On the origin of golden tides in the Caribbean Sea

Yun June Hong Scholten (y.j.h.scholten@student.rug.nl) – MSc. Marine Biology
Student number: s4574869

Supervisor: Klaas Timmermans (k.timmermans@nioz.nl)

26/02/2021

university of groningen

Abstract

Massive Sargassum beaching has become a reoccurring problem in the Caribbean and other parts of the Atlantic. It has caused extensive ecosystem disturbances and has negatively impacted tourism and local economies. Interestingly, this phenomenon has not been observed in the Caribbean prior to 2011. Therefore, this study has researched what could have been the tipping point in 2011, that caused the almost yearly reoccurring Sargassum inundations on the Caribbean beaches. In consideration of that, this study further elaborates on the probability of several hypotheses on the cause of these Sargassum blooms. Plausible hypotheses propose the Amazon River and hurricane season as a new nutrient source fueling Sargassum blooms. Windage from extreme westerlies, a different genetic variety, anthropogenic induced climate change, and natural climate indices are also proposed as possible causes. It is established that the reoccurring pelagic Sargassum blooms originate from the North Atlantic Equatorial Recirculation Region (NERR), entering the Caribbean Sea via several pathways. The onset of Sargassum blooms in the Caribbean in 2011 was most likely initiated in the NERR itself. Pelagic Sargassum was already present in the NERR prior to 2011. Due to high growth rates in pelagic Sargassum and optimal and anomalous environmental circumstances in the NERR, Sargassum was able proliferate. Thus, the tipping point for the initiation of massive Sargassum beaching in the Caribbean in 2011 is likely due to a combination of anomalous environmental circumstances and does not correspond to one single hypothesis. The cooccurrence of extreme warm climate indices and global warming, generated warm sea surface temperatures, calmer waters and enough nutrients for Sargassum to proliferate in the NERR in 2011. The different characteristics of the *Sargassum natans VIII* morphotype might play a key role in the ability to form large blooms under these anomalous circumstances. Therefore, it is suggested that growth responses of Sargassum morphotypes and optimum growth factors should be studied extensively in order to better understand the reoccurring phenomenon.

Table of Contents

Abbreviations

ACE	-	Average Cyclone Energy	NBCR	-	North Brazil Current Retroflection
AMO	-	Atlantic Multi-decadal Oscillations	NEC	-	North Equatorial Current
CS	-	Caribbean Sea	NECC	-	North Equatorial Counter Current
GoM	-	Gulf of Mexico	NERR	-	North Equatorial Recirculation Region
ITCZ	-	Inter Tropical Convergence Zone	SS	-	Sargasso Sea
NAO	-	North Atlantic Oscillations	SST	-	Sea Surface Temperature
NBC	-	North Brazil Current			

1. Introduction

Massive Sargassum beaching has become a reoccurring problem in the Atlantic Ocean since 2011 [1]. Sargassum is a common seaweed or brown macroalga and is known to create important ecosystem functions [2,3]. It provides a species specific habitat for many fish, invertebrates, and micro and macro-epiphytes [2–4]. In addition, sea turtles, birds, and other migratory species use Sargassum patches as a refuge for shelter and food [2,4]. There are over 300 different Sargassum species determined so far [5] . Most of them are benthic species that are attached to the bottom some time in their life stage [5,6]. There are only two pelagic species known, *Sargassum natans* and *Sargassum fluitans*, that are predominant in the SS and Gulf of Mexico (GoM) (see Figure 1) [6–9]. The SS contains approximately 10 million tons of Sargassum, thereby contributing to the global sequestration of carbon with approximately 7% [4,10]. The SS is likely formed and fueled by the GoM, which produces nutrient and species rich Sargassum blooms every year [10]. Around the SS are the Gulf Stream, North Atlantic Current, Azores Current, Canary Current, Antilles Current and North Equatorial Current (NEC) that keep the large patch of floating Sargassum within the north Atlantic subtropical gyre (see Figure 1) [9,11–13]. However, since 2011, mass beaching of Sargassum has occurred in the Caribbean, Central America, Brazil and West African coast [3,4,14,15]. Due to the yellow brownish color of the seaweed, these large amounts of Sargassum are also called golden tides [4,9]. Small patches of beaching Sargassum is a common phenomenon and has a lot of beneficial properties for coastal ecosystems [16]. Small amounts of Sargassum provide ecosystem stability to the beach and introduces new nutrients to beach and dune plants [4,8]. However, in large quantities, Sargassum can negatively affect the local economy, tourism and even rises health concerns [3,4,17].

Efforts to clean up beaches from Sargassum beaching has cost the government millions. For example in Mexico, $ 5 million was spent on the Sargassum beach cleanup [4]. Converting this calculation to the Caribbean would give an amount of at least 120 million for Sargassum clean up on beaches [4]. Another downside to the beach cleaning is the sand removal during cleaning and the destruction of important habitats for the fauna within [4]. When the Sargassum is not removed, the smell of rotten eggs may arise due to the decomposition of the seaweed forming hydrogen sulfide gas [2,3]. Prolonged exposure to this gas can even give rise to health repercussions, causing effects such as headaches, sleep deprivation, nausea and irritated eyes [2,3]. Furthermore, the decomposition of Sargassum has also impact on the physical, physiological and ecological near-shore reef communities [3]. The large floating patches may cause anoxia in the waters below and hypoxia in seagrass and corals due to reduced light [3]. While the large stranded patches on the beach may smother turtle hatchlings [4].

