

SARGASSUM BLOOM DYNAMICS IN THE CARIBBEAN, GULF OF MEXICO, AND
TROPICAL NORTH ATLANTIC

A Thesis

By

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ABSTRACT

Sargassum fluitans and *sargassum natans* have been impacting and inundating coastal communities in massive bloom events along the Caribbean Islands and the Yucatan Peninsula, the Gulf of Mexico and West Africa, creating a matter of precedence to coastal zone management. Although sargassum has been floating ashore for centuries, the last few years have been considered catastrophic to various coastal communities. 2011 marked the beginning of the anomalous blooms, and in 2015 the blooms' distribution nearly doubled. In 2018, the blooms nearly tripled in intensity, forcing many Caribbean Islands to declare a state of National Emergency. The approach applied in this study aims to build upon several previous theories and hypotheses, as well as present new ideas, in order to help further the research to understand these sargassum bloom events which have been developing anomalously off the northeast coast of Brazil. This study investigates the potential relationship between sargassum distribution and sea surface temperature (SST), chlorophyll *a*, particulate organic carbon (POC), Amazon river discharge, Brazil precipitation, sea surface salinity (SSS) and freshwater distribution, North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), and Atlantic Meridional Overturning Circulation (AMOC). The results of this study indicate that in 2010, right before the massive bloom event first occurred, there was a pronounced slowdown in the AMOC, the NAO switched into a negative mode, the ENSO oscillated into a strong positive, and there were warmer than average SSTs. The Amazon watershed also expelled greater than average discharge volume, which is a transport mechanism for nutrients. The increased discharge and a slower AMOC could have allowed for longer residence time of nutrients from the Amazon river. The confluence of these climatic variables quite likely drove the system past a threshold into a new ecological regime, wherein sargassum blooms are gradually beginning to dominate.

DEDICATION

Dedicated, with respect and admiration, to my mom, dad, and grandmothers

“The sea, the great unifier, is man’s only hope.

Now, as never before, the old phrase has a literal meaning:

we are all on the same boat.”

-Jacques Yves Cousteau

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Contributors

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NOMENCLATURE

sargassum seaweed, remote sensing, sea surface temperature, chlorophyll *a*, salinity, organic carbon, water quality, ocean color, climate variability, anomaly, climate indices, ocean currents, ocean circulation, coastal zone management

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1. INTRODUCTION AND LITERATURE REVIEW

Sargassum fluitans and *sargassum natans* have been impacting and inundating coastal communities in the Caribbean Islands and along the Yucatan Peninsula, as well as the Gulf of Mexico, South Florida, West Africa, and North Brazil, making it a top priority for coastal zone management to understand bloom dynamics. At the time, 2011 was considered an uncharacteristically catastrophic year for the Gulf of Mexico and Caribbean. In 2015, it was reported that the sargassum levels had reached a new record high, only for that record to be surpassed by nearly triple in 2018 in the Caribbean, prompting numerous Caribbean Islands to declare a state of national emergency in response to the coastal inundations. This floating seaweed brings with it a multitude of nuisances for coastal communities and resource managers, although it is viewed by oceanographers and marine biologists as important to the oceanwide ecosystem, spawning controversy in regard to methods of management. The blooms negatively impact coastal tourism as popular tourist beaches were covered by seaweed, so many communities work to remove the seaweed both upon landing and at point source. The heavily affected regions all rely on tourism as a major component of local economies, and the sargassum blooms negatively affect the aesthetic appeal of the beaches, deterring tourists from visiting for a beach vacation, and driving homeowners to sell properties, making it a matter of importance for coastal communities to both understand what could be causing the overgrowth as well as monitoring and forecasting the potential landings. Satellites have the ability to see these large algal mats from space.

This study uses remotely sensed data to examine the spatial and temporal distributions of biogeochemical variables that may be linked the anomalous sargassum blooms. Although sargassum and its movements have long been studied, the lack of solid sargassum data has hampered the ability to run a reliable analytical model. Previous models suffered from omission

bias due to the lack of widespread and reliable sargassum data and small sample size. This research incorporated a dataset that was Moderate Resolution Imaging Spectroradiometer (MODIS) derived from 2000-2018 by Wang and Hu (2019) which quantified sargassum area (km²) and then observed the spatial and temporal variability of parameters including sea surface temperature (SST) and primary productivity. It also aimed to understand how climate and ocean circulation is modulating these anomalous bloom events by comparing biomass to climate indices such as the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO), and to Atlantic Meridional Overturning Circulation (AMOC) at 26°N. So, then what is causing these unprecedentedly massive blooms? What influences the variability of these blooms? Hypotheses are (1) that recent massive sargassum blooms are connected to organic nutrient inputs from the Amazon river and its tributaries. This hypothesis will be examined by observing Brazil precipitation, Amazon river volume discharge (m³/s), chlorophyll *a*, and particulate organic carbon; and (2) that climate variability is influencing the growth of the blooms by inducing nutrient upwelling events. This hypothesis will be tested by comparing sargassum abundance to SST anomalies, as well as climate indices NAO, and ENSO, as well as related variables such as AMOC transport at 26°N. The study region has a spatial extent of 40°N, 5°S, 100°W, and 2°E.

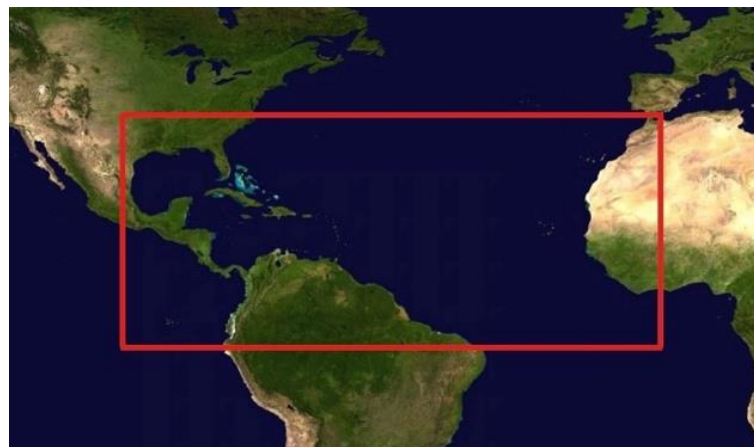


Figure 1. Study Area Extent.

The approach applied in this study aims to build upon a few previous theories and hypotheses, as well as present new ideas, in order to help further the research to understand the sargassum blooms. The use of remotely sensed data offers the unique possibility to study dynamics with spatially distributed large datasets during any season of the year. This research also aims to understand the sargassum seaweed itself by discussing its biological habitat, growth conditions, and existing hypotheses.

Despite the frustration that the seaweed causes coastal zone managers during bloom events, sargassum is regarded by oceanographers and marine biologists as extremely vital to the North Atlantic Ocean's ecosystem (Howard et al., 1969; Hanisak et al., 1987; Kilar et al., 1992; Hanson 1997; Gao et al., 1994; King et al., 2001; Ang et al., 2006). Sargassum offers ecologically supportive structures to a wide variety of important marine species. These seaweed mats serve as a primary habitat, temporary refuge, foraging habitat, breeding ground, and even nursery ground for a wide variety of marine fauna, and for some endangered species, such as the Loggerhead sea turtle.

The two species that have been impacting the coastlines, *sargassum natans* and *sargassum fluitans*, have an entirely holopelagic life cycle, which means they reproduce vegetatively at the surface. Unlike benthic specimens, pelagic species reproduce asexually at the surface of the ocean through continued budding and breaking off of segments known as thallus fragmentation (Kilar et al., 1992). While the majority of benthic seaweed are generally green, the pelagic species *s. natans* and *s. fluitans* are a vibrant gold, standing out against the bright blue sea, until they impact coastlines and begin to decay and decompose into a dark brown. Hanson (1977) found that sargassum and its associated epiphytes released a significant amount of dissolved organic carbon

(DOC) in surrounding waters as well as making fixed nitrogen available to the community. Its undeniable importance in the wider ecosystem adds another facet to the complexities of the threat it poses to coastal resource managers when it washes ashore in tidal blooms, especially massive bloom events.

These massive seaweed mats move and migrate dependent upon sea surface currents and wind conditions. Drifting pieces or colonies of sargassum are typically found as isolated colonies or clustered into windrows or large mats. Windrows, lines of sargassum only 0.5-1 meter across but hundreds of meters long, arise from Langmuir circulation (Langmuir 1938). As segments of the floating algal mats break away, the currents and winds carry the windrows, impacting any islands or coastlines within the trajectory, as shown in Figure 2.

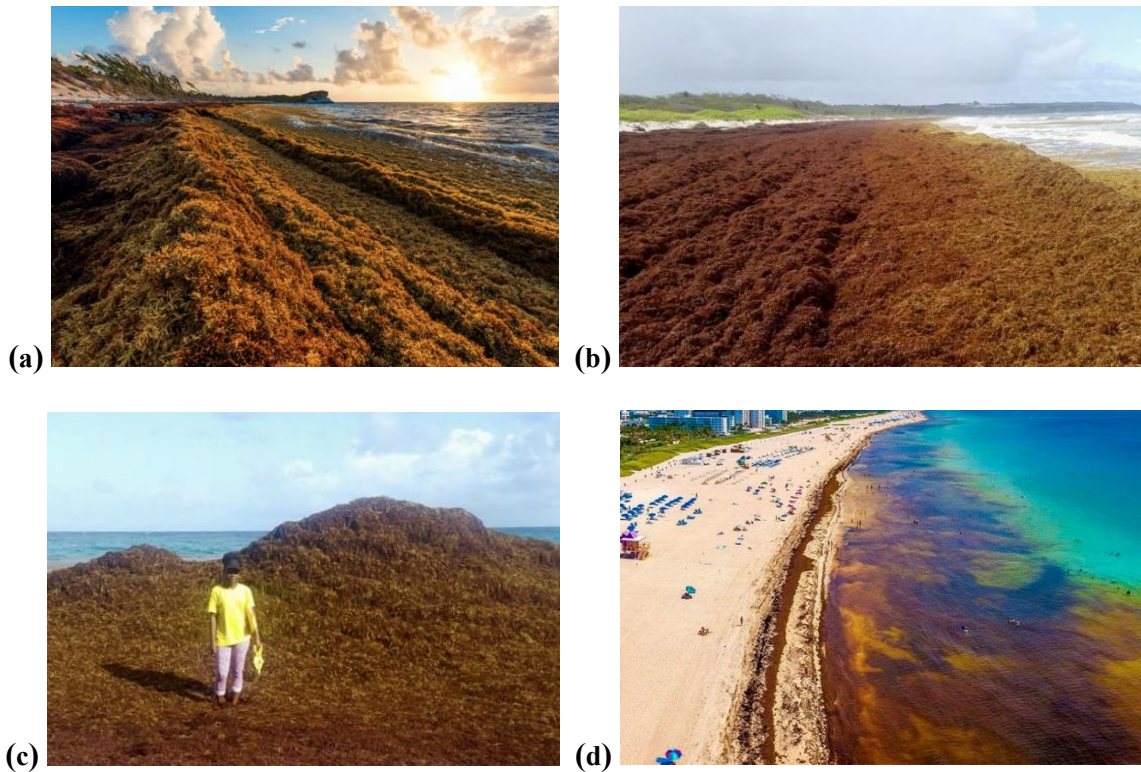


Figure 2. Photos of sargassum seaweed during extreme bloom events in (a) & (b) Quintana Roo North (c) Tulum and (d) South Florida, which pose a threat to coastal zone management and local communities for a multitude of reasons. Photos from news articles.

Although there are still many unknowns about the anomalous sargassum blooms, its growth conditions and growth rate have been studied and described in various scientific papers (Howard et al., 1969; Hanisak et al., 1987; Gao et al., 1994; King et al., 2001; Ang 2006; Sfriso et al., 2013; Xu et al., 2017). Sargassum was found to have a sensitivity to a specific range of sea surface temperature (SST) as well as salinity, and under these ideal growth conditions, the seaweed will thrive. According to laboratory studies conducted by Hanisak et al (1987), growth rate was maximal between 24-30°C for *sargassum fluitans* and 18-30°C for *sargassum natans*. For both species, growth rate decreased significantly above 30°C. Both species halted growth below 12°C. Both species, *s. fluitans* and *s. natans*, were stenohaline with an optimal salinity range of 36-42ppt, so it is believed to enjoy more saline waters compared to freshwater (Hanisak et al., 1987). Surface dwelling pelagic sargassum requires the energy of the sunlight, carbon dioxide, and nutrients such as nitrate, phosphate, and iron intakes for their growth (Ang et al., 2006; King et al., 2011; Sfriso et al., 2013; Xu et al., 2017). Gao et al (1994) specified that the most important variables affecting macroalgae growth, such as sargassum, are temperature, nutrients, irradiance, chlorophyll *a* and plankton grazing. Sargassum has a fast growth rate which, over a two-week period, increased in weight by 47% and length by 20% (Howard et al., 1969). The blooms have a relative seasonal abundance with a peak during summer months (June, July, and August).

These sargassum blooms are not a new phenomenon, as sightings have occurred as far back as when the Portuguese sailors who were sailing to the New World with Christopher Columbus noticed the golden seaweed “salgazo” against the blue ocean surface (Dickson, 1894; Linton and Webster, 2013). It is extremely likely that sargassum was floating around long before it was sighted, although this is the first recorded sighting and identification of it. Upon witnessing the windrows, sailors were overwhelmed and intimidated by the seeming endlessness of them. “At

this juncture they came upon what looked like huge pastures of grass on the sea; thinking they had come to drowned continents and they were lost; the men redoubled their complaints. And for those who had never seen such a thing, doubtless it was a fearful sight” (Dickson, 1894).

