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Using remote sensing techniques to investigate the detection of Sargassum blooms in the Caribbean and possible causes for these events

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Abstract

Sargassum was thought to originate from a single source, the Sargasso Sea in the central west Atlantic. This has been challenged over the past decade after excessive amounts of the macroalgae began washing up on Caribbean coastlines in June 2011, leading the scientific community to investigate causes of this phenomenon. These, now yearly, events are having detrimental environmental and socioeconomic impacts in areas of the Caribbean and central America, providing motivation for uncovering any regime shifts or severe changes in anthropogenic activity.

Anthropogenic sources of nitrate from three rivers surrounding the CWA in addition to wind stress and chlorophyll-a levels within the study area are investigated to determine if any of these drivers are stand-out reasons and to what extent.

The results show some extreme events of river nutrient discharge from all three sources backed up by MERIS imagery that align with reports of sargassum strandings. The report found no significant correlation between excess nutrients and chlorophyll-a concentrations implying there is no competition for nitrate with phytoplankton. There was also no significant difference in wind stress in the months prior to stranding events, leading to the assumption nitrate is the most probable contributing factor to these occurrences.

Keywords: Remote sensing, nutrient discharge, nitrate, phytoplankton, *Sargassum*, blooms, Sargasso Sea, Caribbean

Introduction and background science

Sargassum and remote sensing

Sargassum is a genus of pelagic brown macroalgae comprised of two species; *S. natans* and *S. fluitans* (from here will both be described as Sargassum) and forms an important ecosystem for many small fauna such as crustaceans and juvenile fish in addition to sea turtles and sea birds (Lapointe 1995; Oviatt *et al.*, 2019). Sargassum is thought to have originated in the Sargasso Sea, an ocean gyre located in the central Atlantic, but recent studies suggest various new sources for its production which could explain its newly global distribution (Gower *et al.*, 2011; Wang *et al.*, 2019). The macroalgae clumps together due to ocean basin scale surface currents to form large mats or 'slicks' that circulate in the Sargasso Sea and Central West Atlantic (CWA) before washing up on the shorelines of Caribbean Islands and areas of the Gulf of Mexico (GOM) (Gower *et al.*, 2006). The path and final destination of these mats are influenced by the strength and direction of surface currents and momentum transfer from wind such that a wind speed of 200-300 cm s^{-1} could result in a Sargassum movement speed of 2-3cm s^{-1} (Kwon *et al.*, 2019). Its buoyant property due to its gas-filled vesicles makes this long living algae amenable to detection and tracking from space using satellite imagery, which will form the basis of this report. Patch sizes of up to 75 km^2 enable its detection from satellite instruments of lower spatial resolutions such as MODIS (250m) and MERIS (300m) (Johns *et al.*, 2020). The chlorophyll-c component of Sargassum results in a unique reflectance curve around ~630nm at the near infra-red requiring a multiband radiometric resolution for detection (Hu *et al.*, 2015).

Satellite Remote Sensing (RS) has been used increasingly for oceanographic studies over the past 20 years. There is now a plethora of satellites with ranging passover times carrying sensors of varying resolution and swathes providing us with long term data on marine-related parameters such as sea surface temperature (SST), surface chlorophyll-a and nitrate concentrations and remote sensing reflectance (Rrs) measurements in a range of wavelength bands (Werdell *et al.*, 2018). Current applications of RS in the marine environment include - but are not limited to - fisheries and aquaculture management (Saitoh *et al.*, 2011; Longdill *et al.*, 2018), tracking the movements of icebergs (Gladstone & Bigg, 2002), benthic and shallow water habitat mapping (Pasqualini *et al*, 1997), and marine spatial planning (Ouellette & Getinet, 2016). Using satellites for mass data collection to detect long term changes in the marine environment is economically viable, saves time and can be applied to large study areas (El Mahrad *et al.*, 2020). RS in ocean colour detection, specifically, allows us to monitor large areas that would otherwise be difficult to access and reduces the need for expensive water-resistant equipment. Large scale ocean colour detection was first successfully carried out by the Coastal Zone Coastal Scanner in 1978, but only since the launch of SeaWiFS in 1997 have longer time series exceeding 10 years been achieved. NASA's Terra and the ESA's Envisat satellites launched in 1999 and 2002, respectively, were among the first modern satellites to host ocean colour detection sensors with large swathes and high spectral resolution. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on NASA's Terra satellite in 1999, being the first to accumulate large time series data sets (Melet *et al.*, 2020).

The later launches of Landsat-8 in 2013 and Sentinel-2 in 2015 have contributed to marine RS by offering greater temporal and spatial resolutions with Landsat-8 collecting 15m resolution imagery every 16 days, and Sentinel-2 receiving 20m resolution imagery every 5 days (Chávez *et al.*, 2020). Previous Landsat missions dating back as far as Landsat-1 in 1972 allowed earlier detection of land colour from space and can be applied to monitoring coastal ocean processes including the detection of coastal Sargassum build-up before the ocean-centred missions (Esa.int, 2013). The radiance and irradiance ratios of reflected light at different wavelengths can be used to determine water properties in the upper layer of the water column and identify marine pollution or vegetation which can be applied to Sargassum monitoring (Werdell *et al.*, 2018).

Detection requirements

Pelagic mats of this macroalgae can grow up to an area covering 75km^2 and may cover an even larger area once reaching shorelines (Johns *et al.*, 2020). Detections via satellite imagery, therefore, require a spatial resolution of the same extent; for example, the medium resolution imaging spectrometer (MERIS) sensor can pick up its signature using 1040m resolution. Regarding onshore mapping of washed-up biomass, satellites with greater spatial resolution such as Landsat-8 (15m) or Sentinel-2 (20m) could aid the production of more accurate classification and mapping (Ody *et al.*, 2019). Drifting mats or slicks of Sargassum can exist for weeks and are slow moving so there is a moderate time window for detection. Despite efforts to quickly remove the stranded algae, especially in popular beach destinations, the amount of seaweed reaching the shore far exceeds the rate of removal. As a result of this, there is some leeway in temporal resolution of detectors when mapping stranded biomass.

Sightings of sargassum have been recorded since the mid nineteenth century in the Sargasso Sea by cargo ships passing through the Atlantic (Parr, 1939). Before the application of marine remote sensing, qualitative boat sightings and net tows were the only method of recording and monitoring sargassum presence and abundance (Gower *et al.*, 2006). The collection of boat transect data may be used alongside remote sensing methods in order to validate spectral signatures picked up by satellites. However, is not efficient to only use boat transects in terms of time and expense (Ody *et al.*, 2019). For smaller spatial scale measurements such as monitoring specific beaches or small Caribbean Islands, drone imagery may be used and processed as an alternative. This imagery would allow for the creation of more accurate habitat maps in greater spatial resolution but would reduce the spectral resolution of the imagery.

Only in the past decade has Sargassum come to greater prominence due to the sudden increase in production and the resultant socioeconomic and environmental impacts (Gower *et al.*, 2013). Mass strandings of sargassum became a new phenomenon in 2011 in areas of the Caribbean in amounts never seen before and, since then, has become a yearly occurrence, with 2018 being the worst year on record after an estimated 20 million tonnes washed up between May and August (Wang *et al.*, 2019). This has been evidenced by sufficient sources and beach surveys. At first the reasons for these events were unclear, but the scientific community now have some ideas hypothesising responsible nutrient input sources such as the Amazon river (Gower *et al.*, 2013), the Mississippi delta (Lapointe, 1995) and West African upwellings (Wang *et al.*, 2019). With time, the various socioeconomic and environmental impacts that coincide with these events are starting to become understood in greater detail.