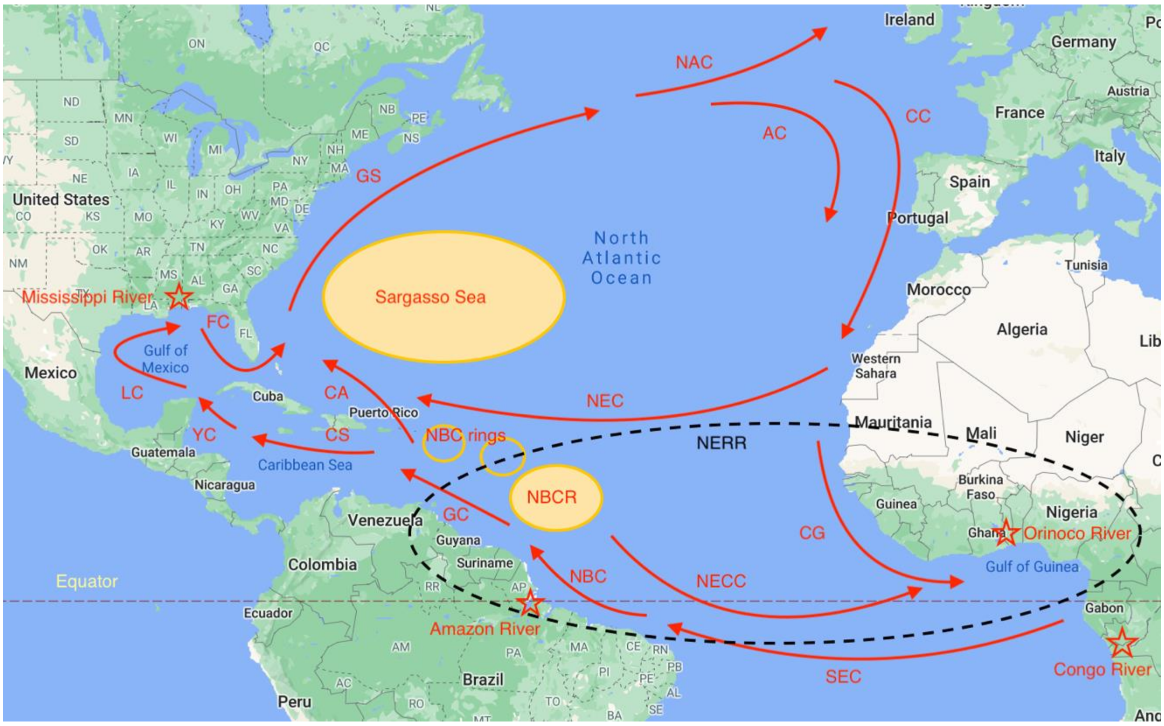

Figure 1: Sargasso Sea and North Atlantic Ocean currents. GS=Gulf Stream, NAC=North Atlantic Current, AC=Azores current, CC=Canary Current, NEC=North Atlantic Equatorial Current, CA=Antilles Current, CS=Caribbean Sea, YC=Yucatan Current, LC=Loop Current, FC=Florida Current, CG= Guinea Current, SEC=South Atlantic Equatorial Current, NBC=North Brazil Current, GC= Guyana Current, NBCR=North Brazil Current Retroflection, NECC=North Atlantic Equatorial Counter Current, NERR= North Atlantic Equatorial Recirculation Region. NECC forms from May-October. NBC rings deflect from NBCR. Stars indicate nutrient discharge sources from major rivers.

As it is evident that the recent Sargassum beaching in the Caribbean is of high concern to the local environment, there is not much certain yet of what's causing these mass blooms in the Caribbean. From 2011 onwards, these blooms seem to reoccur almost annually [8]. Since the blooms within the Caribbean Sea (CS) are correlated with the amount of mass beaching, this will have a great impact on tourism, ecosystem functioning and the local economy [3,8,18].

At first, the pelagic Sargassum in the Caribbean was thought to originate from the SS itself [11,19]. Later on, there were discoveries of a new Sargassum source coming from the North Equatorial Recirculation Region (NERR)[7]. The Western Tropical Atlantic in particular is said to be responsible for the large inundation events in the CS [6,7]. Supplementary to this, Gower et.al (2013) believed that it came from northeastern Brazil, where the North Brazil Current System played a key role in transporting the Sargassum from the equatorial Atlantic to the Caribbean [9,18].

Apart from the geographical origin of the Sargassum rafts, there is still much debate on the actual cause of such blooms. What could have initiated the reoccurring Sargassum blooms and beaching events in the Caribbean from 2011 and onwards? There are several hypotheses that have been considered as the potential cause of these blooms. This study will elaborate on the following plausible hypotheses.

First the introduction of a new nutrient input source will be considered, suggested by Oviatt et al. (2019). Secondly, the importance of high 'windage' has been stated by Johns et al. (2020) and Putman et al. (2018). This would cause sea surface friction, which may tag along Sargassum from the SS [11,18].

Thirdly, Amaral-Zettler et al. (2017) have researched the possibility of a shift in Sargassum morphotypes, shifting towards a genetic variety of pelagic Sargassum that thrives under the new environmental circumstances. Lastly, climate change plays a key role in these events, as they could change sea and wind currents and alter environmental conditions in favor of Sargassum growth [16]. Or perhaps natural Ocean indices are the cause for excessive growth, instead of anthropogenic induced climate change [20]

This study will further elaborate on the feasibility of these hypothesis. It is of great importance to study the origin of these blooms and beaching events in order to find a possible solution to the problem and predict future inundation events. The precarious fact is that there is no precedent of such blooms in the CS before 2011 [3] . Therefore, this literature study will research on what might have been the tipping point for the reoccurring mass Sargassum blooms in the CS since 2011. What are the drivers for these massive Sargassum blooms and where do they originate before entering the CS?

2. Geographic Origin

One hypothesis by Johns et al. (2020) suggests that the novel Sargassum blooms originate from the SS and ended up in the Caribbean through wind and sea currents [11]. However, Gower et al. (2013) and Schell et al. (2015) found that the SS did not supply the new Sargassum to the CS. Instead, the new source is originating from the NERR [12].

Every May the North Equatorial Counter Current (NECC) forms in the NERR due to the northward moving Inter Tropical Convergence Zone (ITCZ) [11,21]. The ITCZ is in essence a low-pressure area where the northeast and southeast trade winds converge and move westward [22]. The westward sea surface friction of the wind results in Ekman transport away from the equator and a weak open ocean upwelling [11]. When the ITCZ moves north away from the equator the NECC forms. In addition, the North Brazil Current (NBC) moves away from the coast and retroflects eastward, joining the NECC (see Figure 1) [21]. This creates the North Brazil Current Retroflection (NBCR) [21].

Putman et al. (2018) describe three routes in which Sargassum enters the CS from the NERR. The fastest and most direct way is via the NBC and Guiana Current [7,23]. This often happens in spring, when Sargassum level is highest in the equatorial Atlantic [18]. A somewhat longer route is via the NBC Rings, which are circulating domes that are deflected from the NBC when it is retroflected into the NECC (see Figure 1) [7,24]. Sargassum that is taken up by these rings often appear in the Caribbean in summer [18]. The longest route, and less often occurring, is via the NBC into the NBCR going towards the NECC, but is taken with the NEC to the Caribbean on its way east [7,23]. Sargassum via this route arrives late autumn in the Caribbean. Putman et al. (2018) propose that the North Brazil Current System is highly connected to the Sargassum inundations in the Caribbean. However, they also acknowledge that not all Sargassum may originate from the western Equatorial Atlantic. Within the North Brazil Current System, the NBCR and Gulf of Guinea are connected with each other through the North Equatorial Counter Current (NECC) and the South Equatorial Current (see figure 1)[7,21]. Therefore, nutrient input from (equatorial) upwelling or the Congo river in the east could have fueled Sargassum blooms as well [14].

