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SHORT COMMUNICATION

PELAGIC *SARGASSUM* IN THE TROPICAL NORTH ATLANTIC

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INTRODUCTION

Pelagic *Sargassum*, a complex of two co—occurring species of floating marine brown macroalgae (*Sargassum natans, Sargassum fluitans*; Class Phaeophyceae), is commonly found in surface waters of the Sargasso Sea and the northwestern Gulf of Mexico (GOM) (Lapointe 1995, Gower and King 2008), areas where ocean eddies tend to retain and consolidate deployed surface drifters. Winds and ocean currents aggregate the *Sargassum* into large neustonic rafts tens of meters wide (Marmorino et al. 2011) and weed lines (windrows) that extend across the ocean surface for tens of kilometers (Butler et al. 1983, Hu et al. 2105, Hu et al. 2016). These *Sargassum* features provide habitat for a large and diverse assemblage of marine organisms (Coston—Clements et al. 1991, Wells and Rooker 2004, Hoffmayer et al. 2005, Hallett, 2011, Huffard et al. 2014) but may also raft invasive species.

Beginning in boreal spring and summer of 2011, massive quantities of pelagic *Sargassum* have intermittently washed ashore along the coastlines of eastern Caribbean islands and West Africa (Franks et al. 2011; Supplemental Figure S1A—F). Pelagic *Sargassum* was also spotted by aircraft offshore of northeastern Brazil where not previously observed (de Széchy et al. 2012). The quantity and the frequency of occurrence of pelagic *Sargassum* in the beach stranding events created immediate problems for fishery and tourism industries of nations on both sides of the tropical Atlantic, and ecological impacts remain largely unknown.

Pelagic *Sargassum* that appeared in the eastern Caribbean events was first suspected to come from the Sargasso Sea (Webster and Linton 2013) and later thought to originate off northeastern Brazil (Gower et al. 2013). However, when the first massive incursions in 2011 were reported online to the Gulf and Caribbean Fisheries Institute (gcfinet@listserv.gcfi.org), it became clear that this was a broad scaled, complex event. A web site was established for documenting locations and dates of mass strandings (gcrl.usm.edu/sargassum).

Following the 2011 strandings, extensive pelagic *Sargassum* lines were observed far offshore by color satellite (Gower et al. 2013), and beach strandings were documented over a broad area of the tropical North Atlantic, including west Africa from Sierra Leone to the Gulf of Guinea (Oyesiku and Egunyomi 2014) and South America from northeast Brazil to the Caribbean (Gower et al. 2013, Smetacek and Zingone 2013). Although pelagic *Sargassum* was previously reported in the tropical North Atlantic (Taylor 1960), it had never been observed in such large quantities as occurred in 2011 (Franks et al. 2011). Since there were no documented reports of pelagic *Sargassum* being transported in large quantities on currents from the North Atlantic Gyre into the tropical Atlantic, and lacking evidence to the contrary from either *in situ* observations or satellite imagery, indications were strong that the *Sargassum* bloomed (Schell et al. 2015) in an area we identified as the North Equatorial Recirculation Region (NERR, Franks et al. 2011; Figure 1). The NERR is substantially larger than could be expected to produce *Sargassum* blooms via coastal eutrophication (Smetacek and Zingone 2013). Our previous work to determine the source of the pelagic *Sargassum* that stranded in the eastern Caribbean demonstrated that it most likely passed through the Guiana Current/North Brazilian Current system (Franks et al. 2011; see Supplemental Figure S2A). This low—latitude limb of the North Atlantic western boundary current originates in equatorial currents (Johns et al. 2002).