The problem with Sargassum in the Caribbean

The Yucatan Peninsula encompasses the Caribbean coast of Mexico and its surrounding coastal Islands and is a popular beach destination and cultural area of interest among tourists (Figure 1). This area has experienced mass stranding events every year in varying levels of severity since the first major occurrence in 2011, making this phenomenon a 'new normal' which is seemingly becoming worse (Wang *et al.*, 2019). Small towns that are reliant on tourism as their primary source of

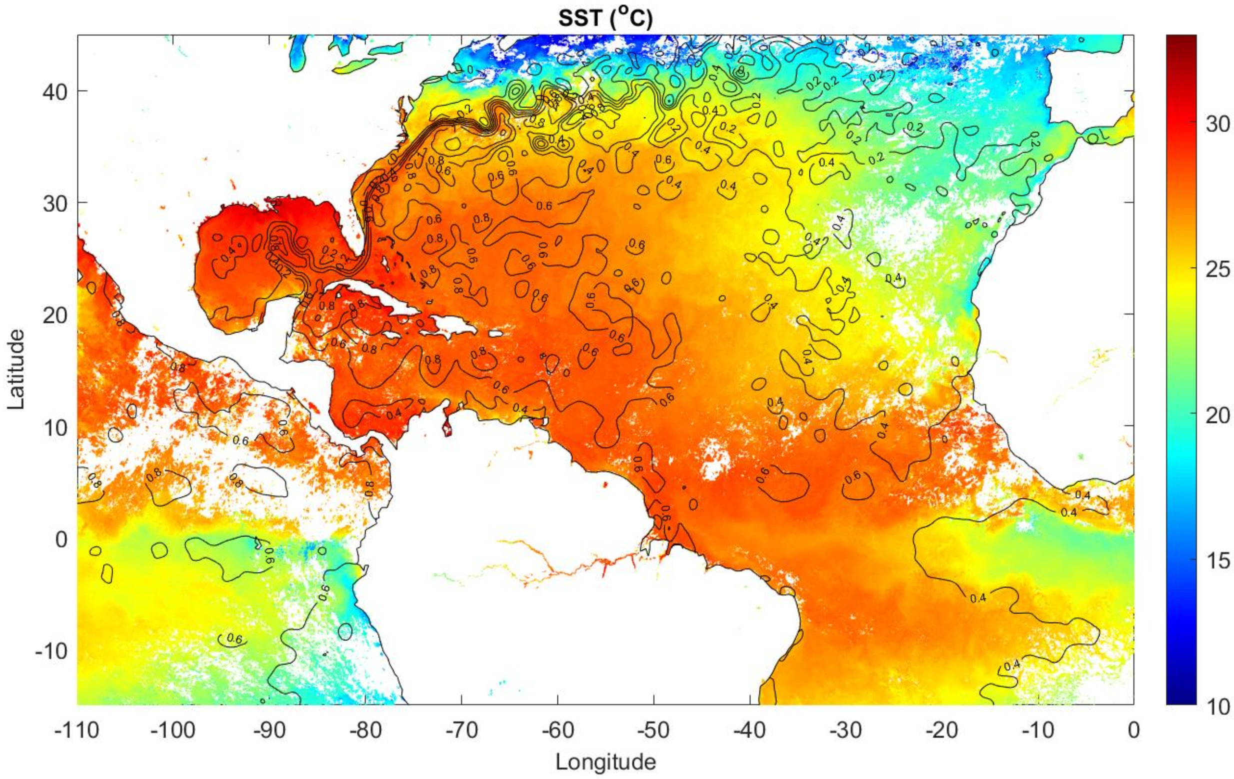

Figure 1: SST map of the study area encompassing the Yucatan peninsula, The GOM, Amazon river plume, Mississippi delta and Congo river outflow area with sea surface height (m) overlaid. SST Data from MODIS-Aqua sensor: NASA OBPG (2020). Contours: Sea surface height above geoid data from AVISO (Altimetry.fr, 2021)

income such as Akumal and Xcalak in Mexico are hit the hardest by these events as they cannot afford the resources and manpower to remove the masses of seaweed (Figure 2).

In 2015 the Mexican government allocated $3.2 billion for the cost of Sargassum removal and employed around 4,404 workers for the removal process (Oviatt *et al.*, 2019; Rodríguez-Martínez *et al.*, 2016). Mexico has experienced an annual falling rate in tourist numbers due to the unsightly mounds of seaweed on the once picturesque beaches in addition to the accompanying 'rotten egg' smell that results from the decomposition of the Sargassum (Rodríguez-Martínez *et al.*, 2016). Hotels, restaurants, and other stakeholders in the tourism industry with privately owned beaches bear the weight of sourcing their own removal costs, which in poorer tourism dependant towns is not viable. The removal process often involves the transportation of the algae inland to be buried, however, it has been found that phosphate compounds leaching out of the decomposing sargassum could be finding its way back into the marine environment (Chávez *et al.*, 2020). Human health implications of the phosphate compounds leaching from the decomposing algae are yet to be studied in depth. However, employees who work on the removal of the algae for long periods of time are encouraged to wear face masks due to health fears.

a) b)

Figure 2: Snapshots of changes in Sargassum biomass washed up in Akumal Bay, Mexico taken three months apart in 2018, firstly in March **(a)** and then in June **(b).** Eley, 2018. Akumal Playa Sur. [photograph] (Louise Eley's own collection)

Additionally, many environmental issues have recently arisen in light of the yearly stranding events. The sargassum mats block sunlight from reaching and entering the water column, smothering delicate ecosystems including seagrass meadows and shallow water coral reefs as the mats of algae make their way shoreward and begin to pile up in the shallows. Beached sargassum has been shown to disrupt turtle nesting behaviour of adult Green turtles *(Chelonia mydas),* Loggerhead *(Caretta caretta),* Hawksbill *(Eretmochelys imbricate)* and Leatherback turtles *(Dermochelys coriacea)* as less turtles are returning to beaches of the Yucatan because of the barrier this alga forms on the shoreline (Eckert and Eckert, 2019). Turtles that do manage to establish their nests on these beaches, however, are faced with the additional obstacle of entanglement for their hatchlings to overcome upon returning to the water (Azanza-Ricardo, 2016). An often-overlooked environmental impact is related to the removal process of the algae; current processes involve transporting the sargassum inland in truckloads to be deposited and buried in the ground. Not only does this involve added emissions from an array of transport vehicles, but the degrading algae continues to leach sulphide compounds which may make its way back into the marine environment through the Yucatan's underground karst system. Lapointe (2019), believes these blooms should be classified as harmful algal blooms (HAB) and considered an environmental crisis due to the detrimental impact on the coastal ecosystems.

Development of monitoring techniques

Gower *et al.* (2006) published the first paper on detecting and monitoring trends in sargassum distribution and growth using satellite RS. This work is the root of a developing interest in algae detection which has been transposed to the Atlantic and Yellow and China Seas. The year-long study was focussed in the GOM following the observation of unusual Sargassum masses and used the MERI) sensor on ESA's Envisat satellite. The 709nm band was used to determine a maximum chlorophyll index (MCI) measurement to detect the floating vegetation; near infra-red reflectance measurements from the 681nm and 754nm bands of MERIS were also used in the creation of the index. Since then, many methods of interpreting ocean colour from space to detect the floating algae have been detailed and expanded upon with the determination of floating algae indexes. The latest research by Hu and Wang (2019) details the formation of the largest pelagic area of sargassum to be recorded and viewed from space to this day which has now been coined 'The Great Atlantic Sargassum Belt'.

Further research into the detection of floating algae using ocean colour sensors carried out by Hu (2009) resulted in the definition of a floating Algae Index (FAI) using the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite. The FAI was developed for the detection of the macroalgae *Ulva prolifera* in the Yellow sea but was then able to be applied to the detection of other floating vegetation such as sargassum. These findings were used by Wang and Hu (2016) to create an Alternate Floating Algae Index (AFAI): an improvement on the latter's previous work to remove the detection of cloud cover. MERIS stopped working in 2012, interrupting the time series data so MODIS observations were used by these researchers instead.