Despite the fact that sargassum has been around for so long, 2011 was a particularly impactful year for coastal zone management. This is the same year when the blooms began originating off the northeast coast of Brazil, as seen from MODIS. Then the blooms traveled from this new origin along the North Equatorial Current, the North Brazil Current, the Guiana Current, and the Caribbean Current, where they impact and inundate the Caribbean Islands, then they migrate along the Gulf Loop Current where they may or may not impact the Gulf of Mexico, and then they float towards South Florida where they feed back into the Sargasso Sea (Wang and Hu, 2019). Since 2011, the problem has been progressively exacerbating (Gower and King, 2008; Webster and Linton, 2013; Ped et al., 2016; Wang and Hu, 2017; Wang and Hu, 2019).

Traditionally, the only known source region of sargassum was the Sargasso Sea, a region of the North Atlantic Ocean that is bounded by four currents forming the North Atlantic Gyre. Based on recently available datasets that highlight a new source region of sargassum, it is possible to research spatial and temporal patterns and draw better conclusions about the causes of the blooms. Gower et al (2013), Wang and Hu (2016), and Wang and Hu (2019) highlighted this new origin of sargassum in a region located off the northeast coast of Brazil, near the North Equatorial Recirculation Region (NERR), a region that before 2011 did not host sargassum seaweed. Now, MODIS satellite derived datasets display this new source region, and quantify these blooms in terms of percent cover per pixel in decimal degrees using the Floating Algal Index (FAI) (Wang and Hu, 2019).

Due to its vibrant color and its tendency to gather in massive windrows, sargassum has a spectral signature that clearly distinguishes it from nearby water (Gower and King, 2008; Webster and Linton, 2013; Ped et al., 2016; Wang and Hu, 2017; Wang and Hu, 2019). Webster and Linton (2013) identified specific pixels in Landsat imagery as sargassum seaweed windrows. These pixels have been used by the Sargassum Early Advisory System (SEAS) to provide offshore observations of these windrows and were then used in early research projects that aimed to understand these blooms specifically along the Texas coast. Although the higher resolution is better for identifying windrows specifically, it is extremely difficult to model the larger issue that is taking place in the Caribbean and North Atlantic with Landsat exclusively, due to the narrow swath and low frequency flyover time. However, this higher resolution (30m) imagery is more ideal for providing imagery of the coastal zone conditions than MODIS (1000m), due to its higher resolution and ability to see large windrows without the need of an applied algorithm. Studies have also used MODIS and MERIS (MEdium Resolution Imaging Spectrometer) to aim to predict, which has been exceptionally useful to research for the purposes of identifying widespread distributions and spatial/temporal variability, but coarser resolutions (1000m) do lead to lower accuracy for detection of windrows, especially in coastal regions and especially for smaller windrows (Gower et al., 2013; Wang et al., 2017). Wang and Hu 2019 utilized MODIS to quantify spatial and temporal abundance of sargassum from 2002-2018, which has been particularly useful for mapping spatial and temporal trends. It is currently unknown which of the two sargassum species dominates these bloom events. Currently, remote sensing does not have the ability to discern between the two holopelagic surface dwelling seaweeds.

As research and science aim to understand the causes behind these bloom events, a wide range of hypotheses have been discussed as potential causal factors. A variety of natural and

anthropogenic variables are debated as contributors to the problem, including: ocean temperatures, fertilizer run-off and nutrient loading, oil spills, Amazon river nutrient input, climate variability and nutrient upwelling, Sahara aerosol dust transport, sewage and pollution, deforestation and land use conversion, and global climate change (Linton and Webster, 2013; Johnson et al., 2013; Gower and King, 2013; Ped et al., 2016; Dogliotti et al., 2018; Sanchez et al., 2018; Wang and Hu, 2019). It has been suggested that warmer SSTs and continental runoff from urban and agro-industrial sources caused the blooms of sargassum in the tropical Atlantic (Sissini et al., 2017). Gower and King showed evidence that these sargassum blooms could be forming off the northern coast of Brazil and then being transported to the Caribbean as a result of anomalously high nutrient input from the Amazon and Orinoco rivers (Gower and King, 2013). Linton and Webster suggested that the North Atlantic Oscillation (NAO) should be further investigated as a driving force (Linton and Webster, 2013). A strong El Niño in 2015 and subsequent increased river discharge levels from high precipitation were hypothesized as a catalyst of nutrient loading coming off of the Amazon and Orinoco River basins (Dogliotti et al., 2018; Sanchez et al., 2018). One study presented a clear upward trend from 1979 to 2015 for nitrates and phosphates in a study concerning the Amazon River, suggesting nutrient loading into the region off the coast of northeast Brazil that would spur algal growth (Djourke et al 2017). However, due to a lack of in situ nitrate (NO_3^-) and phosphate (PO_4^{3-}) data, their conclusions were drawn from statistical modelling using proxy variables such as rate of deforestation and total fertilizer consumption per year (Djakoure et al., 2017). Wang and Hu (2019) implied that an increase in deforestation in the Amazon forest has led to increased land use conversion and agricultural activity which has led to fertilizer runoff in the Amazon river that has caused large scale eutrophication which fed the blooms with increased NO_3^- and PO_4^{3-} . Some theories have also suggested the Orinoco river, the Mississippi River, and the Congo River, all of

whom feed into to the North Atlantic and/or the Gulf of Mexico. It has also been hypothesized that dust aerosols from the Sahara Desert are contributing iron, and further creating conditions in which the seaweed can thrive. This aeolian transported dust can be transported as far west as South America and the Caribbean, where it is then deposited over the Amazon in the form of iron. In such a dynamic oceanic system, it is likely a confluence of these variables, in spite of the difficulties associated with quantifying many of them.

1.1 Amazon River's Influence on Blooms and Primary Productivity

Many existing theories point to the Amazon watershed as being a major driver of the anomalous blooms since 2011, due to the rapid rate of deforestation that it has experienced over the past few decades (Sissini et al., 2017, Djourke et al., 2017, and Wang and Hu, 2019). The Amazon River is the largest river basin in the world with the greatest discharge volume. The organic material and sediment transported by the river have an influence on the biological community structure of the North Brazil Continental Shelf (Dagg et al., 2004; Santos et al., 2008; Medeiros et al., 2015; Gouveia et al., 2018). The Amazon watershed is a major source of terrestrially derived organic carbon to the Tropical Atlantic Ocean, as well as inorganics, such as NO_3^- and PO_4^{3-} . In addition, the Amazon rainforest has been the recipient of large-scale deforestation and land use conversion in the last few decades. Sissini et al. (2017), Djourke et al. (2017), and Wang and Hu (2019) all drew conclusions which implied that land use conversion and deforestation in the Amazon basin had the power to cause increase NO_3^- and PO_4^{3-} , which could then cause a widespread eutrophication event that might have spurred these sargassum blooms. Although the Amazon is the largest river basin in the world, there is still much to study regarding deforestation and its impact on water quality on the plume itself. Although the Amazon rainforest

experienced intense deforestation and land use conversion since the 1970's, deforestation rates have actually decreased since 2005 (Aragão et al., 2018).

Despite this recent decrease, the converted land use is associated with ongoing fertilizer consumption, which has been linked to increased nitrate and phosphate export. *Eutrophication* is pollution of groundwater and river water by nitrate and phosphate (Meyer-Reil and Koster, 2000). It is characterized by an excessive development of seaweed and algae and is a slow process which has a deferred character, meaning it could take years for a drop of nitrate to seep into the soil and find its way into a river (Meyer-Reil and Koster, 2000). The effects of deforestation of continental nitrate and phosphate inputs can be felt years later (Meyer-Reil and Koster, 2000). Biggs et al (2004) studied the relationship between stream nutrient concentrations and watershed characteristics such as deforestation extent, urban population density, and soil properties in the Brazilian state of Rondônia. He showed how stream nutrient concentrations appear to resist disturbance from non-urban land use change up to a threshold level of approximately 66-75% deforestation, and that stream nutrient disturbance was not detectable for watersheds less than 66-75% deforested (Biggs et al., 2004). Biggs concluded that regional deforestation and urbanization do impact nitrate and phosphate concentration for a wide range of stream sizes, from small pasture streams to large river systems. However, the study did not relate back to the Amazon river plume specifically.

Conversely, the argument has been made before that due to increased damming and impoundment of the Amazon river, concentrations of nutrients are being rapidly reduced (Forsberg et al., 2017). Their study analyzed the discharge of total nitrogen and total phosphates and found an 83% and 97% reduction in nutrients, respectively, in six dams which were analyzed (Forsberg et al., 2017). Niell et al. (2006) concluded that links among deforestation, soil biogeochemistry,

and the stoichiometry of NO_3^- and PO_4^{3-} reaching streams in small watersheds have the potential to influence the structure of local aquatic ecosystems but did not explore how this influenced larger oceanic ecosystems from the wider watershed. While there is little doubt that deforestation has local impacts on regional water quality and hydrology, it is still largely unquantified how this relates to the Amazon river plume specifically. However, the plume has been discussed in terms of its rich organics and inorganics and its influence on the continental shelf (Santos et al., 2008). Santos et al. (2008) showed that the chlorophyll *a* in the eutrophic area indicated that there is sufficient nitrogen to maintain high productivity in the region. Chlorophyll *a* is the major photosynthetic pigment in phytoplankton and is often used as an estimate of algal biomass (Nicholls et al., 1978; Portielje et al., 1999; Phillips et al., 2008). Specifically, information about nitrate and phosphate to chlorophyll *a* relationship has allowed for studies to determine highly productive and less productive water columns (Nicholls et al., 1978; Portielje et al., 1999; Phillips et al., 2008).

1.2 North Atlantic Oscillation (NAO)

The North Atlantic Ocean is a pressure driven system, influenced greatly by the trade winds. The NAO index is based on the surface-sea level pressure difference between the North Atlantic Subtropical High (NASH) ($\sim 30^\circ\text{N}$) and the Subpolar Low ($\sim 60^\circ\text{N}$). The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods (several months) of both positive and negative phases of the pattern are common. During positive NAO phases, the steeper pressure gradient between the Subtropical High and Subpolar Low is increased (Hurrell et al., 2003; Bellucci et al., 2006). During positive NAO phases, the steeper pressure gradient amplifies the Atlantic easterly trade winds, which influences vertical mixing in the water column,

and drives more nutrient upwelling events off the west coast of Africa and lowers sea surface temperatures (SSTs) in the subtropical Atlantic (Hurrell et al., 2003; Bellucci et al., 2006). A negative NAO phase results when the pressure differential between the two systems is reduced, producing weaker than average Atlantic easterly trade winds, which leads to fewer nutrient upwelling events, and subsequently warmer SSTs in the North Atlantic and Caribbean (Hurrell et al., 2003; Bellucci et al., 2006). Copper, Hanna, and Bigg (2014) found an influence of the NAO's nutrient upwelling inducing winds as far south as 20°N along the northwest African coastline. Hurrell et al., (2003) discussed how during a positive NAO phase, the prevailing northeasterly trade winds are relatively steady but strongest during boreal summer over the subtropical Atlantic, which does coincide with relative seasonal peak sargassum abundance.

1.3 El Niño Southern Oscillation (ENSO)

The El Niño Southern Oscillation (ENSO) refers to a periodic oscillation of SSTs in the eastern equatorial Pacific (Philander, 1983; McGlone et al., 1993; Trenberth et al., 1998; Stenseth et al., 2003; Li et al., 2012) During positive ENSO phases (El Niño), a reduction in the strength of the easterlies decreases upwelling in the eastern Pacific and produces warmer than average SSTs (Philander, 1983; McGlone et al., 1993; Trenberth et al., 1998). The higher SSTs associated with El Niño produce lower sea surface pressures, which in turn encourage atmospheric convection and moisture-rich air rises and develops into rainstorms and leads to increased rainfall in the eastern equatorial Pacific and over northwestern South America (Ecuador and Peru) (Philander, 1983; McGlone et al., 1993; Trenberth et al., 1998). During negative ENSO anomalies (La Niña), increased upwelling is driven by a strengthening of the trade winds, lowers regional SSTs, and increased surface pressure (Philander, 1983; McGlone et al., 1993; Trenberth et al., 1998). La Niña

events are associated with a decrease in regional rainfall due to decrease water evaporation. As the dominant pattern of interannual climate variability, ENSO anomalies exert a strong influence on global atmospheric circulation (Trenberth et al., 1998; Li et al., 2012). Changes in ENSO impact precipitation over South America. A study by García et al. (2005) examined the time series of streamflows for large rivers in all major catchments of South America, and found that on interannual time scales, El Niño Southern Oscillation (ENSO) can impact the behavior of South American rivers. Hastenrath (1990) found anomalously high river discharges in the northern South America during positive ENSO anomalies.