Gower et al. (2013 & 2011) retrieved satellite images from the North Atlantic clearly showing the formation of the large equatorial blooms in 2011. These images showed no evidence for Sargassum originating from the SS [7]. However, even satellite images have their implications and can make errors in estimating Sargassum amounts [25]. Satellite images can be affected by clouds and sun glint [25]. Furthermore, Sargassum that is too distributed or below surface water may not be detected properly [25].

While Sargassum becomes less buoyant with age, this could be missed with satellite detection [13,14]. Therefore, there is a possibility that small Sargassum patches have stayed unnoticed while moving out of the SS. However, there has not been any proof of Sargassum moving out of the SS thus far. Therefore, it would seem more like for the blooms to have originated in the NERR. Moreover, the two hypotheses do not necessarily contradict each other. While large patches of Sargassum may not stay unnoticed from satellite images, small Sargassum patches may have migrated out of the SS into the NERR, where it could proliferate.

3. Nutrient input

One of the most well accepted hypotheses for the onset of Sargassum blooms in the Caribbean is the influx of new nutrients into the Atlantic Ocean [2,14]. Sargassum in the SS thrives in this oligotrophic region, but primary production is over all increased with increased nutrient availability, light, and temperature [6,9,26,27]. In the oligotrophic SS, the fresh supply of new Sargassum comes from the GoM each summer [27]. The nutrient input comes from the Mississippi river, which opens up in the GoM and fuels new blooms every spring [14,27]. Annually 1 million tons of Sargassum is exported to the Sargassum Sea from the GoM via the Florida Straits [4]. Sargassum is highly nutrient dependent [10]. Thus, the large blooms in the CS need a large nutrient input.

Oviatt et al. (2019) believe that the Sargassum in the Caribbean originates from a new source in the equatorial Atlantic and that the North Equatorial Recirculation Region (NERR) plays a key role in the Sargassum blooms (see Figure 1). They propose several nutrient sources big enough to fuel the golden tides in the Caribbean. According to Oviatt et al. (2019) the flooding of the Amazon River, which opens right into the NERR, would be such a nutrient source.

3.1 Amazon River flooding

In 2009, 2011, 2012, 2014 and 2015 the Amazon River experienced exceptional large floods, which resulted in a large nutrient plume into the Atlantic Ocean (see Table 1)[14,28]. The yearly Sargassum beaching in the Caribbean is believed to be correlated with Amazon River flooding of the same year. However, this does not account for all flooding events. Presuming that Sargassum beaching is correlated with Amazon River flooding, then 2006 to 2009 should also show beaching events. Especially the year 2006, while maximum Amazon River discharge was first measured in this year [26] (see Table 1). Similarly, this also accounts for the year 2017 and 2018, when there was a lot of Sargassum beaching and blooming in the Caribbean, but no Amazon River flooding (see Table 1). A combination of factors is therefore suggested by Oviatt et al. (2019). They state that the blooming of Sargassum is dependent on the timing of the Amazon River flood and the concurrence of the Intertropical Convergence Zone (ITCZ). The precipitation brought by the ITCZ reduces the surface water salinity, thereby retaining nutrients for the Sargassum to grow [14,29]. However, when setting up the time line, all the factors are met to produce a large bloom in 2009. The rainfall from the ITCZ happens mostly during the months January to March in the western Atlantic [14]. Also, the Sargassum mats usually appear in February at the West Equatorial Atlantic before they move to the Caribbean via the NBC [30]. So, the timing of flooding could be of importance to the beaching events in the Caribbean. However, the 2009 Amazon River flood started in January and peaked in March, which is exactly in concert with the ITCZ and Sargassum appearance [31]. So, there is no explanation to why the 2009 Amazon River flooding could not have fueled a large Sargassum bloom in the Caribbean in that year. Therefore, the hypothesis that a combination of both ITCZ and Amazon River flooding would be the cause for the Caribbean Sargassum inundations does not hold either.

Table 1: Sargassum beaching, blooms and nutrient input sources per year in the Caribbean. 2005-2019. Nutrient sources are the Amazon River and hurricane seasons. Adjusted table from Oviatt et al. (2019). Adjustments are cited in the table.

	Amazon River flood	Hurricane season in **previous year**	Sargassum beaching	Blooms
2005	No [31]	Yes [32]	No[26]	No [26]
2006	Yes [26]	Yes [33]	No[26]	No [26]
2007	Yes [34]	No [35]	No[26]	No [26]
2008	Yes [31]	Yes[36]	No[26]	No [26]
2009	Yes [34]	No[14]	No[14]	No [14,26]
2010	No [28]	No [14]	No[14]	No [14,26]
2011	Yes [14]	Yes [14]	Yes[14]	Yes [18]
2012	Yes [28]	Yes [14]	Yes[14]	Yes [18]
2013	No [14]	Yes [14]	No[14]	No
2014	Yes[28]	No [14]	Yes[14]	Yes [18]
2015	Yes [37]	Yes [14]	Yes[14]	Yes [18]
2016	No, El Nino [14]	Yes [14]	No reports[14]	Yes [14]
2017	No [14]	No [14]	No reports[14]	Yes [11]
2018	No [14]	Yes [14]	Yes[14]	Yes [38]
2019	Yes, [37]	No [14]	No [14]	Yes [39]

According to Oviatt et al. (2019), the nitrogen input of the Amazon River would be enough to supply 30 million tons of Sargassum. This calculation is based on a measured amount of 1 million metric tons of nitrogen output from the Amazon River in 2015. Coincidentally, this is about the same amount of nitrogen input the Mississippi river supplies to the GoM [14]. Albeit, this amount of nitrogen only fuels Sargassum blooms of 3-6 million tons wet weight in the GoM [28]. Therefore, it seems unlikely that the Amazon River would support 30 million tons of Sargassum. In fact, in 2015 the large Sargassum bloom comprised of 9 million tons of wet biomass [38]. This is evidently much lower than 30 million tons, though it does not rule out the partaking of the Amazon river flooding in Sargassum bloom formation. On the other hand, the same nutrient values were measured for the year 2013, but no beaching activities or bloom formations occurred that year (see Table 1).