Since the completion of the MERIS mission, some studies have shifted the focus to mapping movement pathways of sargassum in the Equatorial Atlantic (Putman *et al.*, 2018), and the East China Sea and Yellow Sea (Kwon *et al.*, 2019). The former found evidence to suggest sargassum arriving in the Caribbean is originating from the Equatorial Atlantic through many pathways in different ratios dependant on the time of year and other external conditions including wind stress and upwellings. This work uses detection methodologies set out by Gower *et al.* (2013), Hu *et al.* (2016) and Wang and Hu (2017) and focusses their research during high sargassum abundance years observed by these authors.

Increased research and insight into this area has led to the discovery of many factors that could be contributing to the excess growth we are seeing. Prior to the research of Gower *et al.* (2006), the Sargasso Sea was widely believed to be the single source of sargassum production. Gower, Young and King (2013) found evidence to suggest a new source of excess nutrients that may have contributed to abnormal levels of algae production in 2011: the Amazon river. Their study, carried out over a 10-year period, found fluxes in sargassum-like parameters around the river plume area detected by the MERIS sensor at 7ºN and 45ºW. The same year saw a negative flux in an otherwise rising sea level due to the La Niña event (Boening, 2012), but was disregarded by the aforementioned authors as a significant driver. Additionally, Wang & Hu (2017) found an FAI 'hotspot' around a similar area off northern Brazil, suggesting the Amazon river plume may be a major nutrient source contributing to this issue.

Current state of research:

Latest research papers have been able to determine seasonal variability and cycles in the production, abundance, and movement of sargassum in the Atlantic, Caribbean and Gulf of Mexico but are yet to determine any long-term trends due to the constraints in time series data availability (Chávez *et al.*,2020). There are many challenges and limitations involved with mapping and tracing floating vegetation meaning more data processing is required than when dealing with land-based remote sensing applications. Monitoring the marine environment requires correction for the effects of sun glint, Rayleigh scattering and other scattering material in the water such as coloured dissolved organic matter (CDOM), in addition to problems that would also be encountered inland such as cloud cover (Hedley *et al.*, 2005). All of these factors impact the path of reflected light and the detection of coloured light in different ways and to different degrees (Hu *et al.*, 2015). Some techniques for the removal of these obstacles have been outlined by Hedley *et al.* (2005) in regard to shallow coral reef mapping; some of these methods have been built upon and translated into floating algae detection, others may need more refinement.

The focus regarding Sargassum has recently shifted from the refinement of floating algae and ocean colour detection to understanding reasons for its substantial growth and attempting to define long-term trends in stranding events and production rate. Combining refined remote sensing methods with transport pathway simulations and biomass determination, could pave the way for tracing different masses of macroalgae back to its many sources in order to deduce the main controlling parameters. This work hopes to build on these ideas.

Rationale and relevance

An estimated 20 million tonnes of macroalgae stretching a length of 8850km across the Atlantic Ocean pinpointed a record high in production in 2018, highlighting the need for an early warning system for this phenomenon (Wang *et al.*, 2019). There is a lack of data in this field pointing to a single cause for these stranding events as new research tends to uncover more possible nutrient sources, events, or combinations of the two that may have impacted these stranding events. The need for accurate monitoring and early warning systems is justified by the socioeconomic impact on tourism dependant towns and Islands across the Caribbean. However, over time in our constantly changing global environment, it is likely that more factors and new sources will be uncovered in the future.

This work aims to piece together the timings and influences of river nutrient output in three locations and other abnormal activities such as El Niño/ La Niña years, hurricanes, and river flooding events. This study aims to investigate which source of excess nutrients is having the greatest impact on the production of sargassum in the central west Atlantic and Caribbean Sea. This work fits with previous studies in the Caribbean Sea and Yucatan Peninsula area (Wang & Hu, 2017; Cuevas *et al.*, 2018; Putman *et al.*, 2018) and will aim to build on ideas presented by Gower *et al* (2013) and Wang *et al* (2019). A range of remote sensing data will be compiled from a number of sources to determine which source is responsible for the shift in sargassum biomass production from 2011 onwards with the hopes of finding the root of the problem to irradicate it. This paper investigates the excess nutrient outputs from the Amazon and Congo river plume areas and the Mississippi delta output area and analyses this data alongside timings of extraordinary events.

Methods

Nitrate sources

Area averaged time series data of surface nitrate concentrations were taken from the NASA Ocean Biochemical Model (NOBM) sourced through the NASA-run Giovanni website (NASA Giovanni, no date). This was repeated for areas encompassing the Amazon river plume area, the Mississippi Delta, the Congo river discharge extent, and the study area of focus. Daily readings at a 0.67-1.25^{o} spatial resolution were collated over a ten-year period for each area and processed in Matlab (2020b). Seasonal patterns in the readings were identified and removed to leave the residual fluxes in nitrate concentrations for all stations; means and up to 3 standard deviations were also defined and added for all plots (Figure 5). This allowed a direct comparison to be made between the three nitrate source areas in addition to easily identifying any abnormal fluxes outside the seasonal variability of the data sets. This resulted in a clear determination of timings of high nitrate output events from the sources which can then be investigated and related to timings of stranding events over the same period. Extreme events of excess nutrients were identified by overlaying 2 and 3 standard deviations from the mean on each plot and are tabulated in Table 1.

The presence of nutrients such as nitrates, phosphates and silicates in the oceans encourages the growth of phytoplankton. A lack of these nutrients may limit primary productivity locally, but on the other hand, excesses may also lead to regional or seasonal disruption in the marine environment. Nitrogen in the form of nitrate (NO_3^-) specifically is used in the uptake of nutrients for photosynthetic species and is linked to the cause of algae blooms and dead zones. Nitrate enters marine ecosystems naturally through erosion in rivers which are then transported to the open oceans and mixed. In addition to the natural nitrate input, a number of anthropogenic activities contribute to the total amount of land-based output including NO_3^- and ammonia (NH_3) runoff from sewage and the use of fertilisers. Nitrogen in the form of

NO_3^- is mostly taken up by phytoplankton or zooplankton which either get eaten and dismissed as waste or die; either way resulting in the circulation and sinking of nutrients throughout the water column. This may be recirculated in areas of upwelling due to strong surface winds or currents. Excess nitrate has a direct impact on the growth of pelagic algae making these 3 major rivers areas of interest for the purpose of this study.

The abundance of algal blooms and plankton blooms can be observed through satellite imagery due to the differing wavelengths of the reflected light. Green algae and plankton contain chloroplasts that encourage photosynthesis and reflects green light as energy in this wavelength is the least useful for absorbing energy. Main absorption occurs between wavelengths of 400-500nm (blue) and around 700nm at the red end of the spectrum. Consequently, the reflectance peaks in these ranges of wavelengths of light can be used to detect areas of abundance through remote sensing methods. The signals in the blue and green wavelengths of light may be confused with absorption due to coloured dissolved organic matter (CDOM), particularly in river plumes; indexes involving near infra-red (NIR) wavelengths are therefore used due to the lack of impact of CDOM influence in these readings (Blondeau-Patissier *et al.*, 2014).

The areas of interest were decided upon by referencing findings from established literature as previously mentioned. The Amazon river plume extent is defined as the area bound by 53- 37°W and 3°S-10°N for the purpose of this study, after Wang and Hu (2017) identified a sargassum 'hotspot' in the area 40-60°W, 3°S-20°N. Similarly, the extents of the Congo and Mississippi river output regions were based on prior knowledge, covering areas of 10-13°E, 4-10°S and 90-87°W, 28-30°N, respectively (Djakouré *et al.*, 2017). This data was tabulated with the addition of any extraordinary events that occurred in a similar time that may have impacted the resulting surface nitrate and chl-a concentrations and SST. The additional data details river flood months, El Niño/ La Niña years and hurricane occurrences that may have enhanced oceanic nutrient upwellings. A similar table was presented by Oviatt *et al.* (2019) where they compiled annual data starting from 2009; this research looks into monthly events over a longer temporal scale.