1.4 Atlantic Meridional Overturning Circulation (AMOC)

Less discussed with respect to sargassum is the potential influence that the slowing down of the AMOC has on the nutrient concentration over the northeast coast of Brazil. The AMOC is a prominent component of the global ocean circulation and nutrient transport, as it carries warm upper waters into far-northern latitudes and returns cold deep nutrient rich waters southward across the Equator. There is evidence to suggest that the circulation system of the North Atlantic Ocean is in an unprecedented weakened state (Bryden et al., 2005; Lohmann et al., 2008; Srokosz et al., 2012; Rahmstorf et al., 2015; Praetorius et al., 2018) but impacts of this slowing down are still largely unknown. Research has been presenting evidence that since the start of the industrial era, the strength of the AMOC has been gradually weakening, the culprit of which is thought to be anthropogenic global warming and surface-water freshening associated with ice melting (Bryden et al., 2005; Lohmann et al., 2008; Lohmann and Dima 2010; Srokosz et al., 2012; Rahmstorf et al., 2015; Stepanov et al., 2016). The most direct impact of changes in the AMOC is on the heat transport of the ocean, with weakening of the AMOC leading to decreases in northward heat

transport (Lohmann et al., 2008; Srokosz et al., 2012; Rahmstorf et al., 2015). This decrease in northward heat transport causes a decrease or slowdown of the southward transport of cool, nutrient rich water. The northward belt of the AMOC passes the northeast coast of Brazil, and in theory, could allow the Amazon river discharge nutrient rich waters to have a longer residence time. Srokosz et al. (2012) showed a pronounced, but not fully understood decrease in AMOC strength at 25.6°N in the winter of 2009/2010, which is the year before these anomalous sargassum bloom events began to occur. Kelly et al. 2016 showed a pronounced slowdown in the AMOC transport in 2010 at 25.6°N, 10°S, and 35°S. The AMOC is intrinsically linked to the same variables that drive the NAO, such as wind stress and pressure. During a positive NAO phase, there is enhanced interbasin circulation, and during a negative NAO phase, there is reduced interbasin circulation (Bellucci et al., 2006).

2. HYPOTHESES

It is hypothesized here that the Amazon and Orinoco river discharges are influencing the blooms by contributing organic and inorganic nutrients to the region. Due to the lack of in situ nitrate and phosphate data, and the lack of satellite data products that represent NO_3^- and PO_4^{3-} , this study examines chlorophyll *a* and particulate organic carbon (POC). There exists an empirical relationship between surface chlorophyll *a* concentration and primary production (Epply et al., 1985). Behrenfeld and Falkowski (1997) have used chlorophyll *a* satellite derived dataset as a model of net primary production. Chlorophyll *a* was found to be significantly related to both total phosphorus and total nitrogen (Phillips et al., 2008). Furthermore, the existing literature regarding sargassum identifies chlorophyll *a*, nutrients, and irradiance as main ingredients to the recipe of the growth of the holopelagic seaweed (Howard and Menzies, 1969; Gao et al., 1994; Gower et al., 2001; Ang et al., 2006). The algorithm for satellite derived chlorophyll *a* returns the near-surface concentration of chlorophyll *a* in mg/m^3 , calculated using an empirical relationship derived from in situ measurements of chlorophyll *a* and remote sensing reflectance in the blue-to-green region of the visible spectrum.

Particulate organic carbon (POC) has also been used as an estimator for phytoplankton and ocean productivity from space before (Behrenfeld et al., 2005). Behrenfeld (2005) showed an empirical relationship between phytoplankton chlorophyll *a* concentration and backscattering by particulate organic matter to assume what they refer to as phytoplankton carbon. This can be related back to the vascular seaweed plant sargassum in terms of primary productivity. The carbon:chlorophyll ratio (Behrenfeld et al., 2005) is used to estimate growth. The algorithm for satellite derived POC measurements is a power-law relationship applied to a blue-to-green band ratio.

The second hypothesis is that the blooms are being driven by climate variability, which affects sea surface temperature (SST), wind, ocean currents, and sea level pressure (SLP). This in turn affects nutrient upwelling events. Observable recurrent periodicities between specified spatial domains and quantifiable climate metrics (such as SST, currents, and SLP) are expressed using climate indices. The indices evaluated as potential influencers of sargassum distribution in this study are the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO). The Atlantic Meridional Overturning Circulation (AMOC) at 26°N is evaluated as well, in order to model ocean circulation.

3. DATA AND METHODOLOGY

The scope of this research aims to incorporate a series of variables either directly or indirectly associated with primary productivity, nutrient upwelling, climate variability, and ocean circulation in order to draw conclusions about the spatial and temporal variability of the forces potentially acting upon the Sargassum seaweed blooms. The study region has a spatial extent of 40°N , 5°S , 100°W , and 2°E , which covers the North Atlantic, the Caribbean, and the Gulf of Mexico as shown in Figure 3a. Figure 3b shows the transect for Hövmoller time series plots were generated with a spatial extent of latitudes 70°W to 30°E and longitude 15°N , which is approximately the Amazon and Orinoco River plume.

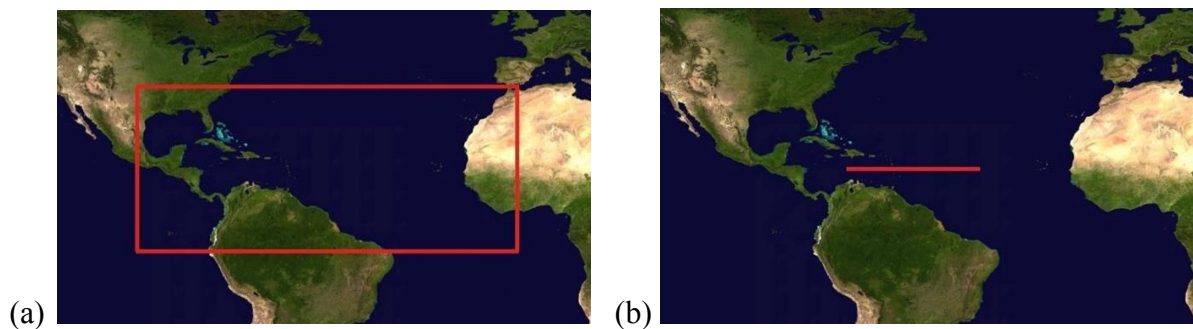


Figure 3. Maps of Study Areas for (a) Maps and (b) Hovmöller time series plots.

3.1 Sargassum Distribution

The datasets for sargassum mean area coverage from Wang and Hu, 2019 was accessed from (<ftp://ftp.nodc.noaa.gov/nodc/archive/arc0139/0190272/>). The dataset was generated by Wang and Hu (2019) and applies the Floating Algal Index (FAI) to a reclassified Aqua-MODIS dataset to yield percent cover for each pixel in decimal degrees that does contain sargassum. For the purposes of this study, the spatial extent is 40°N , 5°S , 100°W , and 2°E .

3.2 Sea Surface Temperature Anomalies

First, the sea surface temperature (SST) climatology level-3 (L3) data product was accessed from NASA Ocean Color Website. Then the L3 monthly mean datasets for summer for each year were retrieved. From that, the deviations from that baseline were calculated in SeaDAS for summer season for years 2011-2018 in order to map a time series for variable SST anomalies. This dataset was mapped against sargassum distribution to the study area spatial extent in order to observe the anomalies for summer as it relates to sargassum distribution in the study area. Then, Multi-scale Ultra-high Resolution (MUR) SST Analysis Anomaly fv04.1, Global, 0.01°, 2002-present, Monthly was processed in NOAA's data portal ERDDAP and plotted into two Hövmoeller time series plots of SST anomalies from 2002-2018. The longitude defined was 70°W to 30°E and the latitude defined was 15°N in order to plot spatial and temporal variability in the region off the northeast coast of Brazil near the plume where sargassum is proliferating.

3.3 Amazon River Discharge and Brazil Precipitation

Precipitation data was collected from a rain gauge station located near the mouth of the Amazon river from <https://climexp.knmi.nl/selectstation.cgi?id=someone@somewhere> at the Manaus Brazil (Brazil) station located at -3.10°N, -60.00°E, 60m, WMO station code: 82331. In order to evaluate river discharge of the Amazon River, the French product HYBAM “Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins” Environmental Research Observatory was used (<http://www.ore-hybam.org/>). The South American data are managed by the Brazilian National Water Agency (ANA). The Amazon

River discharge data, available from 1968 to 2018, was extracted from the Obidos station at 01.92°S in latitude and 55.67°W in longitude for 2000-2018.

3.4 Chlorophyll *a*

In order to evaluate chlorophyll *a* in the study region, two datasets were retrieved. NASA Ocean Color Biology Processing Group Aqua-MODIS chl_*a* Level 3 data from 2011-2018 and then processed in Python using the L3bin and L3mapgen functions, clipped to the spatial extent, and mapped in SeaDAS. In order to present a Hövmoller time series plot which focuses on Amazon river discharge, the ERDDAP data portal from NOAA was used to generate VIIRS Science Quality, Global, Level 3, 2012-present, Monthly data for 70°W to 30°E and latitude 15°N.

3.5 Particulate Organic Carbon

The Visible and Infrared Imager/Radiometer Suite (VIIRS) particulate organic carbon (POC) dataset from NASA Ocean Color Biology Processing Group L3 was attained for summer and then processed in Python using the L3bin and L3mapgen functions, clipped to the spatial extent, and mapped in SeaDAS. The datasets are publicly available through NASA's ocean color L3 portal. NASA's Ocean Biology Processing Group (OBPG) supports the collection, processing, calibration, validation, archive, and distribution of ocean-related products from a number of missions.

3.6 Salinity and Freshwater Distribution

To generate the Hövmoller time series plot of the Amazon plume, the NOAA data product Sea Surface Salinity, Near Real Time, SMAP Daily Composite (smapSSS3ScanDailyAggLoM),

CoastWatch v6.62, 0.25°, 2010-present, and plotted using ERDDAP at 70°W to 30°E latitude 15°N. To generate a map which displays a snapshot of the freshwater plume at the Amazon river, and salinity versus freshwater distribution in general within the study area during summer 2015, the data product Aquarius Sea Surface Salinity, L3 SMI, Version 5, 1.0°, Global, 2011-2015, 1-Month was downloaded and cropped spatially and mapped in SeaDAS.

3.7 North Atlantic Oscillation (NAO) Index

The NAO Index was accessed from https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/nao.long.data (Jones et al., 1997). It is calculated as the normalized pressure difference between a station on the Azores and one on Iceland. The Jones et al is calculated from Gibraltar and SW Iceland. It is in monthly time intervals with a time coverage of 1821 to November 2018 and was retrieved for 2000-2018.

3.8 El Niño Southern Oscillation (ENSO) Index

Nino 3.4 dataset was accessed from https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/nino34.long.data. The dataset was calculated from the HadISST1 and represents the averaged SST from 5°S to 5°N and 170° to 120°W in monthly time intervals from 1870 to near present (Rayner et al., 2003). It was accessed for 2000-2018.

3.9 Atlantic Meridional Overturning Circulation (AMOC) Index

A dataset for the Atlantic Meridional Overturning Circulation (AMOC) Transport at 26.5°N in terms of Sverdrups ($1\text{Sv} = 10^6 \text{ m}^3/\text{s}$) was retrieved from

(https://climexp.knmi.nl/data/imoc_mar_hc10_mon.dat). The data product was created by Ben Moat and David Smeed. These calculations are based on moorings that were deployed in March 2004 across the Atlantic at 26.5°N to measure the southward branch of the MOC.

4. RESULTS

The first bloom in 2011 began developing off the northeast coast of Brazil near the mouth of the Amazon river in March and expanded during the summer months until September (Fig. 4).

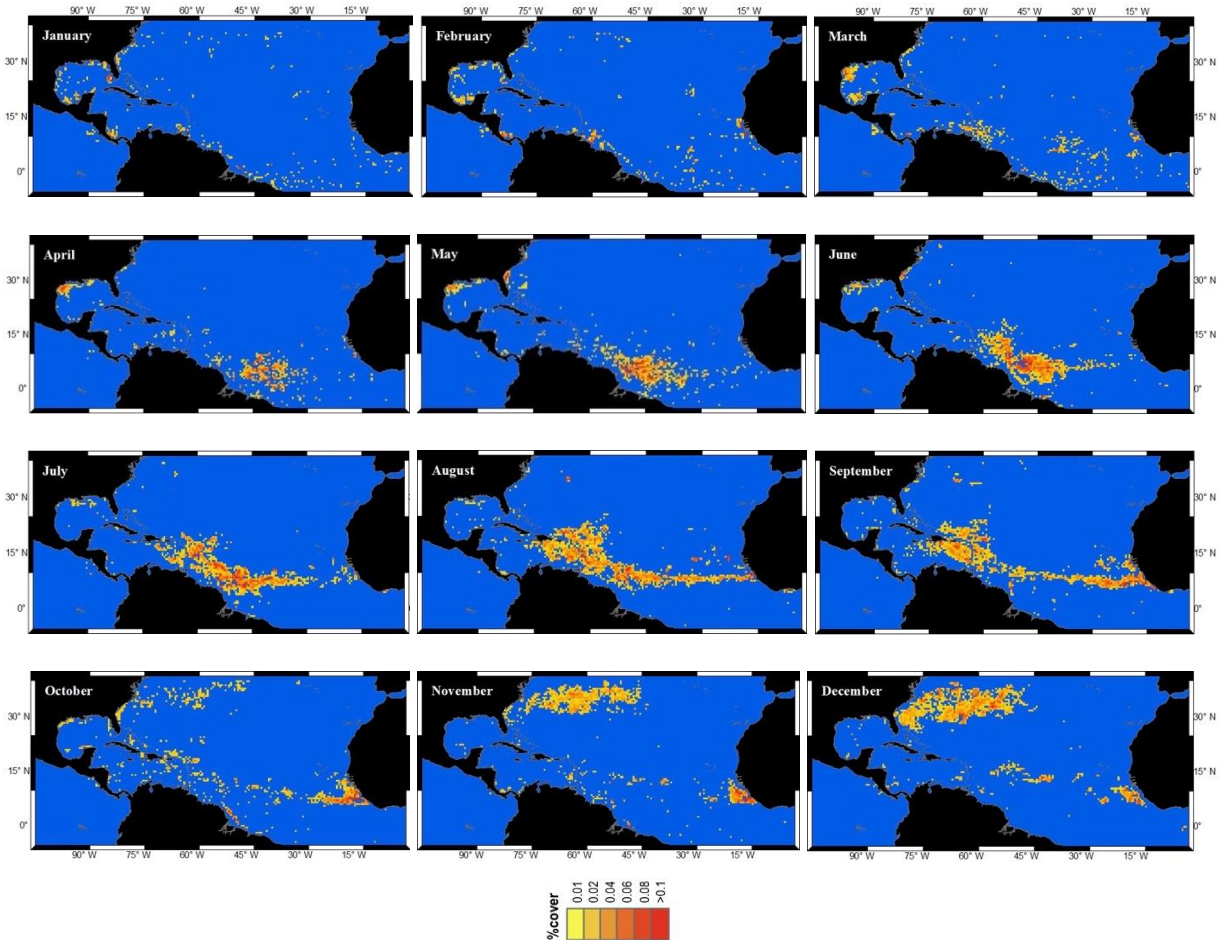


Figure 4. Monthly spatial distribution of sargassum blooms for January to December 2011.

