vrun, F., Peralta, G., Lara, M., Hendriks, I., Soetaert, K., Middelburg, J., 2011. Potential Uptake of Dissolved Organic Matter by Seagrasses and Macroalgae. Marine Ecology Progress Series 427. pp. 71–81. https://doi.org/10.3354/meps09054.

Vogan, M. http://www.markvoganweather.com/2018/08/08/atlantic-multidecadal-oscillation-at-its-lowest-July-value-since-1950/ (Accessed 9-2018).

Vonk, J.A., Middelburg, J.J., Stapel, J., Bouma, T.J., 2008. Dissolved organic nitrogen uptake by seagrasses. Limnol. Oceanogr. 53 (2), 542–548.

Wang, M., Hu, C., 2018. On the continuity of quantifying floating algae of the Central West Atlantic between MODIS and VIIRS. International Journal of Remote Sensing 39 (12), 3852–3869. https://doi.org/10.1080/01431161.2018.1447161.

Wang, M., Hu, C., 2016. Mapping and quantifying *Sargassum* distribution and coverage in the Central West Atlantic using Modis observations. Remote Sensing of the Environment 183, 350–367.

Wang, M., Hu, C., 2017. Predicting *Sargassum* blooms in the Caribbean Sea from MODIS observations. Geophys. Res. Lett. 44, 3265–3273. https://doi.org/10.1002/2017GLO72932.

Wang, M., Hu, C., Cannizzaro, J., English, D., Han, X., Naar, D., Lapointe, B., Brewton, R., Hernandez, F., 2018. Remote sensing of sargassum biomass, nutrients, and pigments. Geophys. Res. Lett. 45. https://doi.org/10.1029/2018GL078858.

Ward, N.D., Bianchi, T.S., Sawakuchi, H.O., Gagne-Maynard, W., Cunha, A.C., Brito, D.C., Neu, V., Valerio, A. de M., da Silva, R., Krusche, A.V., Richey, J.E., Keil, R.G., 2016. The reactivity of plant-derived organic matter and the potential importance of priming effects along the lower Amazon River. Journal of Geophysical Research: Biogeosciences 121, 1522–1539. https://doi.org/10.1002/2016JG003342.

Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309 (5742), 1144–1146. https://doi.org/10.1126/science.1116448.

Wynne, S., 2017. Observational evidence of regional eutrophication in the Caribbean Sea and potential impacts on coral reef ecosystems and their management in Anguilla, BWI. In: Anguilla Fisheries and Marine Resources Research Bulletin No. 08, pp. 1–22.