A test of correlation of nitrate residuals were carried out to see if these fluxes are more or less linked to chlorophyll-a concentration in the western Caribbean by using a regression analysis. The purpose of this is to investigate if chlorophyll-a containing species such as phytoplankton are competing with the sargassum for nutrients. A chlorophyll index (CI) first produced by Hu *et al.* (2012) was calculated from the following equation and used in the analysis.

$$CI = Rrs555 - [Rrs443 + (555-443) / (670-443) * (Rrs670 - Rrs443)]$$

which is equivalent to $CI \approx Rrs555 - 0.5(Rrs443 + Rrs670)$

However, data from the 670nm band was unable to be sourced leading to a slight modification in the equation, replacing this wavelength with data that was available for the 667nm band. Data acquired from the MODIS-Aqua sensor on NASA's Terra satellite at 8-daily temporal and 4km spatial resolution is made available from NASA's Giovanni website (NASA Giovanni, no date). The resultant equation used is as follows:

$$CI = Rrs555 – [Rrs443 + (555–443) / (667–443) * (Rrs667–Rrs443)]$$

Additionally, a comparison of nitrate fluxes in river plume areas were compared against area averaged nitrate readings for the area in the CWA bound by the Sargasso Sea; coordinates 22º-30ºN and 40º-75ºW (Gower *et al.*, 2006). A time averaged map of sea surface salinity for the month of July 2015 was created as this was the earliest available data within the temporal scale of this report. The resulting Figure 3 is used as a reference to encompass an area of the CWA not influenced by any major river plumes.

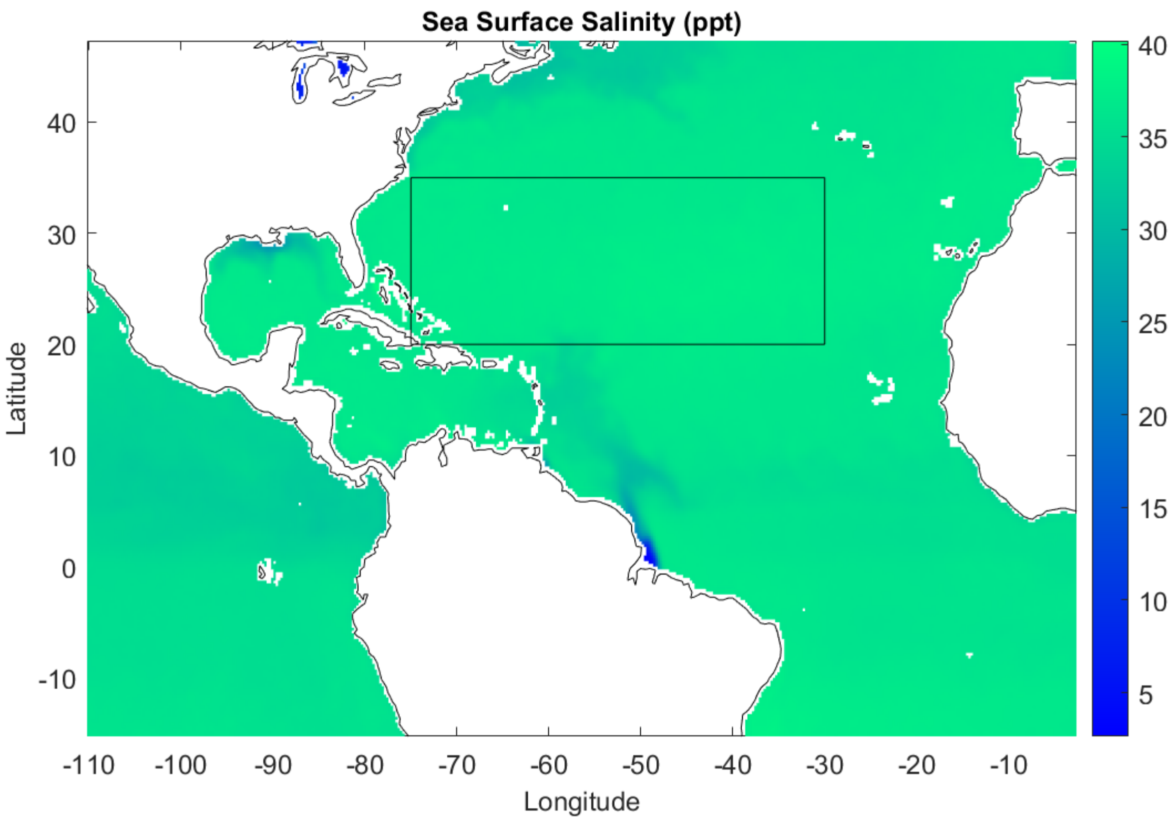

Figure 3: Averaged sea surface salinity for July 2015 over the CWA and GOM, encompassing all river plumes of interest to highlight extent of plumes. With area bound by 22º-35ºN and 30º-75ºW (Gower *et al*., 2006) Data: Oceansciences.org, 2015

Using MCI to detect slicks in the Yucatan Peninsula

Ocean colour imagery from the MERIS instrument on board the ESA's Envisat satellite was sourced through their earth observation website (ESA, no date). Imagery spanning 2009-2012 with a 1040m spatial resolution was collated and processed using Matlab (2020b). Note, the MERIS mission ended in 2012 resulting in the small time frame of data collection. MERIS was used over MODIS for ease of data access and processing using the Matlab interface. The radiance data from 4 wavebands (8, 9, 10, and 13) were processed using the following equation to determine the Maximum Chlorophyll Index (MCI) for floating algae in the Yucatan Peninsula (Gower & King, 2011).

$$MCI = L_{709} - L_{681} - (709 - 681)(L_{754} - L_{681}) / (754 - 681)$$

Where L_{709} references the water-leaving radiance in the 709nm band etc. Since sargassum is only found in masses in this area over the summer months, the data represents findings for months of March to September. Cloud cover was eradicated by creating a histogram containing MCI measurements for each scene; a threshold for cloud and land cover was created by removing values above and below bins containing ~90% of the data. This allowed for a unique threshold to be determined for each scene as the same threshold values were not accurate for all. These readings were set to an extreme value (usually -1 or >maximum MCI value in one case) and appear in dark grey on the scenes to highlight cloud and land, as white was not easily distinguished for the high MCI areas in yellow. An attempt was made to remove data for which radiance measurements in the 865nm band exceeded a threshold of $15sr^{-1}$ (Gower and King, 2013), but for the purpose of this study, was irrelevant and ineffective in cloud masking.

The Caribbean's proximity to the equator makes the acquisition of clear imagery challenging as the sun is often overhead, particularly in the months this study is interested in. This results in a large amount of sun glint in most imagery captured during the day; this can be masked in the data processing by omitting pixels above the threshold but leaves substantial gaps in the original data, rendering many images unusable. To counteract this, imagery from earlier months of the year were taken further away from the study site to in an attempt to capture the path of the macroalgae slicks. Only imagery that fulfilled the following criteria were included; imagery from anytime within the months of March to September as this is typically when Sargassum is present in this area, and data only from years large blooms have been documented to validate spectral signatures as sargassum. In this case, this represented the years 2011 and 2012 for the Caribbean scenes. Out of a total of 112 images returned by meris-ds.eo.esa, only 2 matched the desired criteria and are investigated in the results.

Additionally, a scene from the Amazon river plume area was taken from August 2009 during a flood event (Table 1) after Gower *et al.* (2013) had detected 'Sargassum-like' parameters off the Northern Brazil coast throughout 2003-2010. Additionally, a scene from the GOM encompassing the Mississippi Delta is produced around the time of an extreme nitrate output event which also coincided with a stranding event (Table 1). This data is presented to validate the findings presented in Figure 5 in addition to supporting previous knowledge and existing literature.

Atlantic Wind Stress

Latitude-averaged wind stress data for an area of the Atlantic covering the South Equatorial Current (SEC) was accessed through the NASA Giovanni (no date) website and processed in Matlab (2020b). The data was recorded by the MERRA-2 sensor, recording data at a spatial resolution of 0.5 x 0.625 degrees and a monthly temporal resolution. The data stretches an area 9ºE to 46ºW with values averaged over a latitude of 0ºN to 6ºS for each point. The SEC runs from the west coast of Africa, westwards through the Atlantic to the eastern coast of Brazil (Johns *et al.*, 2020). This current was chosen as an area of interest to facilitate the research regarding the Congo as a key nutrient source for the stimulation of algae in the Caribbean (Djakouré *et al.*, 2017). Moreover, this area was selected as upwellings off the west African coast are theorised by Wang *et al.* (2019) to be a significant contributing source of nutrients.