According to Oviatt et al. (2019), the nitrogen input of the Amazon River would be enough to supply 30 million tons of Sargassum. This calculation is based on a measured amount of 1 million metric tons of nitrogen output from the Amazon River in 2015. Coincidentally, this is about the same amount of nitrogen input the Mississippi river supplies to the GoM [14]. Albeit, this amount of nitrogen only fuels Sargassum blooms of 3-6 million tons wet weight in the GoM [28]. Therefore, it seems unlikely that the Amazon River would support 30 million tons of Sargassum. In fact, in 2015 the large Sargassum bloom comprised of 9 million tons of wet biomass [38]. This is evidently much lower than 30 million tons, though it does not rule out the partaking of the

Amazon river flooding in Sargassum bloom formation. On the other hand, the same nutrient values were measured for the year 2013, but no beaching activities or bloom formations occurred that year (see Table 1).

This might indicate that the Amazon River may not be the dominant factor causing Sargassum beaching in the Caribbean, even though the strandings and blooms of Sargassum are often observed in concert with high flow and ascending Amazon River [26]. It is likely, however, that the nutrient input from the Amazon River could have been part of the tipping point for the large blooms in 2011, along with other environmental factors.

3.2 Hurricanes

Another possible source for new nutrient input are hurricanes [20]. Hurricanes can alter the ecosystem extensively by upwelling new nutrients from deeper waters [20]. In 2010 and the following years 2011 and 2012, there were a lot of high impact hurricanes with wind speeds reaching 250 km/h [40] (see Table 1). According to Oviatt et al. (2019), strong hurricanes were often subsequent to beaching events the next year, except for 2013 and 2016 when no beaching occurred after a hurricane year [14]. Oviatt et al. (2019) attributes this to the lack of Amazon River flooding in 2013 and 2016. Even though nutrient values from the Amazon River in 2013 were similar to the values in flood years and the GoM [14,27]. Additionally, Oviatt et al. (2019) states that in 2012 there was a strong eastward flow of the NBCR, causing the nutrients to deflect. Thus, the nutrients from previous year hurricane season were unavailable in 2013. However, if that was the case for 2012, then the Amazon River plume and nutrients supply from previous year hurricanes would also have deflected eastward. Contrariwise, there was a large Sargassum beaching reported in the Caribbean in 2012 (see Table 1).

The simplest solution would be that the overall impact of hurricanes is not big enough to fuel large Sargassum blooms in the Caribbean. Except maybe for the hurricane season in 2017, when hurricanes were so severe that they caused massive blooms in 2018 (see Table 1). Hurricanes in 2017 reached wind speeds of 287 km/h (Irma) [41]. On the other hand, Venezuela experienced an exceptional large flood in 2018 from the Orinoco river, which could have contributed to the nutrient input for Sargassum blooms as well [42]. Adding to this, the last time there was such an impactful hurricane season was in 2004 and 2005, where windspeeds reached 296 km/h (Wilma) and an accumulated cyclone energy (ACE) of 245 [33,43]. Also, the year 2007 was assigned to as a hurricane year [36]. However, there were no Sargassum bloom or beaching reports prior to 2011 in the Caribbean [14,26]. Thus, the correlation between hurricane seasons and Sargassum blooms is not very evident. Also the hurricane season in 2010 had an ACE of 165, which isn’t even close to the 225 ACE in 2017, that supposedly caused the sargassum beaching in 2018 [43]. Therefore, it is unlikely that the hurricane season in the year 2010 was the main contributor to the onset of Sargassum blooms in the CS in 2011.

4. Windage and North Atlantic Oscillations (NAO)

Johns et al. (2020) proposes that instead of a new source of nutrient input, the blooms in the CS originate from a combination of “windage” and negative North Atlantic Oscillations (NAO). “Windage” is described as the drift of floating objects in the surface ocean produced by wind forcing on the sea surface [44]. In 2009-2010, prior to the Sargassum beaching event in 2011, anomalously strong and southern westerlies were observed due to an extreme negative NAO [11,26]. The NAO is dependent on the sea level pressure difference between the Azores High and the Icelandic Low [45]. In positive NAO years the High- and Low-pressure zones are strong and the westerlies follow the Gulf Stream and North Atlantic Current [46]. But in negative NAO years the High- and Low-pressure zones are weak, thereby moving the westerlies southward [46]. Normally, the westerlies in the northern Atlantic and the north east trade winds meet each other roughly over the SS [11]. Due to the anomalous negative NAO, these westerly winds were suited much more southward than usual [11]. Johns et al. (2020) state that the “windage” caused by the westerlies moved large patches of Sargassum out of the SS. From there on the sea currents advected the Sargassum into the CS via the Canary Current and NEC (see Figure 1). Sargassum that entered the NERR, was able to form large windrows following the seasonality of the ITCZ, occasionally directing large blooms via the NERR into the CS [11,18].

It is unclear if the patches from the SS were extremely large resulting in the excessive Caribbean beaching or that it was able to bloom along the way. Could “windage” be enough to carry such amounts out of the SS? Especially during a negative NAO the westerlies are known to be less strong than in positive NAO years [45]. Measurements on Sargassum properties such as shape and buoyancy have not been done yet in detail with regard to windage [18,47]. However, A. Woodcock (1993) did find that with increased wind speeds he would collect less Sargassum at the sea surface. Also, Putman et al. (2020) and Berline et al. (2020) modelled the effect of windage on Sargassum distribution and found that transport predictions were improved by adding windage to the model. Woodcock also saw that Sargassum may drift at several meters below the sea surface due to downward drag. This could make large patches of Sargassum undetectable to satellite images [25].

Another option is that the Sea Surface Temperature (SST) shift between the temperate and tropical Atlantic aided in Sargassum proliferation. The NEC is warmer during a negative NAO, with weaker trade winds, accommodating calmer surface waters for Sargassum proliferation [45]. In addition, the equatorial Atlantic in general has higher irradiance levels, warmer temperatures, and more nutrient availability [11]. This could have fueled the Sargassum growth along its way to the Caribbean [18].

Webster and Linton (2013) found similar results prior to Johns et al. (2020). They observed with imagery analysis that Sargassum transport occurred from the SS into the CS and eventually into the GoM in a Sargassum Loop System. The Sargassum Loop System has migrated small amounts of Sargassum from the SS into the Caribbean prior to 2011, but never in large blooms [51]. Nonetheless, Schell et al. (2015) state that from observational field data, there was no eastward Sargassum drift seen in the east SS and east Atlantic. On the other hand, this data is based on field observations, which can be difficult to detect in the open ocean. Schell et al. (2015) measured Sargassum during their autumn cruise till spring. Therefore, they could have easily missed Sargassum coming from the SS in months they were not in the East Atlantic. Especially when patches were small and only started proliferating once they arrived in the NERR. Also, Johns et al. (2020) suggested that the SS was the tipping point for beach inundations in the Caribbean in 2011 and other beaching events post 2011 were fueled by the NERR. So Sargassum observations in 2014-2015 coming from the NERR by Schell et al. (2015) are in accordance with Johns et al. (2020).