The summer months (June, July, and August) showed the greatest expansion of sargassum across the tropical Atlantic and Caribbean Ocean. Bloom trajectories appeared to follow the major water circulation features. In October, the blooms began to subside across the Caribbean, but sargassum proliferated in the Sargasso Sea during November and December (Fig. 4).

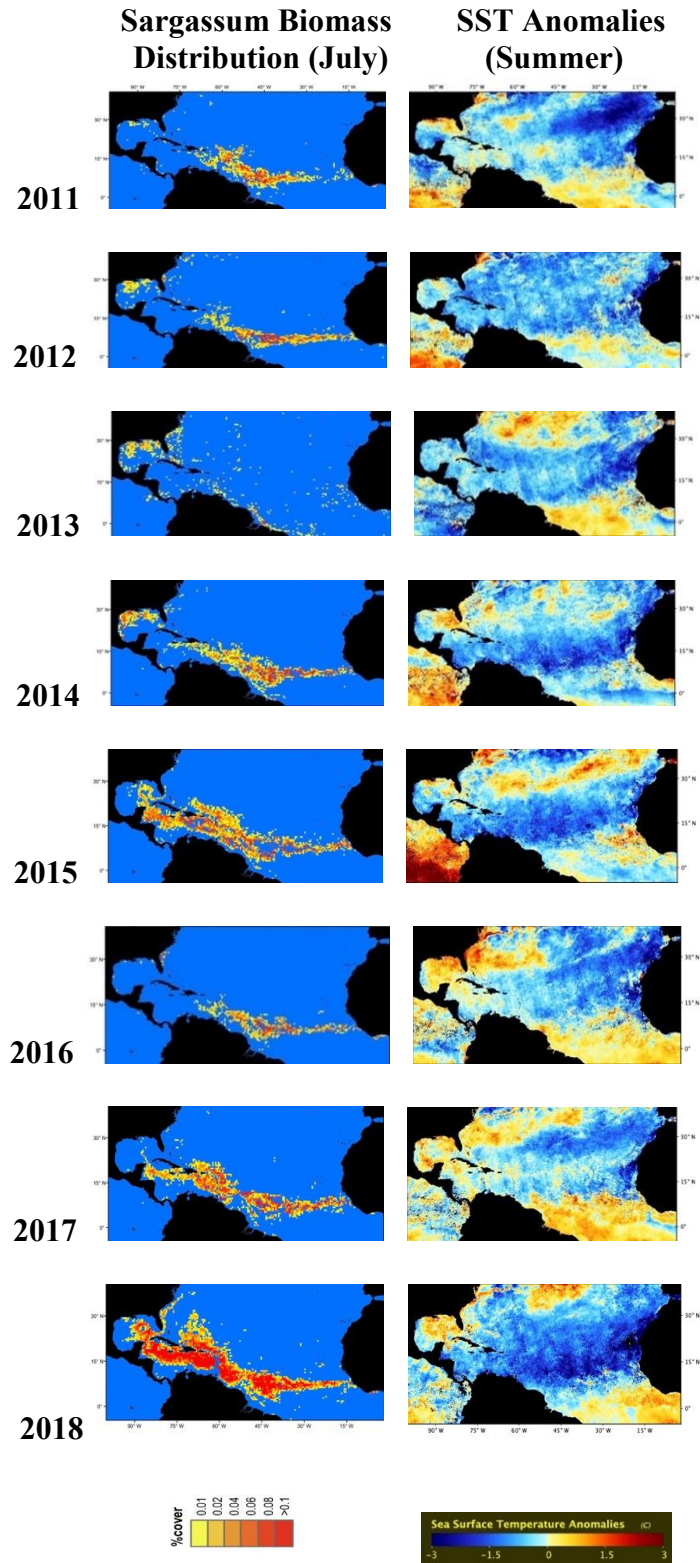


Figure 5. Spatial distribution of sargassum area (%cover) versus mean sea surface temperature (SST) anomalies for summer from 2011-2018.

Following 2011, large sargassum blooms occurred in the tropical Atlantic and Caribbean in 2012, 2014, 2015, and 2018 (Fig. 5). During years with high sargassum abundance, sea surface temperatures (SST) showed negative anomalies in the Atlantic basin-wide between 5-30°N (Fig. 5), indicating cooler waters.

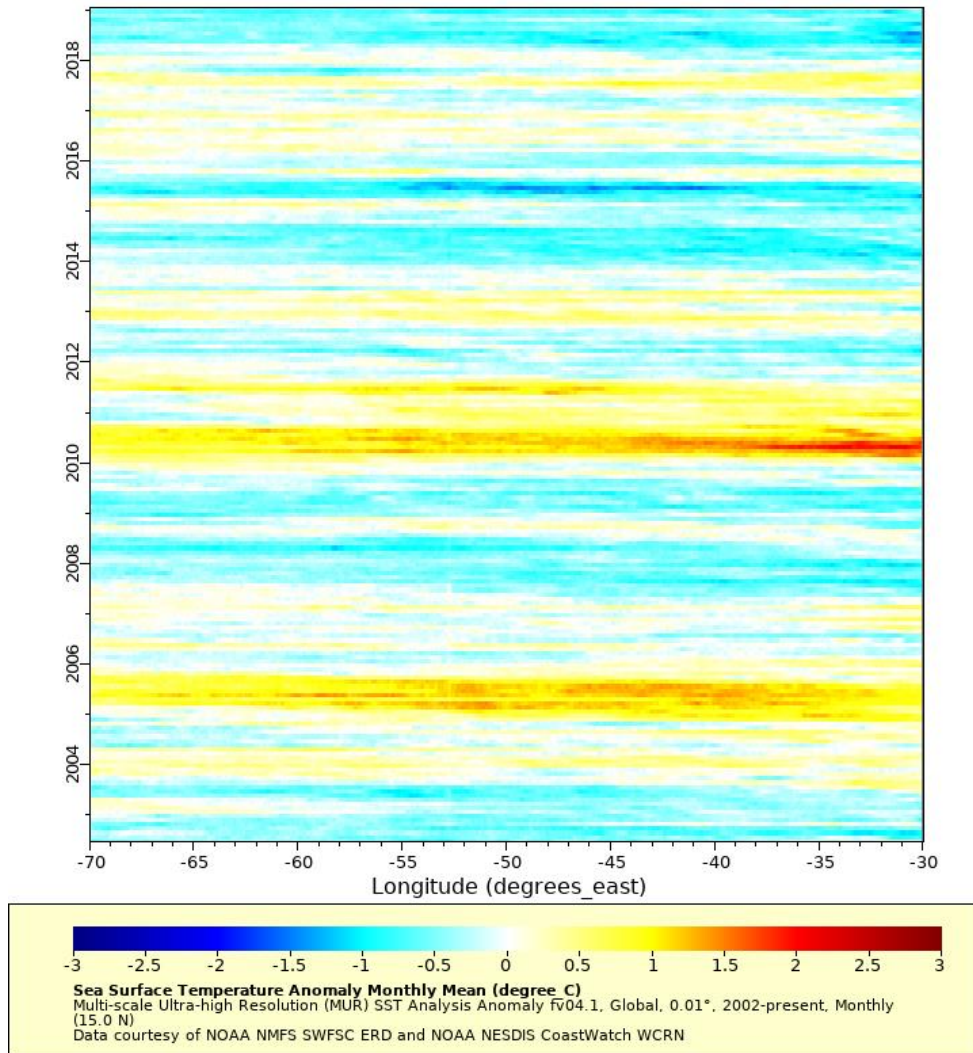


Figure 6. Hovmöller time series plot of SST anomalies from 2002-2018 for 70°W to 30°E at 15°N.

In general, cooler waters are associated with nutrient upwelling, primary productivity, and growth. Sargassum enjoys a temperature range of 18-30°C (Hanisak et al., 1987). All of the temperatures presented fall within that temperature range.

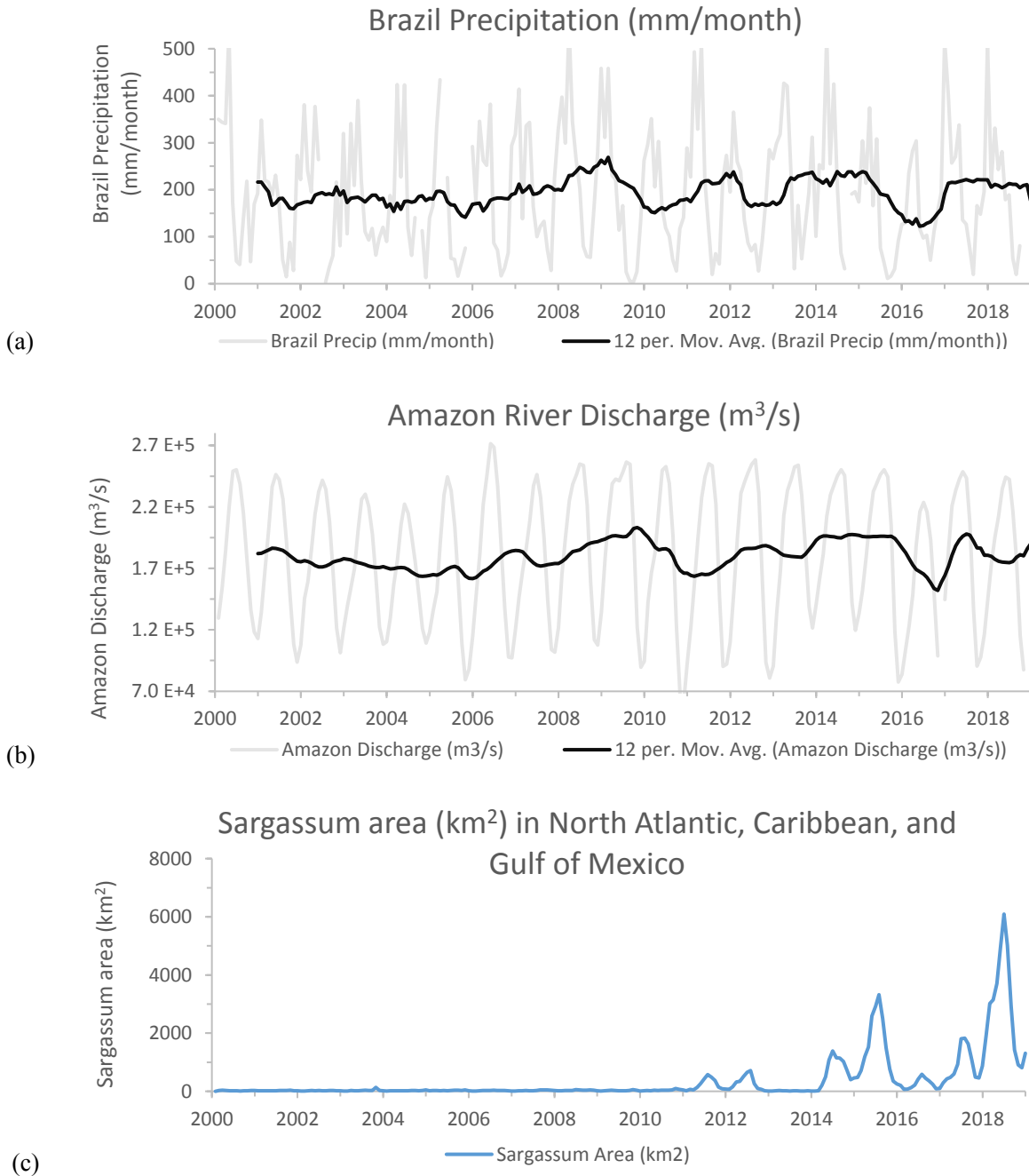


Figure 7. Time series trendlines comparing (a) Brazil Precipitation in mm/month with a 12-month running mean and (b) Amazon river discharge in terms of volume (m^3/s) with a 12-month running mean to (c) Sargassum abundance in terms of area (km^2).

Amazon discharge changes with seasons and generally shows highest discharge between April and July, coinciding with the wet season. In 2010, the Amazon showed higher than average river discharge (Fig. 7a). Higher than normal precipitation was the catalyst for increased river discharge.