All data acquired for nitrate and wind stress observations spans the same ten-year time series starting in the first month of 2006 to the final month of 2015 with supporting MCI data collated within the same time frame.

Results

Timings of Driving Events

Table 1 outlines notable months of high nitrate concentrations in the plume areas of 3 major rivers linked to the Atlantic alongside other exceptional weather events significantly impacting the state of the marine environment. Events of nitrate excess are defined by nitrate levels of a given month of river discharge exceeding +2 standard deviations from the mean as visualised in Figure 5.

Table 1: Timeline of nitrate peaks and stranding events with any coinciding events that may have also impacted sargassum biomass. Nitrate excess defined by data presented in Figure 5.

Date	Parameter	Location	Stranding	Other
Feb 2007	Nitrate Excess	Mississippi	No	
Sep 2007	Nitrate Excess	Amazon	No	
Aug 2009	Nitrate Excess	Amazon (Figure 4c)	No	Amazon Flood (Oviatt *et al*., 2019)
Oct 2009	Nitrate Excess	Congo	No	
March 2010	Nitrate Excess	Mississippi	No	El Niño: abnormally high SST (Djakouré *et al*., 2017)
May 2010	Nitrate Excess	Congo	No	El Niño: abnormally high SST (Djakouré *et al*., 2017)
Feb 2011	Nitrate Excess	Mississippi (Figure 4d)	Yes	Abnormally high SST in early 2011 (Djakouré *et al*., 2017)
Jan 2014	Nitrate Excess	Mississippi	Yes	Amazon flood (Oviatt *et al*., 2019)
Jan 2014	Nitrate Excess	Congo	Yes	Amazon Flood (Oviatt *et al*., 2019)
Feb 2015	Nitrate Excess	Amazon	Yes	Amazon Flood (Oviatt *et al*., 2019)

MCI Mapping

Areas of high chlorophyll can be seen in bay areas on the Caribbean coast of Mexico’s Yucatan Peninsula indicating likely Sargassum build up on the shoreline (Figure 4b). Imagery from MERIS allows clear detection of land interesting areas of ‘likely’ pelagic and beached sargassum along with ‘Sargassum-like’ parameters exiting the Amazon plume as hypothesised by Gower *et al.* (2013). Figure 4 displays scenes with MCI (mW m^{-2} nm^{-1} sr^{-1}) mapped.

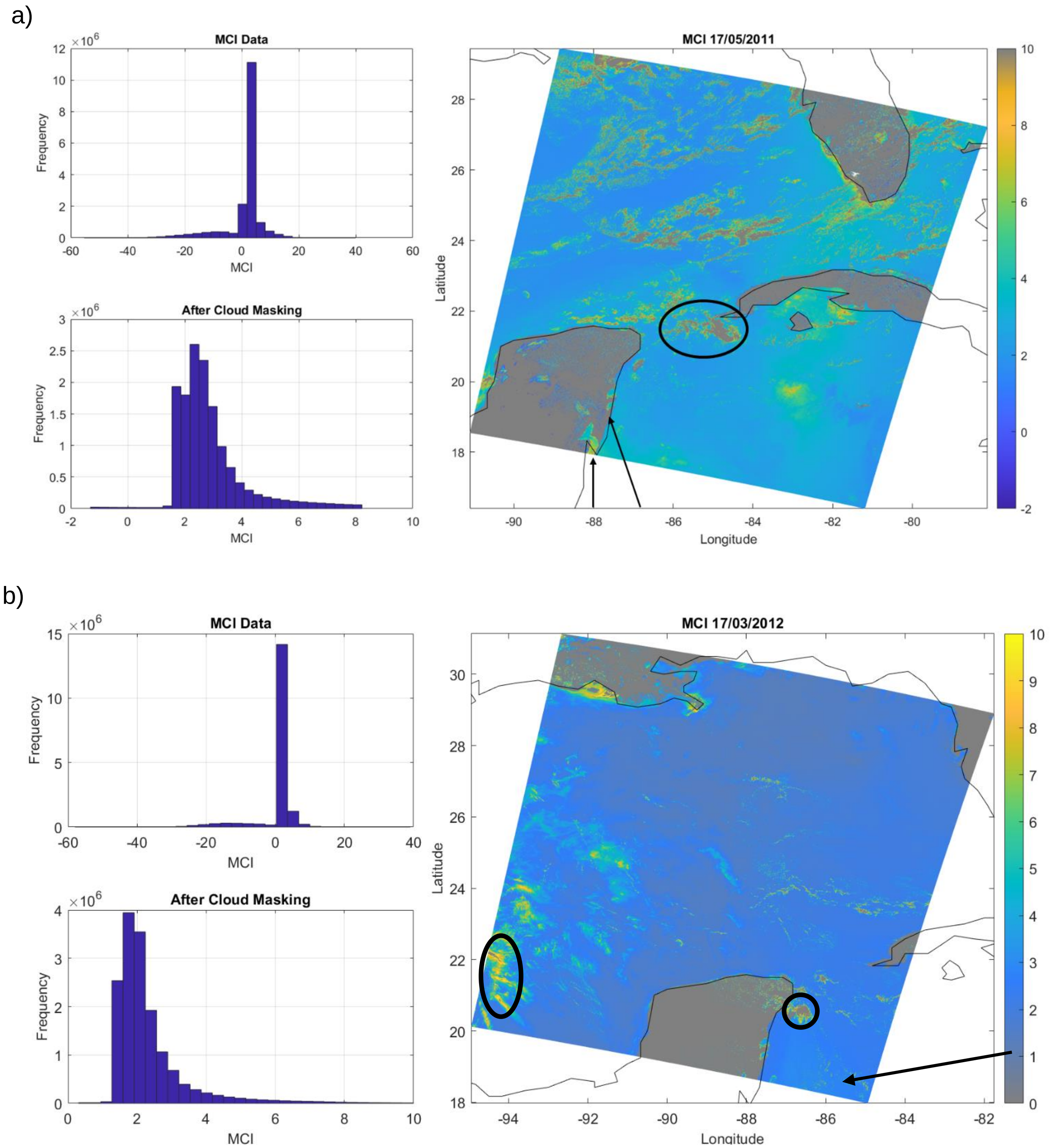

Figure 4: (a): Scenes from various patches of the study area with mapped MCI and histograms showing distribution of initial MCI data (top) and the distribution of only the selected data used in the scene after cloud masking (bottom). This scene is taken from the Yucatan Peninsula on 17th of May 2011 with domains highlighted as 'definitely cloud' circled in black, 'definitely sargassum' indicated by a black arrow and 'open ocean'. **(b)** Additional scene from the Yucatan peninsula on 17th of March 2012 (See following page for **(c)** and **(d)**).