The nature of its origin and reasons for its unusual bloom in recent years will require knowledge of pelagic *Sargassum* growth rates in the NERR, genetic associations and understanding of climate changes in tropical ecosystems (including equatorial ocean dynamics) which would enable a massive broad—scale bloom and regional consolidations to occur. Historical tropical Atlantic circulation patterns (Philander 2001) suggest that pelagic *Sargassum* in the NERR can be retained during summer months (July—September) when the North Equatorial Counter Current (NECC; Supplemental Figure S2A) is established. From January through May, however, the NECC breaks down and surface flow is westward (Supplemental Figure S2B) in the western tropical Atlantic. Our long term interest is in the balance between growth of pelagic *Sargassum* mats within the NERR and export from the NERR. In this short communication we isolate and address the issues of historical recirculation/consolidation dynamics in the NERR and transport pathways as a first step

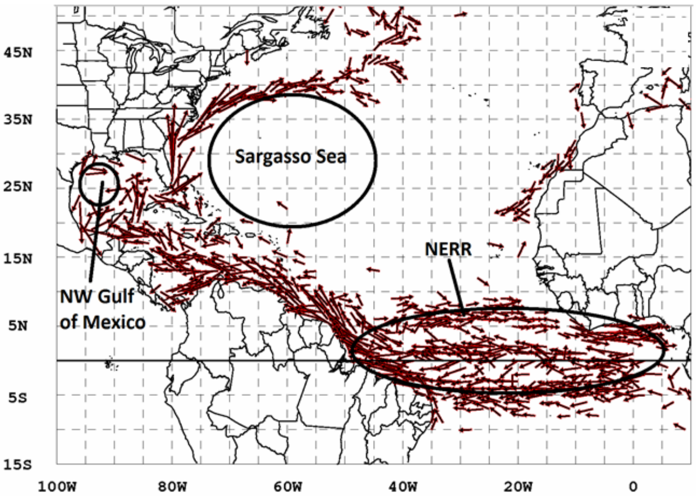


FIGURE 1. *Locations of pelagic Sargassum. Two regions where pelagic Sargassum is commonly found in abundance (northwest Gulf of Mexico and the Sargasso Sea) and a new area, the North Equatorial Recirculation Region (NERR), proposed in Franks et al. (2011). Current vectors are calculated from mixed layer satellite tracked drifters and plotted where the current speed averaged ≥ 0.25 m/s between June-September. This limit shows persistent currents, important for long distance transport, connecting the NERR with the northwest Gulf of Mexico and Sargasso Sea, but little connection from the Sargasso Sea back to the NERR.*

in understanding the timing of the bloom and the coastal incursion.

Materials and Methods

Model

In the present study, movements of pelagic *Sargassum* were backtracked for a period of one year from reported stranding sites in the eastern Caribbean, Brazil and West Africa (Supplemental Table S1) to possible source regions using archived surface currents from the global Hybrid Coordinate Ocean Model (HYCOM; Bleck 2002). The model has 1/12° longitude/latitude resolution and complete coverage of the tropical Atlantic domain of interest. The model uses hybrid vertical coordinates consisting of sigma—coordinates in the upper layer and z—coordinates in the lower layer. Surface boundary conditions (wind stress, heat flux, and salt flux) are supplied by the Navy Operational Global Atmospheric Prediction System (NOGAPS), and climatological river input is included for major rivers. In addition, data assimilation of satellite derived sea surface height and sea surface temperature through the Navy Coupled Ocean Data Assimilation (NCODA) system tends to phase lock the model into real events.

Reverse—time trajectory tracking is a simple process done with a field of finite—difference modeled currents by calculating successive positions of a parcel of water over small time increments: $\delta x(t+\delta t) = U(x+\delta x/2,\ t+\delta t/2)\ \delta t$, where x and t are the initial position and time, U is the current vector located midway in space and time, dt is the time step and dx is the distance traced by the parcel during the time step. The equation for dx was solved explicitly by iteration, and Akima cubic spline (Akima 1970) was used to interpolate gridded model currents to the time and location. The time step was set to 15 min. To accommodate the effects of sub—grid scale motion, 5 parcels were released at each position with a Gaussian (mean of zero, standard deviation of one) addition of 1 km/d to the current vector and center—of—mass averaged for a new position. The process was continued for 365 days from locations of pelagic *Sargassum* stranding events in 2011.