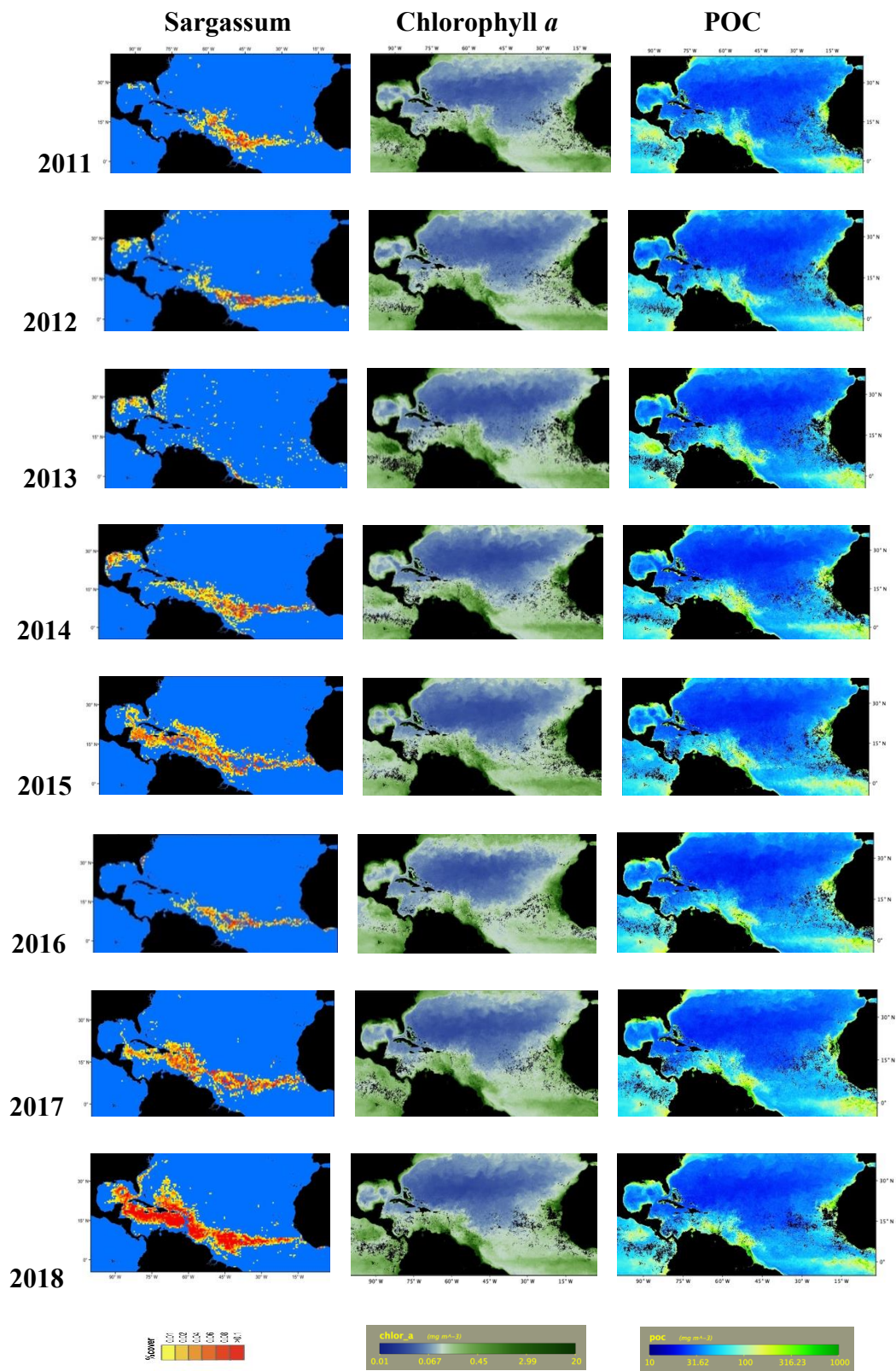


Figure 8. Sargassum distribution (%cover) versus mean chlorophyll *a* concentration versus particulate organic carbon (POC) for the month of July from 2011-2018.

Sargassum blooms were predominantly observed near the mouth of the Amazon and within the Equatorial Countercurrent, generally following peak discharge.

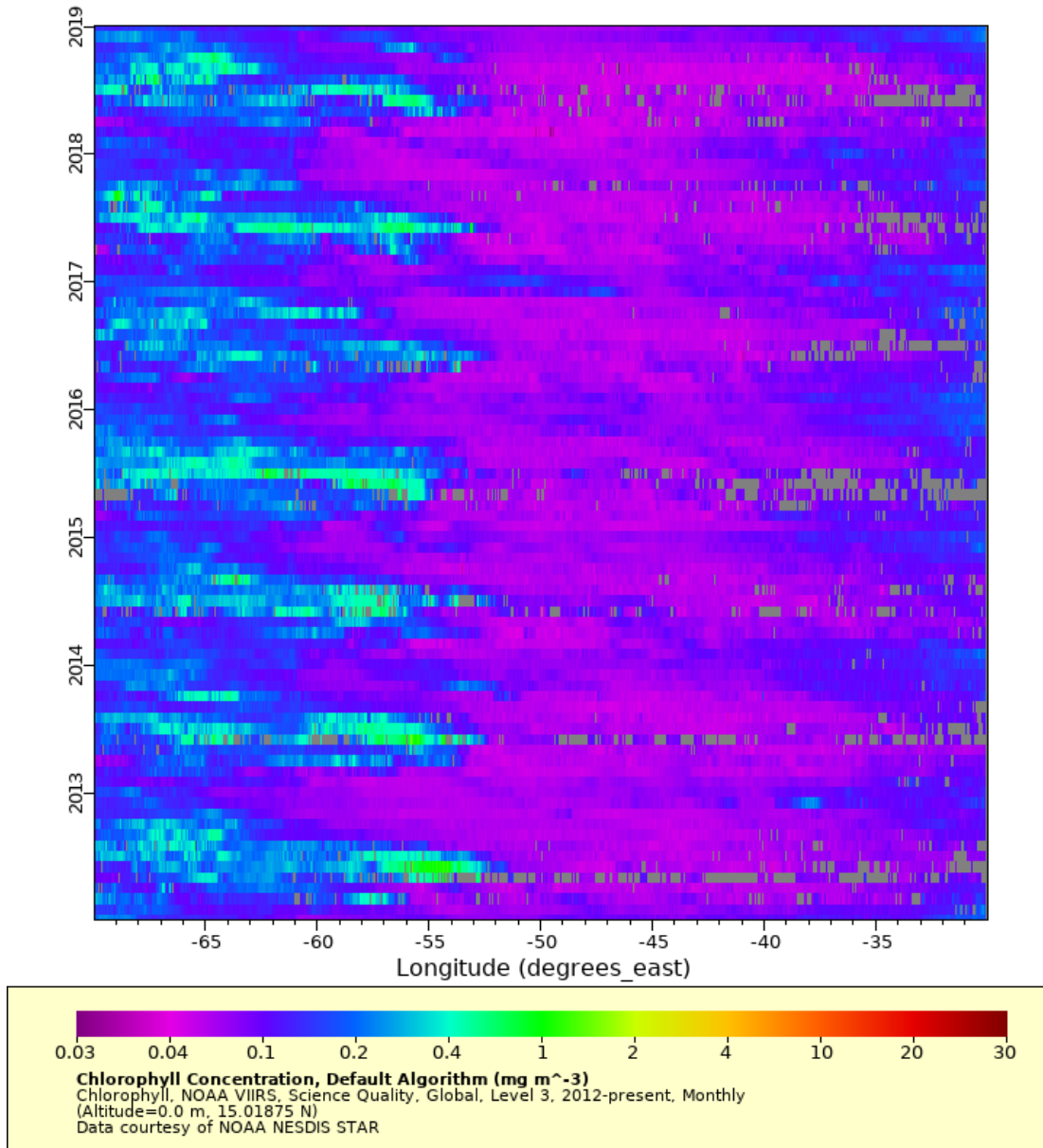


Figure 9. Hovmöller time series plot of chlorophyll *a* concentration for 2012-2018 70°W to 30°E at 15°N.

During each summer between 2012-2018, increased concentrations of chlorophyll *a* were observed in coastal water influenced by the Amazon River and Orinoco plumes (Fig. 9). Chlorophyll *a* is associated with primary productivity. Chlorophyll *a* concentrations in the study region fluctuated

from as low as 0.03 mg m^3 to as high as 1 mg m^3 . The VIIRS sensor was launched in 2012, so this time series only extended back as far as data availability. A more revealing figure would be chlorophyll *a* anomaly, a data product which does not currently exist.

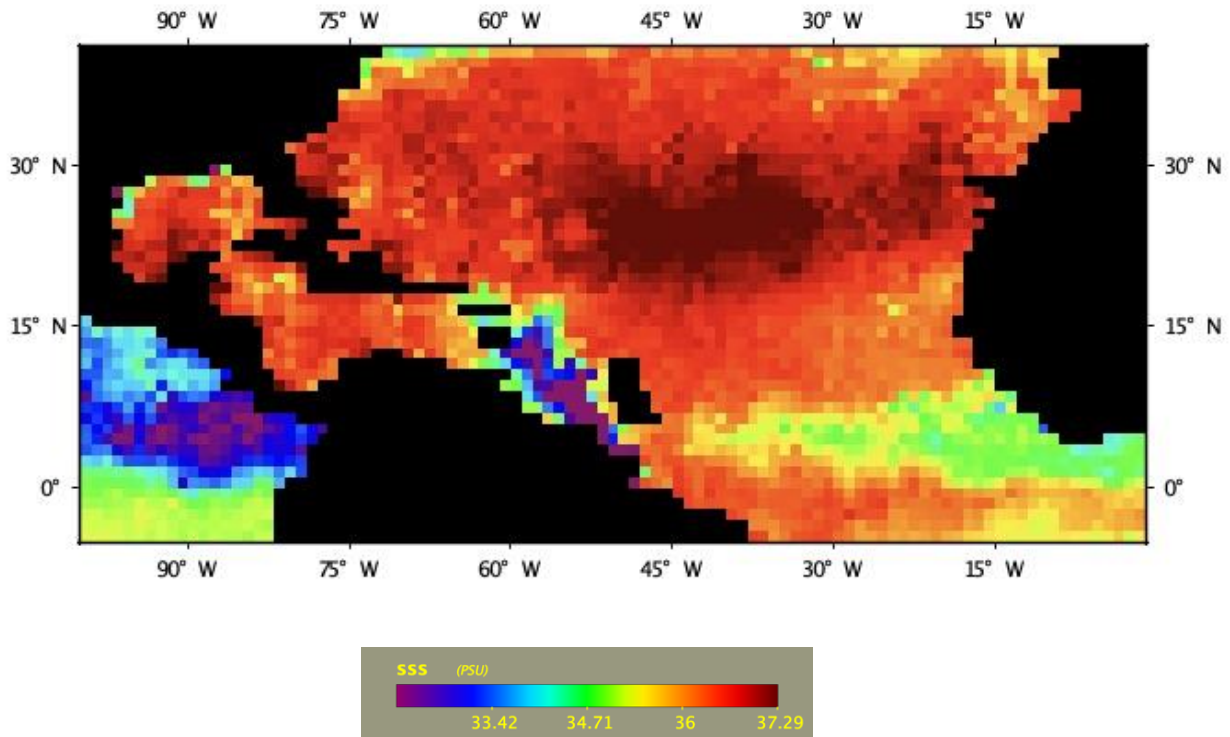


Figure 10. Sea surface salinity (SSS) and freshwater distribution during summer 2015 at 40°N , 5°S to 100°W , 2°E . The Amazon river plume can be seen off the northeast coast of Brazil.

During 2015, a sargassum bloom year, the Amazon plume followed a Northwest trajectory and overlapped with the region where high sargassum abundance was observed (Figs. 8 and 10). Plume waters showed a salinity range of 32-33ppt and were below salinities (36-42) in which sargassum thrives (Hanisak et al., 1987). The North Equatorial Recirculation Region (NERR) was also less saline, with a salinity of about 34-35ppt. The Sargasso Sea was the most saline, with salinity of about 37-38ppt.