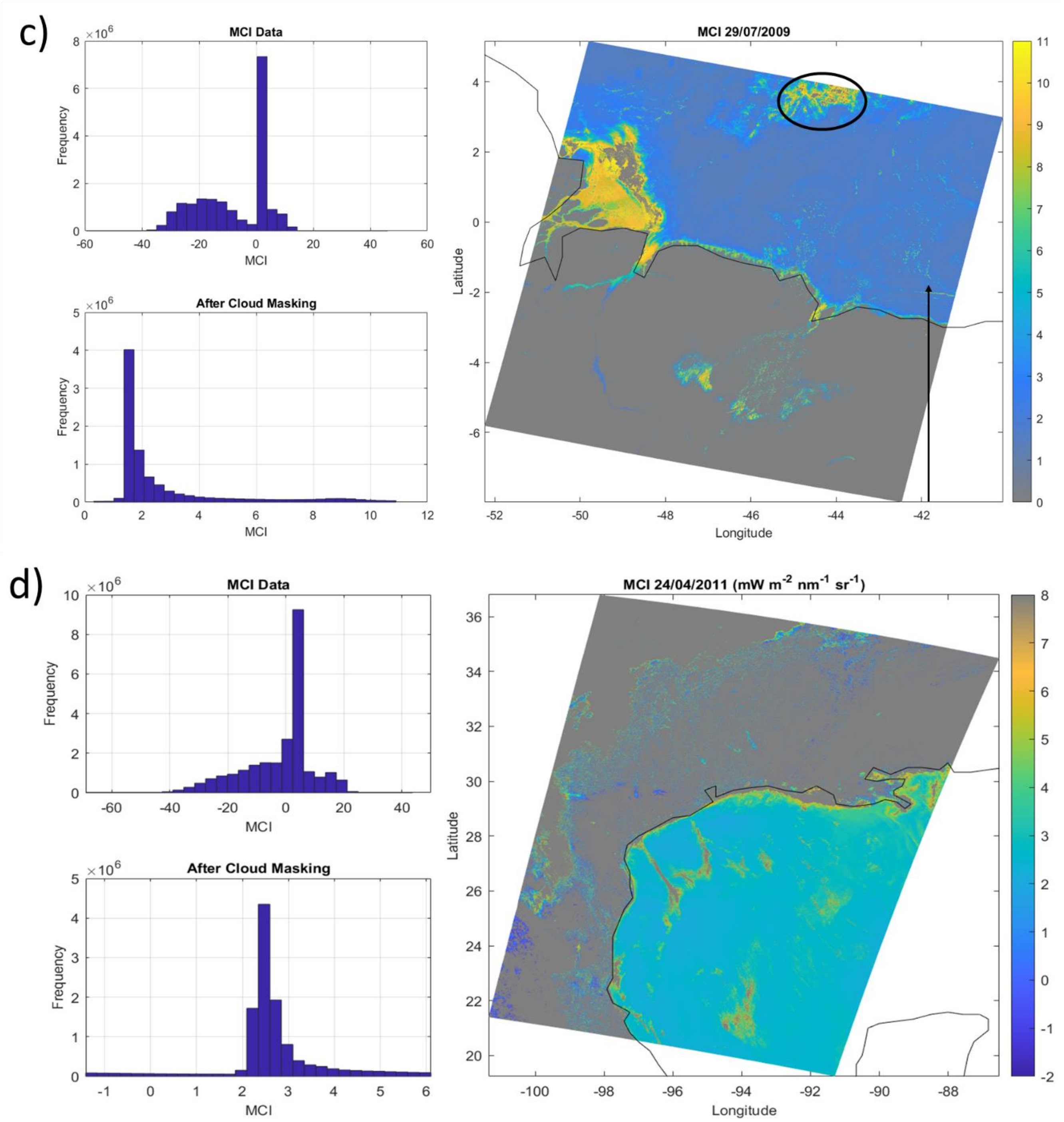

Figure 4 continued: (c) The Amazon river plume in 2009 and **(d)** GOM in 2011. Data: (Esa.int, 2021)

Comparison of Nitrate Sources

A comparison of residual nitrate levels from three river sources shows the Congo river to output the greatest concentration of NO_3^- out of the three (Figure 5). Clear moments of excess nutrient output from the Amazon and Mississippi can be distinguished from the plots in Figure 5 whereas it is difficult to determine any abnormal events in the Congo plot due to the amount of variability even with seasonal cycles removed. There is no significant trend of an increase or decrease with time for any of the sources.

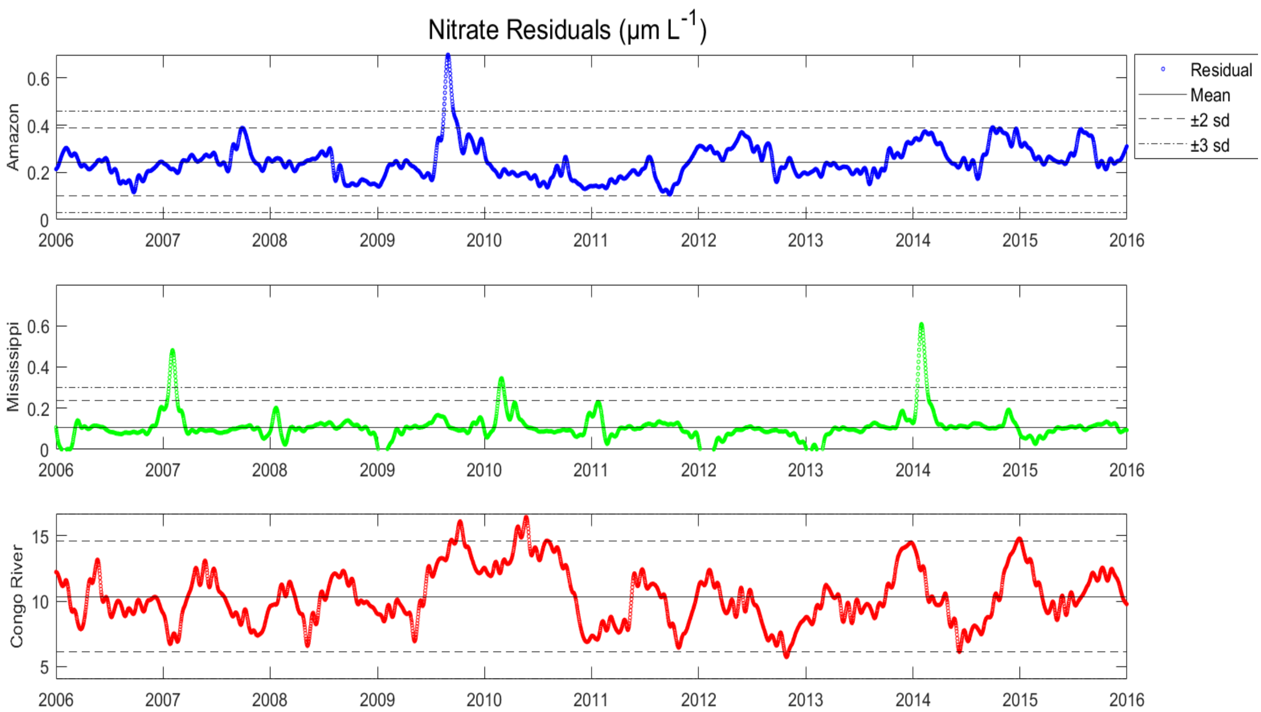

Figure 5: Area-averaged, ten-year time series data for three nitrate sources; the Amazon, Mississippi, and Congo rivers as labelled. Each with mean and standard deviations.

A chlorophyll index (CI) was derived using the equation stated earlier for an area in the Caribbean. The monthly chlorophyll data was measured against month-averaged nitrate data to visualise any correlations between the data sets. This is displayed as three plots with three regression line equations in Figure 6.