Why this event has never happened before is still up for debate. Johns et al. (2020) do not explain where the anomalous negative NAO comes from causing the strong southern westerlies. The Climate Prediction Center of NOAA, have been keeping track of the NAO values since 1899 and have never encountered such negative NAO values before [11,52]. The highly negative NAO is supposedly a tipping point for large Sargassum blooms in the Caribbean since 2011. However, it is unlikely that Sargassum has never entered the NERR before. Pelagic Sargassum is known to reproduce via fragmentation and can grow very fast in a short time [8,53]. Therefore, small colonies could have easily be transported by hurricanes, boats or animals and turn into large blooms under the right environmental circumstances. While there is no clear evidence for large Sargassum patches moving out of the SS through windage, it is more likely that Sargassum blooms have originated in the NERR from already present Sargassum patches. Gower et al. (2013) does mention turtles to be a likely culprit to have migrated Sargassum within the Atlantic Ocean. In fact, small peaks of pelagic Sargassum growth have been measured prior to 2011 in the NERR as well [5,11]. Also *Sargassum natans* has been reported all over the world in Australia, New Zealand, South of Asia, Africa and Europe [54]. This could indicate that the southern shifted westerlies caused by the extreme negative NAO, might not have caused the onset of Sargassum blooms in the CS. Notwithstanding, the extreme negative NAO could have aided in providing the ideal environmental conditions for Sargassum to proliferate in the NERR.

5. Genetic variety

At first it was believed that the new blooms originated from the SS, containing predominantly *Sargassum natans I* and *Sargassum fluitans III* [11,19]. Except when they looked into the species composition, they found out that the novel blooms might be caused by a new genetic variety [5]. It is common knowledge that there are multiple morphotypes existing within the two pelagic Sargassum species, but this is often neglected in studies on Sargassum distribution [12]. So far, the species *Sargassum Natans I, II, VIII, IX* and *Sargassum fluitans III* and *X* have been identified [9]. Schell et al. (2015) indicated *Sargassum fluitans* III and *Sargassum natans I* as the most common morphotypes in the North Atlantic, CS and Gulf of Mexico. However, during the 2014-2015 Sargassum bloom events in the Caribbean, they found that a shift in composition had occurred. The South SS was dominated by *Sargassum natans I,* but the Antilles Current, east Caribbean and west tropical Atlantic were mainly dominated by the rare *Sargassum natans VIII* type. Therefore, they deduced that the novel Caribbean blooms could not have originated from the SS, since the SS has a different species composition. However, these findings do not necessarily exclude each other. The rare morphotype could still be from the SS, but started proliferating once it met its optimal growth circumstances at the NERR. Perhaps this rare morphotype could be the cause for the exceptional inundation events in the Caribbean.

Amaral-Zettler et al. (2017) confirm that this morphotype is not new to the NERR, but just never encountered the ideal circumstances to proliferate. Depending on the species, pelagic Sargassum can have a doubling time of 9-13 days [6,8]. Primary production in *Sargassum natans* is dependent on nutrients, salinity, irradiance, and temperature [6,20,55]. These factors were overall enhanced in the NERR in 2009-2010 prior to the start of Sargassum inundations in 2011. SST was anomalously high in the NERR in 2010, with the highest anomaly value of a 0.9 °C increase since 1980 [26]. This might be correlated with the highest positive Atlantic Multi-decadal Oscillation (AMO) and most negative NAO measured from 1950 to 2016, which are discussed in the next chapter [26]. The combination of these factors could have aided in the proliferation of *Sargassum natans VIII*.

Hence, due to the readily available nutrients from equatorial upwelling and the Amazon River plume, the Sargassum was supposedly no longer limited in its growth. However, supporting data for this is lacking. So far, research on the different morphotypes and their growth response is absent in literature.

Amaral-Zettler et al. (2017) has pressed the importance of the different morphological characteristics of the morphotypes. Characteristics such as leaf structure, branching, air bladders, thorns and lanceolata length could all have an influence on its growth, buoyancy and reproductive success [4]. Unfortunately, not much is studied on this topic yet. Characteristics measured for biogas production, that have been studied so far, show no exceptional differences between the morphotypes [53]. On the other hand, Schell et al. (2015) and Martin et al., 2016 have observed lower species richness on the *Sargassum natans VIII* type, compared to the other common morphotypes. As a consequence, the rare morphotype may have a longer life spam. As their life spam mostly depends on the weight of organisms that attach to the Sargassum patch. Sargassum normally floats due to their gas filled bladders called pneumatocysts [14]. When the Sargassum becomes too heavy due to attachment of sessile epibionts plankton or other meiofaunal organisms, the patch eventually sinks [14,57]. This normally occurs after a year or so [15], but with *Sargassum natans VIII* this might take longer.

6. Anthropogenic origin or natural cause?

Anthropogenic induced climate change has been the cause for many environmental changes in ocean properties [58]. The increase in greenhouse gasses has resulted in global warming and resulting ocean warming and increases of SST [58]. In turn, the SST increase affects ocean convection through increased stratification of the surface ocean and is also associated with increased salinity in the subtropical gyre [58]. Sargassum's optimum growth temperature has not been well documented yet [26]. Increased temperatures increases growth in some species of Sargassum and this might have triggered large Sargassum blooms in the NERR and Caribbean [59]. *Sargassum natans* has a broad growth temperature between 18-30 ˚C, but the optimum temperature might also be dependent on nutrient availability [26,59]. Growth response to environmental factors in the different Sargassum morphotypes has gotten little attention thus far. Compared to benthic Sargassum species pelagic Sargassum has a low salinity range of 36-42 ppt [59]. On the other hand, pelagic Sargassum thrives under high light saturation values of 200-300 (µmol m-2 s-1) compared to benthic Sargassum [59]. However, details on *Sargassum natans VIII* are still lacking in the available literature. The increase in SST due to climate change might have aided Sargassum to reach its optimum growth circumstances. In order to justify these hypotheses, the growth response of pelagic Sargassum should be researched in depth. In particular the dominant proliferating morphotype *Sargassum natans VIII,* which thus far has been studied poorly.