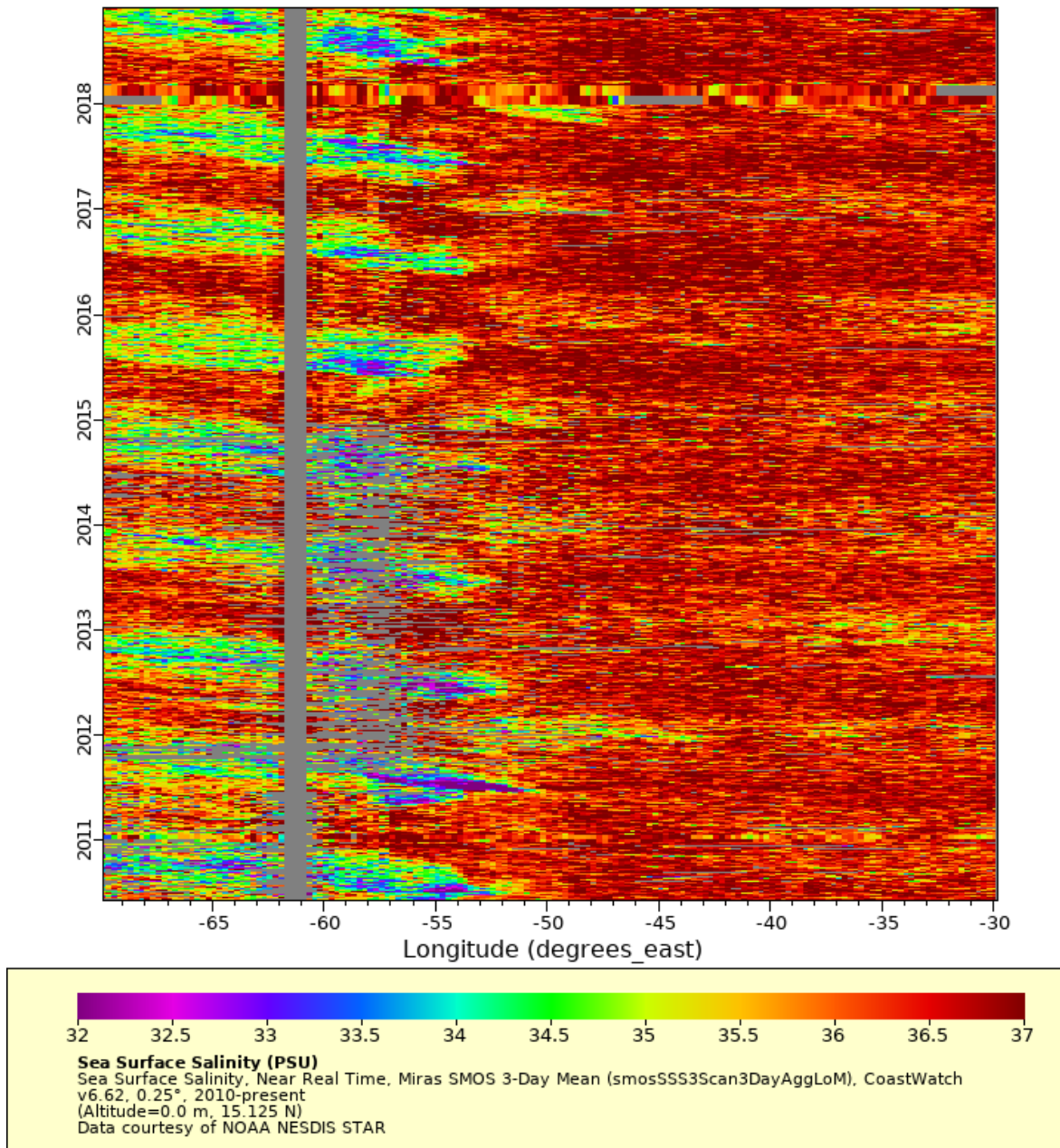


Figure 11. Sea surface salinity (SSS) and freshwater distribution from 2011-2018 at the mouth of the Amazon river. The seasonal freshening in the tropical Atlantic was a regular feature between 2011-2018 due to entrainment of Amazon river water. Amazon peak discharge influenced freshening of surface waters in summer months coincided with sargassum blooms (Figs. 8, 10, and 11).

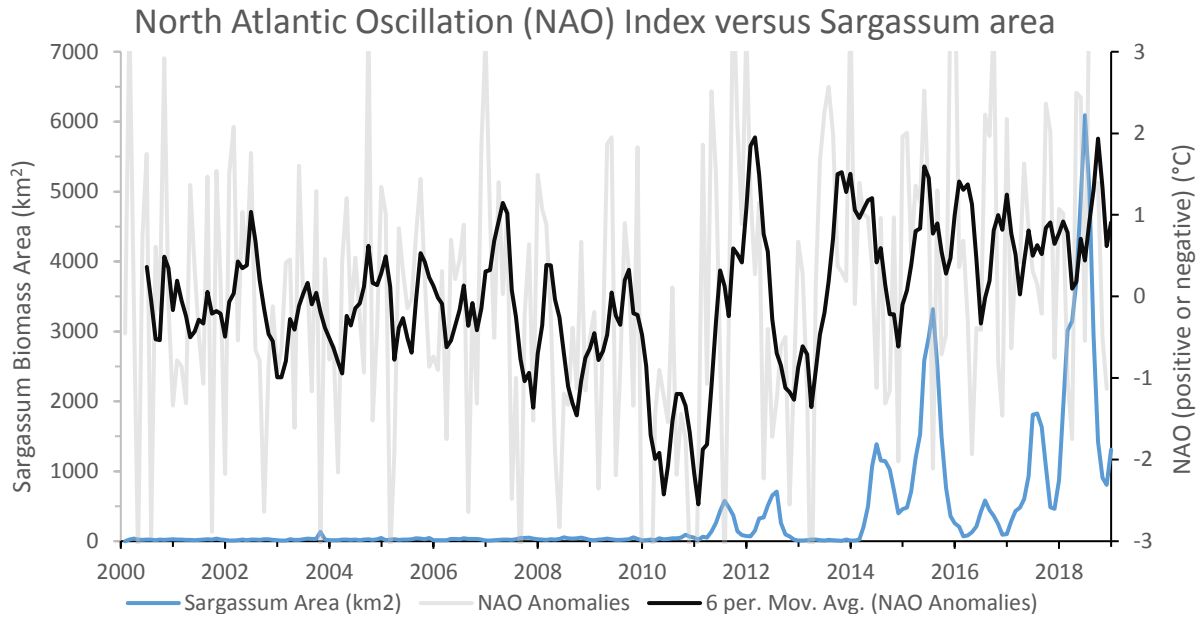


Figure 12. Time series trendlines comparing Sargassum area (km^2) from 2000-2018 to the North Atlantic Oscillation Climate Index with a moving 6-month average.

The NAO was in a negative phase during the genesis of the first bloom event, and then switched into a strong positive phase (Fig. 12). It is negative again in 2013, a nonbloom year, and then remained mostly in a positive phase until 2018.

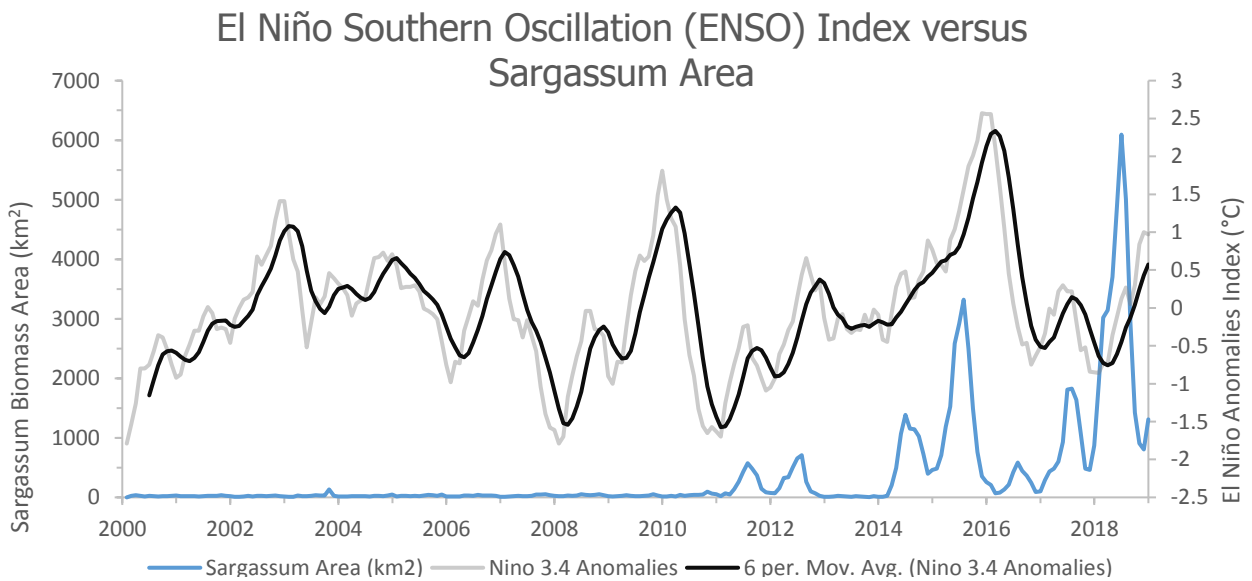


Figure 13. Time series trendlines comparing Sargassum area to the El Niño Southern Oscillation Climate Index with a moving 6-month average applied.

In 2010 and 2015, there were strong El Niño events (Fig. 13). The 2015 El Niño coincided with the 2015 sargassum event, although the sargassum signal peak slightly preceded the signal, which implied that although ENSO is most likely not the direct cause of the blooms, the mechanisms which drive ENSO could also be connected to sargassum development patterns. However, there was no linkage in 2018.

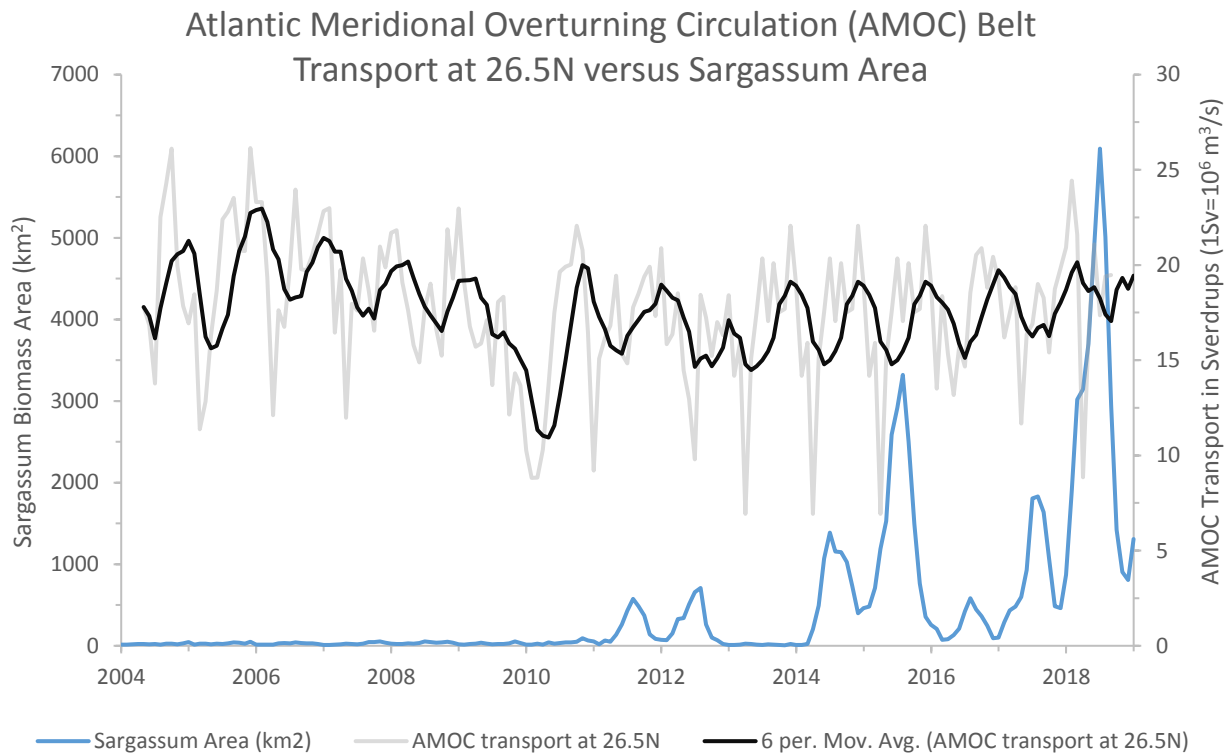


Figure 14. Time series trendlines comparing Sargassum area to a dataset that represents the AMOC transport at 26°N in terms of Sverdrups (1Sv = 10⁶ m³/s) with a 6-month moving average.

In 2010, there was an abrupt and pronounced slowdown in the AMOC transport, immediately before the blooms began developing off the northeast coast of Brazil. The AMOC passed the northeast coast of Brazil, so this slowdown could have allowed for the Amazon river plume to have a longer residence time that year, allowing for the nutrients to influence primary productivity.

5. SUMMARY

5.1 Drivers of Sargassum Blooms

The seasonal delivery of freshwater by the Amazon River was closely linked to sargassum abundance in bloom years suggesting freshwater associated nutrients could be an important driver of sargassum blooms. The Amazon watershed has experienced dramatic changes over the last century including deforestation, expansion of agriculture and increased use of fertilizers, as well as construction of large dams, which alter river hydrology and sediment transport (Forsberg et al., 2017). It is unclear why river discharge did not trigger sargassum blooms before 2011, and deforestation and land use change decreased over the last decade (Aragão et al., 2018). Long-term data on nutrient concentrations for the Amazon River are unavailable. The Amazon river also provides large amounts of dissolved organic matter to coastal seas, which can serve as a nutrient source after mineralization.

The North Atlantic Oscillation was in a negative phase during the genesis of the first bloom event (Fig. 12). Since 2011, the system has been in a positive NAO phase mostly, with the notable exception of 2013. During a negative NAO phase, there is decreased interbasin circulation, and warmer SSTs due to the decreased pressure gradient and weaker easterly trade winds. During a positive NAO phase, there is increased interbasin circulation, cooler SSTs, and more nutrient upwelling events driven by the stronger easterly trade winds.

In 2010 and 2015, there was a strong El Niño signal (Fig. 13). Although ENSO was detected by anomalous sea surface temperature over the Pacific, it can influence pressure and trade winds over the North Atlantic Ocean (Li et al 2012; Hastenrath 1990; Trenberth 1998; Garcia et al 2005). It is also associated with increased precipitation over South America. Right before the 2011 event, there was a positive ENSO signal. The 2015 sargassum event coincides with the 2015

El Niño signal, although the sargassum peak slightly precedes the signal (Fig. 13). There was increased Amazon river discharge in 2010 and 2015 (Fig. 7b).