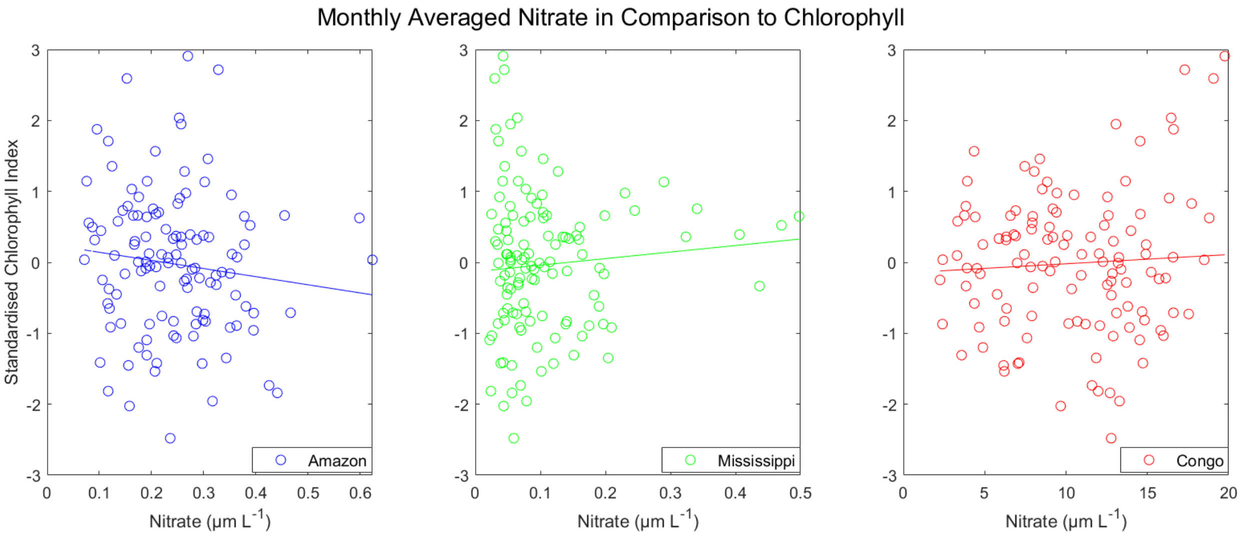

Figure 6: Chlorophyll Index in the Caribbean plotted as a function of monthly averaged nitrate residuals from each source.

A regression line for each plot was created;
y = 0.256 ± 0.235 μm L^{-1} -1.146 ± 0.888 (Amazon)
y = -0.132 ± 0.141 μm L^{-1} + 0.922 ± 1.012 (Mississippi)
y = -0.150 ± 0.236 μm L^{-1} + 0.013 ± 0.021 (Congo)

The month-averaged nitrate concentrations from each river plume were then directly compared against area-averaged nitrate concentrations for an area of the Sargasso Sea basin in Figure 7, clear of all river plumes; see Figure 3 for selection of comparison area.

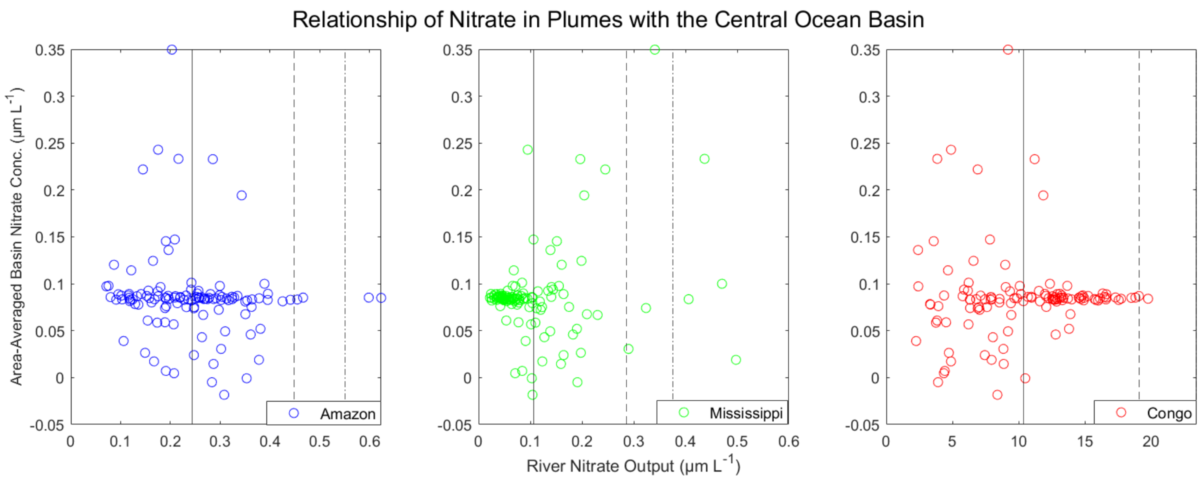

Figure 7: Comparison of relationship between nitrate in plumes with total nitrate in central ocean basin clear of plumes (Figure 3). With mean presented as a black line and +2 and +3 standard deviations in dashed and dashed-dotted lines, respectively.

The nitrate outputs from rivers in all three instances show no correlation with overall nitrate levels in the sargasso sea where Sargassum primarily originates.

Wind Stress in the Atlantic South Equatorial Current
Wind stress for all years tend to follow the same pattern without any stark outliers and at any given point, all values are at most within 0.04Nm^{-2} of each other (Figure 8a). The year of 2011 saw the first mass stranding event in June, and was followed by excess nutrient output from the Congo river (Figure 5) in 2010 addition to being an El Niño year (Table 1). The wind stress for 2011 was investigated further by comparing average wind stress for April & May (pre-stranding event) to an average for September & October (Figure 8b).

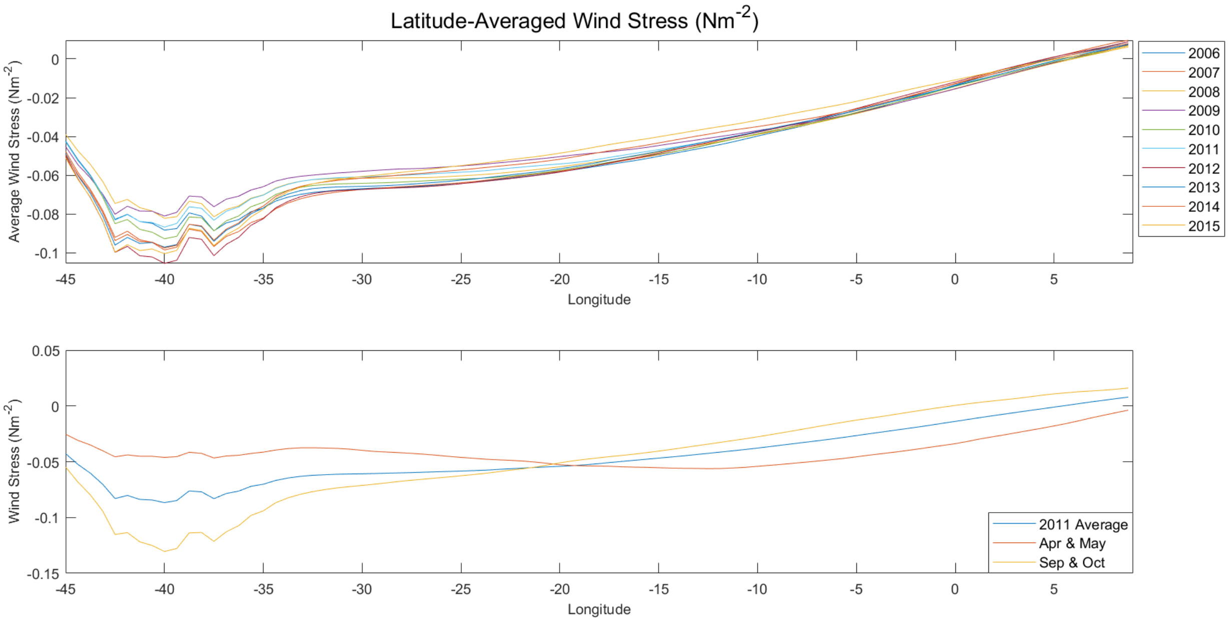

Figure 8(a): Yearly-averaged wind stress stretching 45ºW to 9ºE over the SEC through years 2006-2015. Values averaged over a Latitude of 0ºN to 6ºS. (b) Averaged wind stress in 2010 compared to combined average of years 2006-2009 and 2011-2019 combined.

A two-sample t-test was conducted to compare the average wind stress in April & May of 2011 and the average for September & October. A p-value of $p = 0.202$ was returned and allows the assumption that there was no significant difference in wind stress in the months leading up to the stranding event (M= -0.0412, SD= 0.0125) and wind stress averaged over the following months (M= -0.0470, SD= 0.0407); $t(174) = 1.282$, $p = 0.202$.