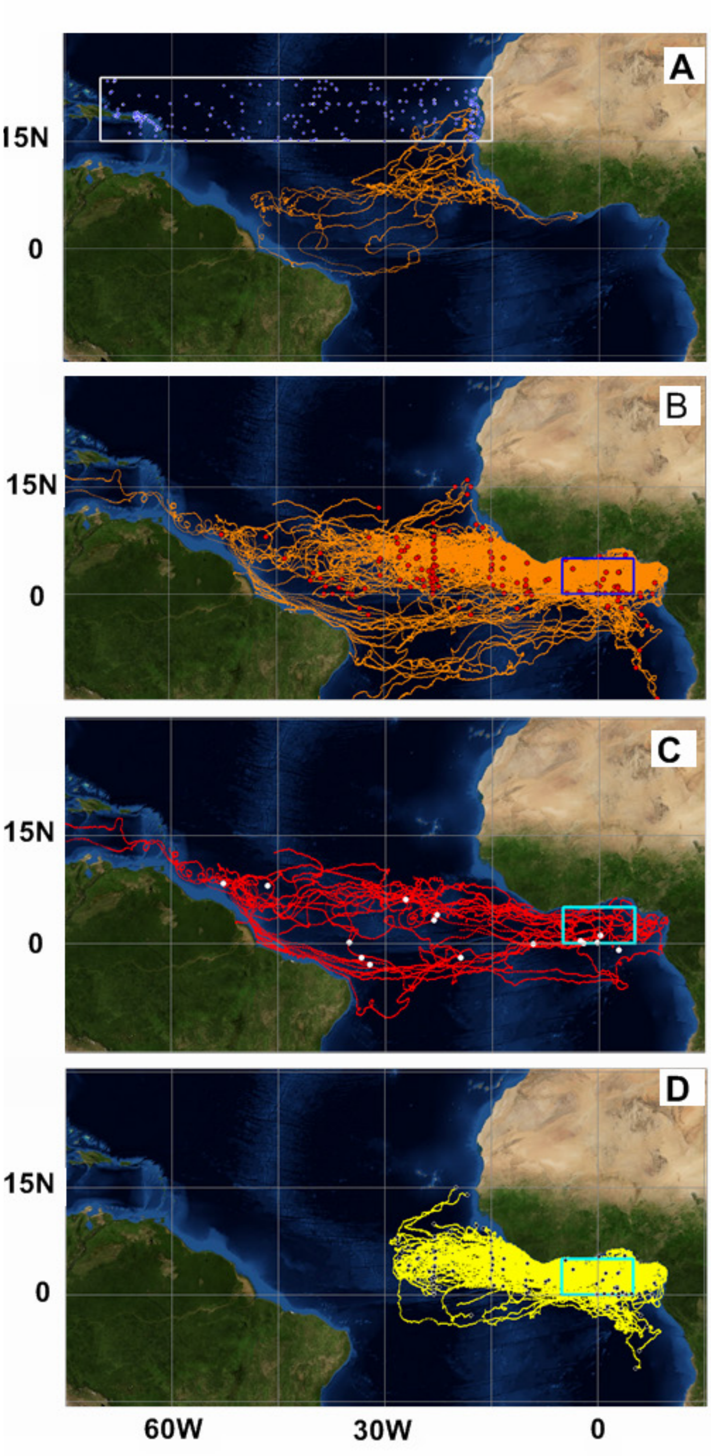
Drifting Buoys

In order to isolate transport pathways that can demonstrate recirculation and consolidation in the NERR together with reported stranding's on both sides of the Atlantic, designed experiments were conducted using selected drifting buoys. Satellite tracked drifting buoys have been deployed globally as part of the World Ocean Circulation Experiment, with records starting in 1979 and archived at NOAA'S Atlantic Oceanographic and Meteorological Office (http://www.aoml.noaa.gov/phod/dac/index.php). Buoys are drogued to reduce wind slippage and hence are reasonable simulators of surface drifting pelagic *Sargassum*. Buoy tracks are interpolated to 6 hourly positions, with currents calculated from successive positions. The data are quality controlled, archived and made available for general use (Lumpkin and Pazos 2007). In order to simulate transport pathways of the surface drifting *Sargassum* both into and within the NERR, boxes were created at strategic locations and the pathways of satellite tracked buoys which passed through the boxes were studied.