Unstudied with regard to sargassum is the weakening of the AMOC. There was a pronounced and abrupt slowdown of the AMOC in 2010 (As shown in Figure 14) right before the sargassum blooms began developing off the northeast coast of Brazil. The northward belt of the AMOC passes the northeast coast of Brazil and could allow for the Amazon river plume to have had a longer time to dwell before its northward transport, allowing for the nutrients to have a longer residence time in the region.

Right before the blooms began, there was a slowdown in the AMOC, a negative NAO, a positive ENSO phase, and increased river discharge. The concurrence of these variables, especially the deceleration of the AMOC, potentially encouraged the northeast coast of Brazil to exhibit ideal growth conditions. The decrease in northward heat transport allowed for more residence time of nutrients in the region, warmer SSTs, and decreased interbasin circulation, which encouraged stagnation, and may have led to the anomalous bloom event of 2011. Since then, the system has remained in a mostly positive NAO phase, which is associated with stronger easterly trade winds, cooler SSTs, increased interbasin circulation, and nutrient upwelling events, further encouraging ideal growth conditions for the sargassum blooms in this New Sargasso Sea.

Previous studies hypothesized that it was warming sea surface temperatures (SSTs) that were driving the growth of these blooms; however, this study shows that during the timeframe of these events, the study region was actually predominantly anomalously cooler compared to the climatology. In general, cooler SSTs are associated with nutrient upwelling events, which encourages primary productivity and growth. These cooler SSTs were most likely driven by stronger easterly trade winds from positive NAO phases. The 2011 heat wave is linked to the

negative NAO, weaker trade winds, decreased interbasin circulation, and slowdown of the AMOC. Sargassum reached the highest abundance on record in 2018. This year exhibited cooler than average SSTs (See Figure 5). The *warmer* years were 2013, 2016 and 2017, as seen in Figure 6, which are the same years when there was relatively less sargassum in terms of abundance.

This study examined sea surface salinity and freshwater distribution as well. According to Hanisak et al. (1987), sargassum is believed to enjoy a salinity range of 36-42ppt. This study finds contradictory results, as river-influenced Atlantic and NERR water were fresher than the Sargasso Sea (Fig. 10). By these findings, it would appear that sargassum has a salinity range that is much wider than previously assumed. It is most likely other variables, such as nutrients, and climate variability that drove sargassum to proliferate in the region so unexpectedly.

5.2 The Newly Sargassum Dominated North Atlantic System

In 2010, preceding the first massive sargassum bloom event in the Caribbean region, there was a noticeable deceleration in the AMOC, the NAO switched into a negative mode, the ENSO fluctuated into a strong positive, and there were warmer than average sea surface temperatures across the tropical North Atlantic. In addition, the Amazon River showed abnormally high freshwater discharge volume induced by increased precipitation. The increased discharge and associated nutrients combined with a slower AMOC would have allowed for longer residence time of nutrients from the Amazon River plume. The convergence of these climatic variables may have tipped the system past a threshold into a new ecological regime, wherein sargassum blooms are gradually beginning to dominate. The ramifications of which we may just be beginning to experience.

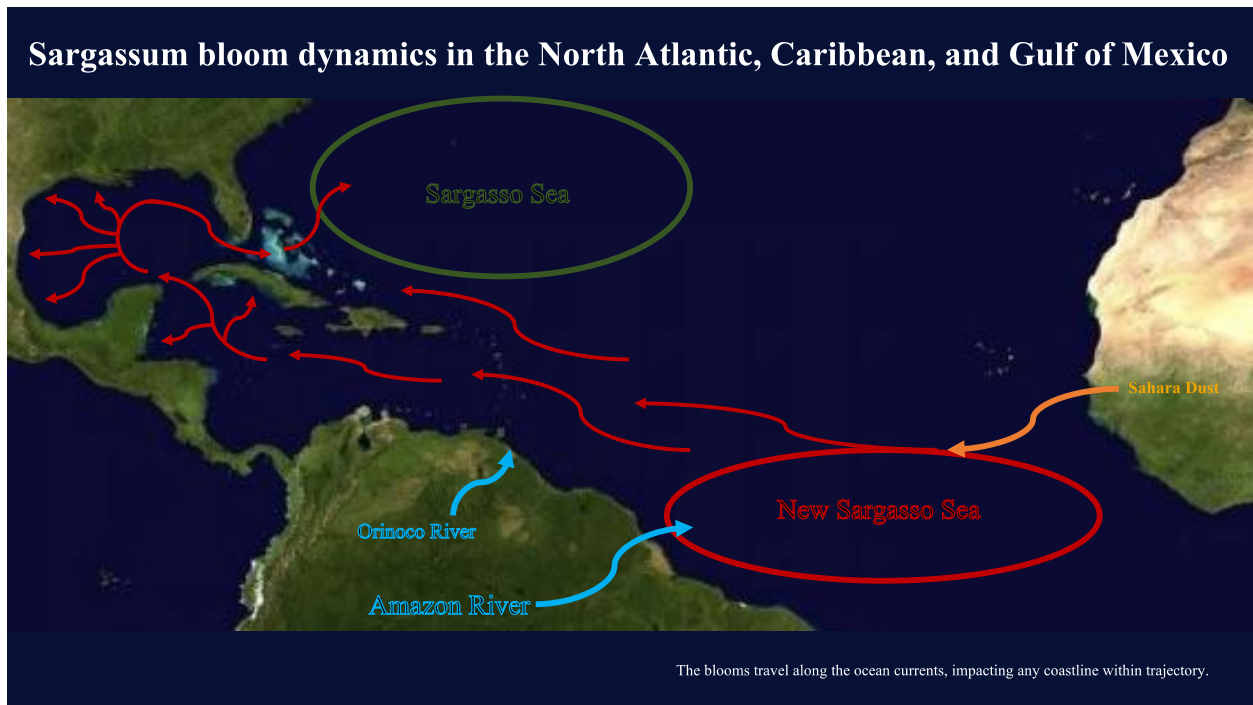


Figure 15. *Sargassum bloom dynamics summary in the Study Region.*

Resilience is the ability of a system to absorb disturbances, and still retain its original function (Walker and Salt, 2006). Natural systems are resilient. However, once a threshold is crossed, resilience is lost, and a regime shift occurs, wherein a new species dominates. Once the threshold has been crossed, the system has been altered, and it cannot be returned to its original state. It could be argued that in this case, the confluence of several factors in 2010 led to sargassum seaweed blooms originating outside of their observed habitat, the Sargasso Sea. This New Sargasso Sea forming off the northeast coast of Brazil has developed as a result of 2010 conditions and has thrived in the almost entirely positive NAO phase since then. Furthermore, the Amazon basin has been the recipient of decades of deforestation, land use conversion, and fertilizer consumption. Although there is no long term NO_3^- and PO_4^{3-} in situ data, this should not be discounted as a possible variable. We as coastal societies are in many ways only beginning to unfold the mysteries behind how we as humans impact our oceans, and how in turn, they affect us.

Due to the fact that these impacts have become such a major coastal zone management issue, *how* to manage the blooms from a coastal perspective remains a challenge for coastal managers. Future research should explore potential impacts of these events. Sargassum bloom events have the ability to negatively impact tourism, fisheries, human health, the environment, marine shipping, and finances. Sargassum management plans should be incorporated into regional plans for vulnerable coastlines. Future research should also explore the potential valorization of the seaweed. It has been shown to be a viable resource as a biofuel, as well as paper, fabrics, plastic, and building materials. Belize and the Yucatan have been converting the seaweed to bricks which can then be used in infrastructure. A coastal community's resilience can be enhanced through adaptive capacity. Adaptive capacity is the degree to which a coastline can mitigate the potential for impact by taking action to reduce exposure or sensitivity a certain hazard (Walker and Salt, 2006). There are many organizations who currently utilize remote sensing to provide monitoring and forecasting of sargassum blooms. These forecasts should be communicated to vulnerable coastlines so that communities can decide on a plan of action to reduce risk of exposure to the bloom events. There are now companies who manufacture nets designed to capture massive sargassum windrows nearshore before impact. If it is true that this is the new norm, and ocean conditions could lead to more future seasonal bloom impacts, then coastal zone leaders should adopt a mindset of resiliency and implement planning strategies based on how vulnerable they are to impact. Regions such as the Caribbean, who are extremely vulnerable to these impacts, should consider this a high priority for coastline management. Regions such as Texas, who are within trajectory, should be prepared for the possibility of a future impact, such as Summer of Seaweed 2014.

The scope of this research focused specifically on the sargassum seaweed bloom dynamics in the Caribbean, Gulf of Mexico, and tropical North Atlantic, and some of the potential driving biogeochemical variables, but its methods could be applied to a wide range of research topics.

REFERENCES

- Aragão, L. E., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., ... & Barlow, J. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature communications*, 9(1), 536.
- Bellucci, A., and K. J. Richards. (2006) Effects of NAO Variability on the North Atlantic Ocean Circulation. *Geophysical Research Letters*, vol. 33, no. 2.
- Berner, Elizabeth Kay and Berner, Robert A. (2012) Global Environment: Water, Air, and Geochemical Cycles: Second Edition. *Princeton, New Jersey by Princeton University Press*. Print.
- Behrenfeld, M. J., Boss, E., Siegel, D. A., & Shea, D. M. (2005). Carbon-based ocean productivity and phytoplankton physiology from space. *Global biogeochemical cycles*, 19(1).
- Behrenfeld, M. J., & Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and oceanography*, 42(1), 1-20.
- Binswanger, H. P. (1991). Brazilian policies that encourage deforestation in the Amazon. *World Development*, 19(7), 821-829.
- Biggs, T.w., et al. (2004) Natural Controls and Human Impacts on Stream Nutrient Concentrations in a Deforested Region of the Brazilian Amazon Basin. *Biogeochemistry*, vol. 68, no. 2, pp. 227–257.
- Boyer, T.P., O. K. Baranova, C. Coleman, H. E. Garcia, A. Grodsky, R. A. Locarnini, A. V. Mishonov, T.D. O'Brien, C.R. Paver, J.R. Reagan, D. Seidov, I. V. Smolyar, K. Weathers, and M. M. Zweng. (2018) *World Ocean Database 2018*.

- Butler, J., Morris, B., Cadwallder, J., and Stoner, A. (1983). Studies of Sargassum and the Sargassum community. *Bermuda Biological Station*, special publication.
- Branford, Sue, and Thais Borges (2019) Land Thieves Ramp up Deforestation in Brazil's Jamanxim National Forest. *Mongabay Environmental News*, 4 July 2019, news.mongabay.com/2019/07/land-thieves-ramp-up-deforestation-in-brazils-jamanxim-national-forest/.
- Bryden, Harry L., et al. (2005). Slowing of the Atlantic Meridional Overturning Circulation at 25° N. *Nature*, vol. 438, no. 7068, pp. 655–657.
- Castello, Leandro, and Marcia N. Macedo. (2015). Large-Scale Degradation of Amazonian Freshwater Ecosystems. *Global Change Biology*, vol. 22, no. 3, pp. 990–1007.
- Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*. 556, 191-196.
- Carder, K. L., Steward, R. G., Betzer, P. R., Johnson, D. L., & Prospero, J. M. (1986). Dynamics and composition of particles from an aeolian input event to the Sargasso Sea. *Journal of Geophysical Research: Atmospheres*, 91(D1), 1055-1066.
- Cousteau, Fabien. (2014). Ocean: The Definitive Guide. *American Museum of Natural History*. London, New York, Melbourne, Munich, and Delhi, DK.
- Chérubin, L. M., & Garavelli, L. (2016). Eastern Caribbean circulation and island mass effect on St. Croix, US Virgin Islands: a mechanism for relatively consistent recruitment patterns. *PloS one*, 11(3).
- Dagg, M., Benner, R., Lohrenz, S., & Lawrence, D. (2004). Transformation of dissolved and particulate materials on continental shelves influenced by large rivers: plume processes. *Continental Shelf Research*, 24(7-8), 833-858.

- Deacon, G. E. R. (1942). "The Sargasso Sea."
- Dow, Kirstin and Downing E. Thomas. (2006) *The Atlas of Climate Change: Mapping the World's Greatest Challenge. Los Angeles, California.*
- Dogliotti, A., Gossn, J., Vanhellefont, Q., & Ruddick, K. (2018). Detecting and quantifying a massive invasion of floating aquatic plants in the río de la plata turbid waters using high spatial resolution ocean color imagery. *Remote Sensing*, 10(7), 1140.
- Djakourè, S., Araujo, M., Hounsou-Gbo, A., Noriega, C., & Bourlès, B. (2017). On the potential causes of the recent Pelagic Sargassum blooms events in the tropical North Atlantic Ocean. *Biogeosciences*.
- Falkowski, P. G., Barber, R. T., & Smetacek, V. (1998). Biogeochemical controls and feedbacks on ocean primary production. *Science*, 281(5374), 200-206.
- Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P. (1998). Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science*. 281.
- Forsberg, Bruce R., et al. (2017) The Potential Impact of New Andean Dams on Amazon Fluvial Ecosystems. *Plos One*, vol. 12, no. 8.
- Franks, James S., et al. (2016) Pelagic Sargassum in the Tropical North Atlantic. *Gulf and Caribbean Research*, vol. 27, no. 1.
- García, N. O., & Mechoso, C. R. (2005). Variability in the discharge of South American rivers and in climate/Variabilité des débits de rivières d'Amérique du Sud et du climat. *Hydrological Sciences Journal*, 50(3).
- Garrison, Tom. (2015). *Essentials of Oceanography. Canada, Cenage Learning. National Geographic.*

- Gower, J. F., & King, S. A. (2011). Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. *International Journal of Remote Sensing*, 32(7), 1917-1929.
- Gower, J., Hu, C., Borstad, G., & King, S. (2006). Ocean color satellites show extensive lines of floating Sargassum in the Gulf of Mexico. *IEEE Transactions on Geoscience and Remote Sensing*, 44(12), 3619-3625.
- Gower, J., Young, E., & King, S. (2013). Satellite images suggest a new Sargassum source region in 2011. *Remote Sensing Letters*, 4(8), 764-773.
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*.
- Gouveia, N. A., Gherardi, D. F. M., Wagner, F. H., Paes, E. T., Coles, V. J., & Aragão, L. E. O. C. (2019). The Salinity Structure of the Amazon River Plume Drives Spatiotemporal Variation of Oceanic Primary Productivity. *Journal of Geophysical Research: Biogeosciences*, 124(1), 147-165.
- Hanisak, M. D., & Samuel, M. A. (1987). Growth rates in culture of several species of Sargassum from Florida, USA. In *Twelfth International Seaweed Symposium* (pp. 399-404). Springer, Dordrecht.
- Hans Petter Langtangen, (2009) A Primer on Scientific Programming with Python. *Springer*.
- Hanson, R. (1977). Pelagic Sargassum community metabolism: carbon and nitrogen. *Journal of Experimental Marine Biology and Ecology*, 29(2), pp. 107-118.
- Hastenrath, S. (1990). Prediction of Northeast Brazil rainfall anomalies. *Journal of Climate*, 3(8), 893-904.