Besides anthropogenic induced climate change, natural climate indices are said to play a key role as well on the ocean-atmosphere variability in the tropical Atlantic [26]. The combination of the two might have supplied the right environmental circumstances for Sargassum to bloom in 2011. Important climate indices related to the Atlantic Ocean dynamics and possibly the Sargassum growth are the AMO and NAO [26]. The AMO is based on the SST being lower or higher than normal in the North Atlantic Ocean [20,26]. Warm or cold AMO periods usually take about 65-80 years [20]. There was a warm period from the 1930s – 1950s and the current warming period has started in the 1990s till present [20]. On top of the warm AMO period, the global warming SST has increased with 1 ˚C since the last warm AMO period [14]. In addition, the warm AMO period has also significantly increased precipitation since 1990 [14].

Perhaps, the combining effects of global warming and the warm AMO resulted in anomalous high SST in 2010 for Sargassum to proliferate in 2011. In addition to the warm AMO, there was an extreme negative NAO in 2010 [26]. NAOs respond to multi-decadal but also seasonal time scales [20]. This resulted in weaker trade winds and even warmer SST in the tropical Atlantic [26,45]. Weaker trade winds may support a better environment for Sargassum to grow due to little currents [14].

Notwithstanding, negative NAO occurrences do not match with occurrences of Sargassum blooms in the Caribbean. Johns et al. (2020) states that southward-shifted westerlies during a highly negative NAO are the reason for Sargassum beaching in the Caribbean in 2011. These extreme negative NAOs and strong westerlies happened in December 2009, December 2010 and March 2013 and resulted in a large Caribbean bloom about a year later in 2011, 2012 and 2014 [11]. While the data extends till 2016, there were no further negative NAOs observed even though there was a very large Sargassum beaching in 2015 [38]. Djakouré et al. (2017) also acknowledges that these climate anomalies cannot directly explain Sargassum blooms in the Caribbean. However, these findings do not rule out that the combination of anomalous climate indices and global warming was the initial cause for the Sargassum inundations in the Caribbean in 2011.

7. Discussion & Conclusion

Massive Sargassum beaching has become a reoccurring problem in the Caribbean and other parts of the Atlantic [1]. It is of great importance to study the origin of these blooms and beaching events in order to find a possible solution to the problem and predict future inundation events. This study has researched the probability of several hypotheses on the origin of golden tides in the CS. Plausible hypotheses propose the Amazon River and hurricane season as a new nutrient source fueling Sargassum blooms [14]. Others think that windage from extreme westerlies supposedly dragged the Sargassum out of the SS and into the Caribbean [11,18]. Also, global warming and natural climate indices may have caused anomalous environmental conditions, optimal for Sargassum proliferation [16,20]. In addition, a different genetic variety could have been well suited to these anomalous environmental changes [2,5].

So far, it is established that the current pelagic Sargassum blooms originate from the North Atlantic Equatorial Recirculation Region (NERR), entering the CS via several pathways [18]. Via the NBC to the NBCR and the NEC into the CS, via the NBC rings or via the NBC and the Guiana Current into the CS [18]. Pelagic Sargassum is able to return and proliferate every year due to the recirculation of the NERR from the NBCR to the NECC, CG and eventually the South Equatorial Current going back to the NBC and into the CS via the several pathways [18]. Sargassum has a high growth rate under optimal environmental circumstances and reproduces easily via fragmentation [10]. In addition, the *Sargassum natans VIII* morphotype might have different characteristics, enhancing its proliferation and survival. Small patches may stay afloat and proliferate the next year when returning to the NBC via the South Equatorial Current.

The reoccurring Sargassum blooms in the Caribbean in 2011 were likely initiated in the NERR itself. Pelagic Sargassum was already present in the NERR prior to 2011 [54]. Due to the high growth rates of Sargassum and the optimal environmental circumstances in the NERR, small patches of Sargassum are able to proliferate into large blooms very quickly [5,6,8,16,20].. Depending on the species, pelagic Sargassum can have a doubling time of 9-13 days [6,8]. Thus, it is plausible that already present Sargassum patches in the NERR were responsible for the onset of the massive Sargassum blooms in the Caribbean.

Anomalous climatic events have possibly aided in this event. In 2010 there was an extreme warm AMO and negative NAO [26]. In concordance to the ongoing global warming, these climatic events resulted in increased sea surface temperatures [26]. In 2011 there was an extreme Amazon river flooding, which possibly supported the needed nutrients for a large sargassum bloom[14]. Most importantly, the dominant morphotype *Sargassum natans VIII*, causing these Sargassum blooms, is likely well adapted to these anomalous environmental circumstances. Schell et al. (2015) and Martin et al., 2016 have observed lower species richness on the *Sargassum natans VIII* type, compared to the other morphotypes. As a consequence, the rare morphotype may have a longer life spam, because Sargassum sinks with age due to increased weight from epibionts [27,48]. Perhaps this morphotype contains more beneficial characteristics, which has aided its growth in its initial bloom in 2011 and its reoccurring years. All these combining factors could have easily resulted in the excessive Sargassum growth in the NERR in 2011.

This study has researched what could have been the tipping point in 2011, that caused the almost yearly reoccurring Sargassum inundations on the Caribbean beaches.
In conclusion, the tipping point for the initiation of massive Sargassum beaching in the Caribbean in 2011 is likely due to a combination of anomalous environmental circumstances and does not correspond with one single hypothesis. The cooccurrence of extreme warm climate indices and global warming generated warm sea surface temperatures, calmer waters and enough nutrients for Sargassum to proliferate in the NERR in 2011. The different characteristics of the *Sargassum natans VIII* morphotype might play a key role in the ability to form large blooms under these anomalous circumstances. Therefore, it is suggested that growth responses of Sargassum morphotypes and optimum growth factors should be studied extensively in order to better understand the reoccurring phenomenon.

8. References

1. Langin K. Seaweed masses assault Caribbean islands. *Science (80-)*. 2018;360(6394):1157-1158. doi:10.1126/science.360.6394.1157

2. Doyle E, Franks J. Fact sheet pelagic Sargasssum influx in the wider Caribbean. *Gulf Caribb Fish Inst*. Published online 2015:1-4. Accessed January 8, 2021. http://www.usm.edu/gcrl/sargassum/sargassum.observation.form.php.