Results and Discussion

Backtracking pelagic *Sargassum* movements from stranding sites lead to the equatorial region (Supplemental Figure S3). Prior to the incursion into the eastern Caribbean, consolidation of the *Sargassum* off NE Brazil is apparent from the density of tracks in the model run and in local cycling of a validation buoy. The West Africa strandings were also traced, first to the interior of the NERR and then to the equatorial region where the tracks joined the eastern Caribbean tracks. To check these findings, back traces calculated for a few strandings that occurred in early 2014 (Supplemental Figure S4) in the eastern Caribbean confirmed the connection with the equatorial region.

Transport connections between the Sargasso Sea/North Atlantic and the NERR (Figure 1) are a major issue for deciphering if the *Sargassum* incursions into the Tropical Atlantic arrived *en masse* or bloomed in the area from seedings. This issue can be addressed using historical drifting buoys. A virtual box (Figure 2A) was created across the Atlantic from 13.9°N to 16°N, where *Sargassum* from the Sargasso Sea would have to cross to reach the NERR (≤ 7.5°N latitude). Buoy identification numbers were obtained for all drifting buoys deployed within the box (regardless of year or season) and only those buoy tracks which led into the NERR were plotted (Figure 2A, orange lines). Our results show the only historical connection between the North Atlantic surface gyre and the NERR is along an intermittent, narrow coastal current off West Africa. Of the 305 buoys that were deployed in the 13.9°N to 16°N area (1992–2014), only 6 (~2%) entered the eastern NERR via this coastal current where they cycled for an average of 18 months until they died or grounded. None of the buoys lived long enough to enter the NERR along the African boundary and subsequently reach the eastern Antilles. This exercise demonstrates that historical transport pathways show limited connection between the NERR and the Subtropical North Atlantic, and that drifter retention in the eastern NERR for periods longer than a year is possible.



A second buoy experiment was conducted in order to address surface circulation and resulting *Sargassum* distribution throughout the NERR along with connections among areas of retention/consolidation within the NERR where *Sargassum* growth could occur. This was done with another virtual box experiment in the Gulf of Guinea (Figure 2B). The tracks of all buoys (170 total) that passed through this box showed 2 patterns of particular interest. One path connects the Gulf of Guinea with the recycling area in the eastern NERR found in the above experiment. After spending considerable time in the eastern NERR, many of these buoys grounded along the African coast from Sierra Leone to the Gulf of Guinea. The second path went westward in the South Equatorial Current (SEC; Supplemental Figure S2B) to the coast of northeast Brazil and then into either the Caribbean, or back to the eastern NERR via the NECC during boreal summer. In both pathways, the dominant transport pattern is clockwise.

In order to isolate the 2 patterns and determine potential consolidation areas, buoys that went through the Gulf of Guinea virtual box were further separated into those that also drifted west of 45°W (Figure 2C, red lines) and those that remained east of 30°W (Figure 2D, yellow lines). Fifteen of the buoys were entrained in the SEC in January/February, arriving along the coast of northeast Brazil in the North Brazil Current (NBC) the following boreal spring (Figure 2C). Some of these grounded along the coast of northeast Brazil, some entered the Caribbean and some returned eastward in the North Brazil Current Retroflection (NBCR), crossing the entire Atlantic to the Gulf of Guinea. A total of 111 other buoys cycled between the Gulf of Guinea and the eastern NERR (Figure 2D), many eventually

FIGURE 2. *(A) Experiment using satellite tracked mixed-layer drifting buoys to determine level of connection between the North Equatorial Recirculation Region (NERR) and the North Atlantic gyre (and the Sargasso Sea). Blue dots are locations of first-calculated currents (near deployment location). Only 6 of the 305 buoys entered the NERR in a narrow band along the coast of Africa. Orange dots indicate tracks of these 6 buoys. B. Experiment using satellite tracked mixed-layer drifting buoys to determine potential pelagic Sargassum consolidation areas and area connections. Identification numbers of all drifting buoys that passed through the virtual blue box in the Gulf of Guinea were obtained and the entire track of these buoys plotted from locations of first-calculated currents (red dots) to last report. C. Separation of all drifting buoys from the above experiment (Figure 2B) that passed through the Gulf of Guinea virtual box and also passed west of 45°W. White dots are locations of first-calculated currents. This demonstrates entrainment (in January and February) into the South Equatorial Current in the Gulf of Guinea and westward transport to the northeast coast of Brazil. D. Separation of all drifting buoys from the above experiment (Figure 2B) that passed through the Gulf of Guinea virtual box, but remained east of 30°W. Black dots are locations of first-calculated currents.*