- Hinds, C., Oxenford, H., Cumberbatch, J., F. Fardin & 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.
- Howard, K, and Menzies, R. (1969). Distribution and production of Sargassum in the waters off the Carolina coast. *Botanica Marina*, 12(1-4), pp. 244-254.
- Hu, C., Lee, Z., & Franz, B. (2012). Chlorophyll a algorithm for oligotrophic oceans: A novel approach based on three-band reflectance difference. *Journal of Geophysical Research*, 117(C1). doi: 10.1029/2011jc007395
- Hu, Chuanmin, et al. (2016) *Sargassum Watch from Space*. NASA, NOAA, and University of South Florida, modis.gsfc.nasa.gov/sci_team/meetings/201606/presentations/plenary/hu.pdf.
- Hurrell, James W., et al. (2003). An Overview of the North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact Geophysical Monograph Series*, pp. 1–35.
- Johnson, D.R., Ko, D.S., Franks, J.S., Moreno, P, and Sanchez-Rubio G (2013). The Sargassum Invasion of the Eastern Caribbean and Dynamics of the Equatorial North Atlantic. *Center for Fisheries Research and Development*. 65th Gulf and Caribbean Fisheries Institute, Santa Marta Columbia.
- Johnny Wei-Bing Lin. (2012). A Hands-On Introduction to Using Python in the Atmospheric and Oceanic Sciences, <http://www.johnny-lin.com/pyintro>.
- Jules Kouatchou and Hamid Oloso. (2013). Python Programming for Data Processing and Climate Analysis. *Goddard Space Flight Center Software System Support Office*.

- Kelly, Kathryn A., et al. "Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports." *Geophysical Research Letters* 43.14 (2016): 7625-7631.
- Kilar, J., Hanisak, T., and Yoshida, T. (1992). On the expression of phenotypic variability: why Is Sargassum so taxanomically difficult? *Taxonomy of Economic Seaweeds, California Sea Grant College, La Jolla, California*, pp. 95- 118.
- Kingsford, M. and Choat, J. (1986). Influence of surface slicks on the distribution and onshore movements of small fish. *Marine Biology*, 91, pp. 161-171.
- Kishcha, P., da Silva, A., Starobinets, B., Long, C., Kalashnikova, O., & Alpert, P. (2015). Saharan dust as a causal factor of hemispheric asymmetry in aerosols and cloud cover over the tropical Atlantic Ocean. *International Journal of Remote Sensing*, 36(13), 3423-3445.
- Kremling, K., & Streu, P. (1993). Saharan dust influenced trace element fluxes in deep North Atlantic subtropical waters. *Deep Sea Research Part I: Oceanographic Research Papers*, 40(6), 1155-1168.
- Laffoley, D., Roe, H., Angel, M., Ardron, J., Bates, N., Boyd, L., Brooke, S., Buck, K., Carlson, C., Causey, B., Conte, M., Christiansen, S., Cleary, J., Donnelly, J., Earle, S., Edwards, R., Gjerde, K., Giovannoni, S., Gulick, S., Gollock, M., Hallet, J., Halpin, P., Hanel, R., Hemphill, A., Johnson, R., Knap, A., Lomas, M., McKenna, S., Miller, M., Miller, P., Ming, F., Moffitt, R., Nelson, N., Parson, L., Peters, A., Pitt, J., Rouja, P., Roberts, J., Roberts, J., Seigel, D., Siuda, A., Steinberg, D., Stevenson, A., Sumaila, V., Swartz, W., Trott, T., and Vats, V. (2011) *The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean: Summary Science and Supporting Evidence Case*. Bermuda, BM, Sargasso Sea Alliance.

- Langmuir, I. (1938). Surface motion of water induced by wind. *Science*, 87(2250), pp. 119-123.
- Latif, M., et al. (2019). Decadal Atlantic Meridional Overturning Circulation Slowing Events in a Climate Model. *Climate Dynamics*, vol. 53, no. 1-2, pp. 1111–1124.
- Levitus, S., J. I. Antonov, T. P. Boyer, O. K. Baranova, H. E. Garcia, R. A. Locarnini, A.V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, M. M. Zweng. (2012) World Ocean heat content and thermosteric sea level change (0-2000 m) 1955-2010. KNMI Climate Explorer and National Oceanographic Data Center (NODC).
- Li, Ying, and Ngar-Cheung Lau (2012). Impact of ENSO on the Atmospheric Variability over the North Atlantic in Late Winter—Role of Transient Eddies.” *Journal of Climate*, vol. 25, no. 1, pp. 320–342.
- Lohmann, Gerrit, et al. (2008). “Estimating Trends of Atlantic Meridional Overturning Circulation from Long-Term Hydrographic Data and Model Simulations.” *Ocean Dynamics*, vol. 58, no. 2, pp. 127–138.
- Maurer, A., De Neef, E., and Stapleton, S. (2015). Sargassum accumulation may spell trouble for nesting sea turtles. *Frontiers in Ecology and the Environment*, 13(7), pp. 394-395
- Medeiros, P. M., Seidel, M., Ward, N. D., Carpenter, E. J., Gomes, H. R., Niggemann, J. & Dittmar, T. (2015). Fate of the Amazon River dissolved organic matter in the tropical Atlantic Ocean. *Global Biogeochemical Cycles*, 29(5), 677-690.
- Meyer-Reil, L. A., & Köster, M. (2000). Eutrophication of marine waters: effects on benthic microbial communities. *Marine Pollution Bulletin*, 41(1-6), 255-263.
- Millero, Frank J. (2006). Chemical Oceanography: Third Edition. Boca Raton, FL. *CRC Press Taylor & Francis Group*.

- National Center for Atmospheric Research Staff. “The Climate Data Guide: CMORPH (CPC MORPHing technique): High resolution precipitation.
- NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS Chlorophyll a. NASA OB.DAAC, Greenbelt, MD, USA. doi: 10.5067/ENVISAT/MERIS/L3B/POC/2012. Accessed on 02/07/2019.
- NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Aqua Sea Surface Temperature Data. NASA OB.DAAC, Greenbelt, MD, USA. doi: 10.5067/AQUA/MODIS/L3B/SST/2014. Accessed on 02/07/2019.
- Neill, Christopher, et al. (2006). Deforestation Alters the Hydraulic and Biogeochemical Characteristics of Small Lowland Amazonian Streams. *Hydrological Processes*, vol. 20, no. 12, pp. 2563–2580.
- Neill, Christopher, et al. (2001). Deforestation for Pasture Alters Nitrogen and Phosphorus in Small Amazonian Streams. *Ecological Applications*, vol. 11, no. 6, p. 1817.
- Neuberger, Hans and Cahir, John. (1969). Principles of Climatology: A Manual in Earth Sciences. *Pennsylvania State University, Library of Congress*.
- Nicholls, K. H., & Dillon, P. J. (1978). An evaluation of phosphorus-chlorophyll-phytoplankton relationships for lakes. *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, 63(2), 141-154.
- Ometto, J. P., Aguiar, A. P. D., & Martinelli, L. A. (2011). Amazon deforestation in Brazil: effects, drivers and challenges. *Carbon Management*, 2(5), 575-585.

- Pauly, D., & Maclean, J. (2003). In a perfect ocean: the state of fisheries and ecosystems in the North Atlantic Ocean (Vol. 1). *Island Press*.
- Ped, J., Scaduto, E., Accorsi, E., & Torres-Perez, J. (2016). Caribbean Oceans: Utilizing NASA Earth Observations to Detect, Monitor, and Respond to Unprecedented Levels of Sargassum in the Caribbean Sea.
- Portielje, R., & Van der Molen, D. T. (1999). Relationships between eutrophication variables: from nutrient loading to transparency. In *Shallow Lakes '98* (pp. 375-387). Springer, Dordrecht.
- Putman, N. F., Goni, G. J., Gramer, L. J., Hu, C., Johns, E. M., Trinanes, J., & Wang, M. (2018). Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Progress in oceanography*, 165, 205-214.
- Praetorius, S. K. (2018). North Atlantic circulation slows down.
- Philander, S. G. H. (1983). El Nino southern oscillation phenomena. *Nature*, 302(5906), 295.
- Phillips, G., Pietiläinen, O. P., Carvalho, L., Solimini, A., Solheim, A. L., & Cardoso, A. C. (2008). Chlorophyll–nutrient relationships of different lake types using a large European dataset. *Aquatic Ecology*, 42(2), 213-226.
- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, A., Kaplan. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, 108 (D14), 4407, doi:10.1029/2002JD002670.
- Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature* **419**, 207–214

- Rahmstorf, Stefan, et al. (2015) Erratum: Corrigendum: Evidence for an Exceptional Twentieth-Century Slowdown in Atlantic Ocean Overturning. *Nature Climate Change*, vol. 5, no. 10, pp. 956–956.
- Rudolph W. Preisendorfer and Curtis D. Mobley. (1998). Principal component analysis in meteorology and oceanography. Elsevier.
- Sanchez-Rubio, G., Perry, H., Franks, J. S., & Johnson, D. R. (2018). Occurrence of pelagic Sargassum in waters of the US Gulf of Mexico in response to weather-related hydrographic regimes associated with decadal and interannual variability in global climate. *Fishery Bulletin*, 116(1), 93-107.
- Santos, Maria L.s., et al. (2008). Nutrient and Phytoplankton Biomass in the Amazon River Shelf Waters.” *Anais Da Academia Brasileira De Ciências*, vol. 80, no. 4, pp. 703–717.
- Smetacek, V., & Zingone, A. (2013). Green and golden seaweed tides on the rise. *Nature*, 504(7478), 84.
- Sweeney, B. W., Bott, T. L., Jackson, J. K., Kaplan, L. A., Newbold, J. D., Standley, L. J., ... & Horwitz, R. J. (2004). Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proceedings of the National Academy of Sciences*, 101(39), 14132–14137.
- Stenseth, N. C., Ottersen, G., Hurrell, J. W., Mysterud, A., Lima, M., Chan, K. S., ... & Ådlandsvik, B. (2003). Studying climate effects on ecology through the use of climate indices: The North Atlantic Oscillation, El Nino Southern Oscillation and beyond. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1529), 2087-2096.

- Stramski, D., Reynolds, R. A., Babin, M., Kaczmarek, S., Lewis, M. R., Röttgers, R., Claustre, H. (2008). Relationships between the surface concentration of particulate organic carbon and optical properties in the eastern South Pacific and eastern Atlantic Oceans. *Biogeosciences*, 5(1), 171-201. doi:10.5194/bg-5-171-2008
- Stepanov, Vladimir. Iovino, Doroteaciro. Masina, Simona. Storto, Andrea & Cipollone, Andrea. (2016). Methods of calculation of the Atlantic meridional heat and volume transports from ocean models at 26.5N. Retrieved from <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015JC011007>.
- Walker, Brian, and David Salt. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press, 2006.
- Wang, M., & Hu, C. (2017). Predicting Sargassum blooms in the Caribbean Sea from MODIS observations. *Geophysical Research Letters*, 44(7), 3265-3273.
- Wang, M., Hu, C., Barnes, B. B., Mitchum, G., Lapointe, B., & Montoya, J. P. (2019). The great Atlantic Sargassum belt. *Science*, 365(6448), 83-87.
- Webster, R. K., & Linton, T. (2013). Development and implementation of Sargassum early advisory system (SEAS). *Shore & Beach*, 81(3), 1.
- Werdell, P. J., & Bailey, S. W. (2005). An improved bio-optical data set for ocean color algorithm development and satellite data product validation. *Remote Sensing of Environment* 98, 122-140, doi: 10.1016/j.rse.2005.07.001.
- Winge, Ö. (1923). *The Sargasso Sea, Its Boundaries and Vegetation, &c.*
- Wondolleck, Julia M. and Yaffee, Steven L. (2017). *Marine Ecosystem-Based Different Pathways: Management in Practice, Common Lessons*. Washington. Island Press. Print.

Xie, P., and P.A. Arkin. (1997). Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, 78, 2539 - 2558.

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