3. Arellano-Verdejo J, Lazcano-Hernandez HE, Cabanillas-Terán N. ERISNet: Deep neural network for sargassum detection along the coastline of the mexican caribbean. *PeerJ*. 2019;2019(5):e6842. doi:10.7717/peerj.6842

4. Milledge JJ, Harvey PJ. Golden Tides: Problem or golden opportunity? The valorisation of Sargassum from beach inundations. *J Mar Sci Eng*. 2016;4(3). doi:10.3390/jmse4030060

5. Amaral-Zettler LA, Dragone NB, Schell J, et al. Comparative mitochondrial and chloroplast genomics of a genetically distinct form of Sargassum contributing to recent “Golden Tides” in the Western Atlantic. *Ecol Evol*. 2017;7(2):516-525. doi:10.1002/ece3.2630

6. Brooks MT, Coles VJ, Hood RR, Gower JFR. Factors controlling the seasonal distribution of pelagic Sargassum. *Mar Ecol Prog Ser*. 2018;599:1-18. doi:10.3354/meps12646

7. Franks JS, Johnson DR, Ko DS. Pelagic Sargassum in the Tropical North Atlantic. *Gulf Caribb Res*. 2016;27(1):6-11. doi:10.18785/gcr.2701.08

8. Thompson TM, Young BR, Baroutian S. Pelagic Sargassum for energy and fertiliser production in the Caribbean: A case study on Barbados. *Renew Sustain Energy Rev*. 2020;118:109564. doi:10.1016/j.rser.2019.109564

9. Hanelin D. *Sailing the Sargasso Sea for a Floating Golden Forest: The Application of Genetic Markers to Investigating Sargassum Diversity and Distribution in the Field*.; 2019. Accessed January 18, 2021. https://ida.mtholyoke.edu/handle/10166/5716

10. Lapointe BE, West LE, Sutton TT, Hu C. Ryther revisited: Nutrient excretions by fishes enhance productivity of pelagic Sargassum in the western North Atlantic Ocean. *J Exp Mar Bio Ecol*. 2014;458:46-56. doi:10.1016/j.jembe.2014.05.002

11. Johns EM, Lumpkin R, Putman NF, et al. The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event. *Prog Oceanogr*. 2020;182:102269. doi:10.1016/j.pocean.2020.102269

12. Schell JM, Goodwin DS, Siuda ANS. Recent sargassum inundation events in the caribbean: Shipboard observations reveal dominance of a previously rare form. *Oceanography*. 2015;28(3):8-10. doi:10.5670/oceanog.2015.70

13. Huffard CL, von Thun S, Sherman AD, Sealey K, Smith KL. Pelagic Sargassum community change over a 40-year period: temporal and spatial variability. *Mar Biol*. 2014;161(12):2735-2751. doi:10.1007/s00227-014-2539-y

14. Oviatt CA, Huizenga K, Rogers CS, Miller WJ. What nutrient sources support anomalous growth and the recent sargassum mass stranding on Caribbean beaches? A review. *Mar Pollut Bull*. 2019;145:517-525. doi:10.1016/j.marpolbul.2019.06.049

15. Salter MA, Rodríguez-Martínez RE, Álvarez-Filip L, Jordán-Dahlgren E, Perry CT. Pelagic Sargassum as an emerging vector of high rate carbonate sediment import to tropical Atlantic

coastlines. *Glob Planet Change*. 2020;195:103332. doi:10.1016/j.gloplacha.2020.103332

16. Louime C, Fortune J, Gervais G. *Sargassum* Invasion of Coastal Environments: A Growing Concern. *Am J Environ Sci*. 2017;13(1):58-64. doi:10.3844/ajessp.2017.58.64

17. Gower J, Young E, King S. Satellite images suggest a new Sargassum source region in 2011. *Remote Sens Lett*. 2013;4(8):764-773. doi:10.1080/2150704X.2013.796433

18. Putman NF, Goni GJ, Gramer LJ, et al. Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Prog Oceanogr*. 2018;165:205-214. doi:10.1016/j.pocean.2018.06.009

19. Webster RKTL. Development and implementation of Sargassum Early Advisory System (SEAS). *Shore & Beach*. 2013;81(3):1-6. http://seas-forecast.com/Pages/stories article/Papers/Development_Implementation_of_SEAS.pdf

20. Sanchez-Rubio G, Perry H, Franks JS, Johnson DR. Occurrence of pelagic Sargassum in waters of the U.S. Gulf of Mexico in response to weather-related hydrographic regimes associated with decadal and interannual variability in global climate. *Fish Bull*. 2018;116(1):93-106. doi:10.7755/FB.116.1.10

21. Fonseca CA, Goni GJ, Johns WE, Campos EJD. Investigation of the North Brazil Current retroflection and North Equatorial Countercurrent variability. *Geophys Res Lett*. 2004;31(21):n/a-n/a. doi:10.1029/2004GL020054

22. Byrne MP, Pendergrass AG, Rapp AD, Wodzicki KR. Response of the Intertropical Convergence Zone to Climate Change: Location, Width, and Strength. *Curr Clim Chang Reports*. 2018;4(4):355-370. doi:10.1007/s40641-018-0110-5

23. Lumpkin R, Garzoli SL. Near-surface circulation in the Tropical Atlantic Ocean. *Deep Res Part I Oceanogr Res Pap*. 2005;52(3):495-518. doi:10.1016/j.dsr.2004.09.001

24. Mendez-Tejeda R, Rosado, Jiménez GA. Influence of climatic factors on Sargassum arrivals to the coasts of the Dominican Republic. *J Oceanogr Mar Sci*. 2019;10(2):22-32. doi:10.5897/joms2019.0156

25. Gower J, King S. Satellite Images Show the Movement of Floating Sargassum in the Gulf of Mexico and Atlantic Ocean. *Nat Preced*. 2008;(April 2008):1-13. doi:10.1038/npre.2008.1894.1

26. Djakouré S, Araujo M, Hounsou-Gbo A, Noriega C, Bourlès B. On the potential causes of the recent Pelagic Sargassum blooms events in the tropical North Atlantic Ocean. *Biogeosciences Discuss*. Published online 2017:1-20. doi:10.5194/bg-2017-346

27. Gower J, King SA. Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic ocean mapped using MERIS. *Int J Remote Sens*. 2011;32(7):1917-1929. doi:10.1080/01431161003639660

28. Marengo JA, Espinoza JC. Review Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. *Int J Climatol Int J Clim*. 2016;36:1033-1050. doi:10.1002/joc.4420

29. Schneider T, Bischoff T, Haug GH. Migrations and dynamics of the intertropical convergence zone. *Nature*. 2014;513(7516):45-53. doi:10.1038/nature13636

30. Wang M, Hu C. Predicting Sargassum blooms in the Caribbean Sea from MODIS observations. *Geophys Res Lett*. 2017;44(7):3265-3273. doi:10.1002/2017GL072932

31. Chen JL, Wilson CR, Tapley BD. The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE. *Water Resour Res*. 2010;46(12). doi:10.1029/2010WR009383

32. Bump DO. Hurricane Charley. *Lippincotts Case Manag*. 2006;11(3):185-187. doi:10.1097/00129234-200605000-00013

33. Pasch RJ, Blake ES, Cobb HD, Roberts DP. Tropical Cyclone Report: Hurricane Wilma. *Natl Hurric Center-USA*. 2014;1(October 2005):27.