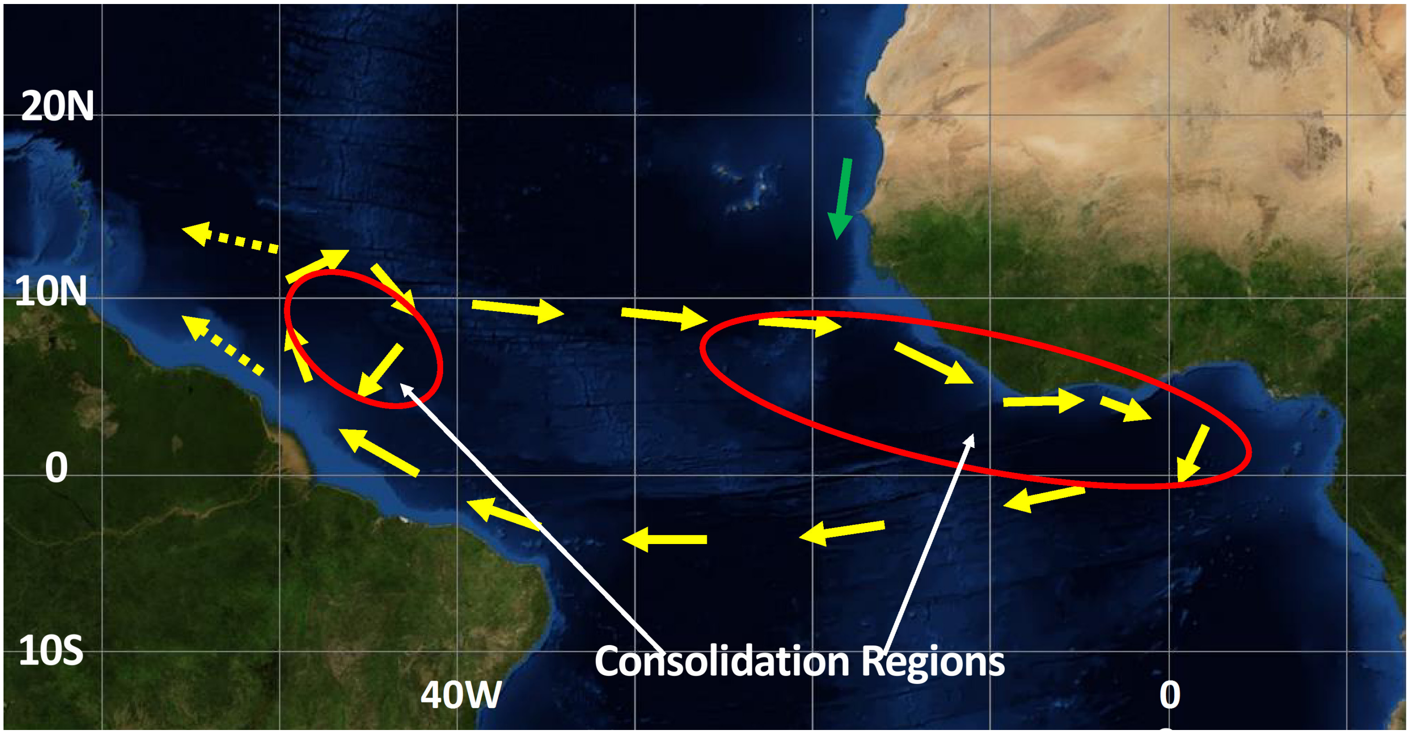


FIGURE 3. *Schematic of proposed pelagic Sargassum transport pathways in the North Equatorial Recirculation Region (NERR). From the drifting buoy experiments, there are 2 buoy consolidation regions: in the eastern NERR (large red ellipse) which includes the Gulf of Guinea and in the western NERR (small red ellipse) which includes the North Brazil Current Retroflection (NBCR). The 2 areas are connected by the South Equatorial Current (SEC) and the North Equatorial Counter Current (NECC) (yellow arrows). Buoy transports to the Caribbean occur in spring/summer through the North Brazil Current/ Guiana Current (NBC/GC) and NBCR rings, and in the winter through the North Equatorial Current (NEC). Connections to the subtropical North Atlantic are weak with an intermittent flow to the NERR by a coastal current along West Africa (green arrow).*

grounding along the coast of Africa. Other buoys (Figure 2B) were spread between the eastern NERR and the coast of northeast Brazil. These latter buoys are in position for winter transport to the eastern Caribbean when the NECC breaks down and the transport is predominantly westward throughout the North Tropical Atlantic. Within the NERR, consolidation areas where the buoys cycle for extensive periods were apparent.