Discussion

Rivers as Nutrient Sources

The mean area averaged concentration of nitrate in the area leaving the Amazon river is 0.244 ± 0.107 µm L^{-1}; in comparison the maximum measured level recorded in late 2009 of 0.888 µm L^{-1}. Where this may be viewed as a large increase from the mean by an order of four, we must consider if a maximum increase of just 0.644 µm L^{-1} is significant enough to be responsible for an excess of 20 million tonnes of sargassum 18 months later? Similarly, a substantial increase in concentrations comparative to a mean of 0.107 µm L^{-1} ± 0.096 µm L^{-1} over a ten-year period around the Mississippi delta was observed. But, again, does a maximum flux of 0.694 µm L^{-1} to a maximum value of 0.801 µm L^{-1} provide a big impact on overall nutrient levels in the west Atlantic? The third source, the Congo river plume, is extremely variable in terms of nitrate output even with seasonal cycles removed. This source, out of the three areas studied, has the highest difference from its ten-year average and the largest variability. However, this source is much further away from the production area than the others raising the question; is the Congo river output located too far away to significantly impact the events happening in the Caribbean?

The results show no significant correlation between the concentrations of nitrate surrounding each river plume and chlorophyll-a concentrations around the Yucatan peninsula (Figure 6). This could suggest the dismissal of nitrate as a restricting factor for sargassum growth. This lack of relationship can lead us to speculate there is no competition or no significant competition from phytoplankton for the uptake of the excess nitrate. If nitrate was a key limiting factor in the production of sargassum, there would be a clear relationship of increasing nitrate with increasing chlorophyll; this, however is not observed in the results. In the nutrient-poor waters of the CWA, excess nitrate is not always the limiting factor in phytoplankton growth; Barcelos *et al.* (2017) found that phosphorus and other trace metals are more so of a limiting nutrient than nitrogen in this area.

All three rivers display a significantly high (>+2 std from mean) discharge of nitrate from 2009-2010; one year prior to the first mass stranding events (Figure 4). In the cases of the Amazon and Congo rivers, around this period is the only time the nutrient outflow exceeds 2 standard deviations above the mean for the 10-year data set. However, Figure 7 suggests there is no or little relationship between extreme events of river nitrate discharge and overall nitrate concentrations in the Sargasso Sea, where the formation of the macroalgae typically takes place. The greatest recorded concentration of nitrate recorded in the Sargasso Sea occurs when the output of nitrate from the Amazon and Congo rivers are around their average levels, suggesting influences from these river plumes are not directly impacting Sargassum growth within the gyre, but could be stimulating growth elsewhere.

The Amazon River Plume

While some researchers believe the Amazon river plume is a key driver in sargassum production (Gower *et al.*, 2011), others believe this nutrient source is negligible when discussing the overall impact (Wang & Hu, 2016). The low fluctuations of nitrate levels exiting the river may not have an impact on the overall nutrient composition in the CWA, however the close proximity of the river plume to the sargassum production area may nevertheless qualify this as a contributing factor. Regarding nitrate levels in the Sargasso Sea gyre, even in extreme events where the outflow of nutrients from the Amazon plume exceeds 2 standard deviations above mean concentrations, the open ocean sees no significant increase in nutrients in response to this (Figure 7).

The Mississippi Delta
This river exhibits the most variability in nutrient discharge in terms of extremes; the levels of nitrate output exceed 3 standard deviations above the mean on three occasions in comparison to the Amazon with only one extreme event (Figure 4). Not only do these extremes occur more often, but 2 of these events are followed by sargassum bloom years.

The Congo River Plume
The results show, out of the three chosen nutrient sources, the Congo river discharge fluctuations are more correlated to surface chlorophyll levels in the Yucatan Peninsula than for the Amazon or Mississippi in terms of timings of peaks and sizes of residuals. However, it cannot be certain to what extent these two parameters are connected; high Congo residuals were only connected to reported mass stranding on one occasion in early 2014 which was also in line with an Amazon flood year (Table 1). High nitrate output recorded in March 2010 did not align with a stranding event in the same year, however the following year saw the first major sargassum event in the Caribbean, suggesting a possible lag time to allow for the distribution and uptake of said excess nutrients.

These results might suggest a link between the surplus nitrate exiting the Congo plume in March 2010 and the subsequent mass stranding sargassum event in 2011 around the Caribbean. However, this does not explain the reasoning behind subsequent stranding years. Perhaps surveying the changes in a larger or smaller area around the river outflows would lead to the uncovering of different results.

Wind Stress
The wind stress data shows no striking peaks or troughs over the ten-year period; the time series data for all years tend to follow the same pattern with no abnormality. There is no significant difference in wind stress. This parameter, therefore, may be disregarded as a key contributing factor to the algal growth seen in this time period. This disproves the hypothesis that the SEC water may have been preconditioned by wind in the months prior to the 2011 stranding event. However, Mcgregor *et al.* (2007) believe west African upwelling systems are intensifying and will continue this trend as global temperatures and CO_2 emissions continue to rise, suggesting this may play a key role in nutrient cycling in the Atlantic in years to come. Wind stress is more variable around the lower longitudes of the SEC but show little variation between years and within years around the higher longitudes of the west African coast in proximity to the Congo river plume.

Conclusions

It is established in existing literature that increased sargassum production, like with many HABs, is a result of more than one changing condition. For example, fluctuations of SST, increased wind stress causing upwellings, the frequency and severity of hurricanes or a combination of two or more of the forementioned may also be at play (Oviatt *et al.*, 2019). The Atlantic is a dynamic ocean, and it is difficult to distinguish which combination of parameters are influencing the mass production of macroalgae and even more so to determine which is the more or less significant contributor (Djakouré *et al.*, 2017).

Mapping the movement and distribution of Sargassum alongside the long-term monitoring of nutrient fluctuations and other oceanic processes such as wind stress can aid an understanding of the bigger picture of macroalgae formation and its causes of excess growth in the CWA. The results indicate nutrient runoff from anthropogenic activity transported by rivers and eutrophication in river plume areas does not have a significant impact on the production of Sargassum in the CWA despite multiple significant extreme events of nutrient enrichment throughout the study period. The Amazon river plume and Mississippi Delta outflow areas have previously been topics of interest regarding nitrate pollution as a stimulant for sargassum production. However, this is the first study that directly compares both sources in addition to a third: the Congo river plume. As three major anthropogenic and natural pollutant sources linked to the Atlantic Ocean, it is interesting to observe how nitrate output varied over time in three very different global locations.

To address a secondary aim in this research, an analysis of wind stress along the SEC was completed after the literature suggested upwellings due to hurricanes and increased wind stress may be stimulating nutrient cycling. This report finds the effect of wind stress may be disregarded as a contributing factor as no extremities in wind speed were observed prior to the mass stranding events.

This study is the first to highlight the Congo river plume as a possible source of significant nitrate input to the CWA and, additionally, the first to directly compare three sources of nitrate to uncover any trends or relationships to the growing sargassum production problem.

As none of the parameters explored in this research have highlighted any striking links to the problem with sargassum, it leads to the possibility of other contributing factors or perhaps even a regime shift; blooms have become a ‘new normal’ since 2011 and have not significantly diminished since. A regime shift may be possible given the current length of available RS time series data is not long enough to detect this kind of event. It is difficult to pinpoint changes such as regime shifts in this length of data, especially since blooms and transportation leading to strandings of Sargassum follow an annual cycle consisting of seasonal river floods, the cycling of nutrients from currents and upwellings and the uptake time of nitrate to produce the macroalgae. So far, only processes within the CWA or around the equator have been reviewed. The North Atlantic is widely known as being a very productive area in terms of nutrient richness and cycling and water mass movement, suggesting further research may consider investigating the North Atlantic for possible drivers and events.

Climate change is a driver to many changes in the marine environment; this factor must be considered as a possible driver for extreme Sargassum biomass production in addition to the anthropogenic factors discussed. Going forward, perhaps methods to distinguish changes due to climate change and anthropogenic pressures can be developed to further our understanding of the workings of the CWA. Methods on differentiating impacts due to climate change and anthropogenic eutrophication could be developed to facilitate this research.

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