34. Rudorff CM, Melack JM, Bates PD. Flooding dynamics on the lower Amazon floodplain: 2. Seasonal and interannual hydrological variability. *Water Resour Res*. 2014;50(1):635-649. doi:10.1002/2013WR014714

35. Lau WKM, Kim K-M. How nature foiled the 2006 hurricane forecasts. *Eos, Trans Am Geophys Union*. 2007;88(9):105-107. doi:10.1029/2007EO090002

36. Franklin JL. Tropical Cyclone Report: Hurricane Dean (2007). *Natl Hurric Cent*. 2008;(August 2007):13-23.

37. Maciel, J. S. C., Simões Alves, L. G., Dos Santos Corrêa, B. G., Rodrigues De Carvalho, I. M., & Oliveira MA. Flood forecast in Manaus, Amazonas, Brazil. In: *Urban Water Systems & Floods III*. Vol 1. WIT Press; 2020:63-72. doi:10.2495/friar200061

38. Wang M, Hu C, Barnes BB, Mitchum G, Lapointe B, Montoya JP. The great Atlantic Sargassum belt. *Science (80-)*. 2019;364(6448):83-87. doi:10.1126/science.aaw7912

39. Marx UC, Roles J, Hankamer B. Sargassum blooms in the Atlantic Ocean – From a burden to an asset. *Algal Res*. 2021;54:102188. doi:10.1016/j.algal.2021.102188

40. Pasch RJ, Kimberlain TB. 2010-Hurricane Igor. 2011;(September 2010):8-21.

41. Ginzburg E, Zakrison TL, Pust GD, et al. Hurricane Irma. *J Trauma Acute Care Surg*. 2018;85(3):635-636. doi:10.1097/ta.0000000000002006

42. Castellanos B, Laraque A. The extraordinary flood of the Orinoco River in 2018. 2019;(September):1-4.

43. Klotzbach PJ, Schreck CJ, Collins JM, Bell MM, Blake ES, Roache D. The extremely active 2017 North Atlantic hurricane season. *Mon Weather Rev*. 2018;146(10):3425-3443. doi:10.1175/MWR-D-18-0078.1

44. Allshouse MR, Ivey G, Lowe R, et al. Article in Environmental Fluid Mechanics. Published online 2017. doi:10.1007/s10652-016-9499-3

45. Önskog T, Franzke CLE, Hannachi A. Predictability and non-Gaussian characteristics of the North Atlantic Oscillation. *J Clim*. 2018;31(2):537-554. doi:10.1175/JCLI-D-17-0101.1

46. Wanner H, Brönnimann S, Casty C, et al. North Atlantic oscillation - Concepts and studies. *Surv Geophys*. 2001;22(4):321-381. doi:10.1023/A:1014217317898

47. Kwon K, Choi BJ, Kim KY, Kim K. Tracing the trajectory of pelagic sargassum using satellite monitoring and lagrangian transport simulations in the East China Sea and Yellow Sea. *Algae*. 2019;34(4):315-326. doi:10.4490/algae.2019.34.12.11

48. Woodcock AH. Winds subsurface pelagic Sargassum and Langmuir circulations. *J Exp Mar Bio Ecol*. 1993;170(1):117-125. doi:10.1016/0022-0981(93)90132-8

49. Putman NF, Lumpkin R, Olascoaga MJ, Trinanes J, Goni GJ. Improving transport predictions of pelagic Sargassum. *J Exp Mar Bio Ecol*. 2020;529:151398. doi:10.1016/j.jembe.2020.151398

50. Berline L, Ody A, Jouanno J, et al. Hindcasting the 2017 dispersal of Sargassum algae in the Tropical North Atlantic. *Mar Pollut Bull*. 2020;158:111431. doi:10.1016/j.marpolbul.2020.111431

51. van Tussenbroek BI, Hernández Arana HA, Rodríguez-Martínez RE, et al. Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. *Mar Pollut Bull*. 2017;122(1-2):272-281. doi:10.1016/j.marpolbul.2017.06.057

52. Pereira JM, Paiva VH, Ceia FR, Ramos JA. Facing extremes: Cory's shearwaters adjust their foraging behaviour differently in response to contrasting phases of North Atlantic Oscillation. *Reg Environ Chang*. 2020;20(3):1-13. doi:10.1007/s10113-020-01662-1

53. Milledge JJ, Maneein S, López EA, Bartlett D. Sargassum inundations in Turks and Caicos: Methane potential and proximate, ultimate, lipid, amino acid, metal and metalloid analyses. *Energies*. 2020;13(6). doi:10.3390/en13061523

54. de Széchy MTM, Guedes PM, Baeta-Neves MH, Oliveira EN. Verification of Sargassum natans (Linnaeus) Gaillon (Heterokontophyta: Phaeophyceae) from the Sargasso Sea off the coast of Brazil, western Atlantic Ocean. *Check List*. 2012;8(4):638-641. doi:10.15560/8.4.638

55. Jouanno J, Benshila R, Berline L, et al. A NEMO-based model of *Sargassum* distribution in the Tropical Atlantic: description of the model and sensitivity analysis (NEMO-Sarg1.0). *Geosci Model Dev Discuss*. Published online 2020:1-30. doi:10.5194/gmd-2020-383

56. Martin LM, Schell JM, Goodwin DS, Biggs DC, Siuda ANS. Sargassum and its associated fauna in the Gulf of Mexico , Caribbean , Sargasso Sea. 2016;(February):0-1.

57. Witherington B, Hirama S, Hardy R. Young sea turtles of the pelagic Sargassum-dominated drift community: Habitat use, population density, and threats. *Mar Ecol Prog Ser*. 2012;463:1-22. doi:10.3354/meps09970

58. Alexander MA, Shin SI, Scott JD, Curchitser E, Stock C. The response of the Northwest Atlantic Ocean to climate change. *J Clim*. 2020;33(2):405-428. doi:10.1175/JCLI-D-19-0117.1

59. Redmond S, Kim JK, Yarish C. Sargassum culture in the U . S . Published online 2014.