A summary of the isolated circulation patterns is schematically presented in Figure 3. From the drifter experiments, there appear to be 2 consolidation regions within the NERR; one on the eastern side of the tropical Atlantic, associated with the Gulf of Guinea but broadly extending westward into the central NERR, and one on the western side associated with the NBCR. The large path conforms to climatological summer clockwise circulation around the NERR where flow is westward along the equator in the SEC, turning northwest along the northeast coast of South America and returning to the Gulf of Guinea via the NECC.

Timing associated with the schematic pattern can be summarized as follows: during January—February, entrainment occurs from the Gulf of Guinea into the SEC where drifters travel westward and ground off northeast Brazil in the early spring. In the following months, buoy groundings take place progressively further north along the northeast coast of South America until late spring/early summer when most drifters continue along the coast until they reach the southern Lesser Antilles.

It is worth pointing out that discharge from the Amazon River reaches its peak in June/July (Filizola and Guyot 2004), pushing drifters further off the coast of Brazil where they are less likely to ground. Furthermore, the NBCR forms at about the same time which shunts drifters into the NECC. Drifters can reach the Lesser Antilles in summer either through a narrow coastal current (Guiana Current) or via rings which break off from the NBCR and drift northwestward to the Caribbean (Johns et al. 2014). A ring break—off occurred in the first pelagic *Sargassum* incursion events of the Lesser Antilles in 2011 (Franks et al. 2011), creating uncertainty in direction of incursion until model backtracking revealed its path. During summer and fall, drifters that have been caught in the NBCR drift eastward in the NECC until they reach the eastern consolidation region with spreading along the coast of West Africa. This eastward drift is confirmed in satellite images (Gower et al. 2013). In winter, drifters can be caught in westward transport to the Caribbean as the NECC breaks down. This provides 3 generic ways that pelagic *Sargassum* incursion events in the Caribbean can occur: (1) into the southern Lesser Antilles via the Guiana

Current in late spring and summer, (2) into the northern Lesser Antilles in winter via the North Equatorial Current (NEC; Supplemental Figure S2B) and (3) intermittently in summer due to formation of an NBCR ring.

In the spring of 2016, incursion events again took place in both the Lesser Antilles and Sierra Leone, West Africa. The first appearance in satellite images (Supplemental Figure S5) was recognized on 24 May 2016 in the area of the NBCR. Our efforts at predicting arrival in the Lesser Antilles using archived model data suggested that *Sargassum* would begin stranding in late July 2016. Subsequent images and on—ground sightings showed that it arrived in mid—July 2016. Both forward tracking (Supplemental Figure S5) and back-tracking tended to confirm the transport patterns identified in our 2011 study (Franks et al. 2011).

It is expected that prolonged time spent in recirculation within the higher nutrient, warmer NERR (Franks et al. 2016) can significantly increase the biomass of *Sargassum*. LaPointe et al. (2014) found different growth rates of pelagic *Sargassum* between nutrient poor waters (oceanic) and nutrient richer waters (neritic) in the GOM and the western North Atlantic. In oceanic waters the mass was found to double in ~50 days for both *Sargassum fluitans* and *Sargassum natans*, whereas in neritic waters the mass doubled in ~11 days. This means that over one year of growth with poor nutrients, and without reference to mortality, one ton of pelagic *Sargassum* could grow to ~158 tons. However, in higher nutrient waters one ton could grow to ~10 billion tons in one year. Modeling pelagic *Sargassum* blooms in the NERR will require growth rates, mortality rates, and finding the balance between a better understanding of recycling in the NERR and export from the NERR.

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