Mass Strandings of Pelagic *Sargassum* Along Caribbean and West Africa Coastlines: Understanding and Prediction — A Technical Report

Masas de *Sargazo Pelagico* Varadas a lo Largo de las Costas del Caribe y Africa: Informe Tecnico para Entender y Predecir

Echouage en Masse de Sargasses au Long des Côtes de l'Afrique de l'ouest et de la Région des Caraïbes: Analyse du Phénomène et Prédictions a Rapport Technique

JAMES S. FRANKS[1*], DONALD R. JOHNSON[1], and DONG S. KO[2]
[1]*Center for Fisheries Research and Development, Gulf Coast Research Laboratory, University of Southern Mississippi, 703 East Beach Drive, Ocean Springs, Mississippi 39564 USA. * jim.franks@usm.edu.*
[2]*Oceanography Division, Naval Research Laboratory, Stennis Space Center, Mississippi 35929 USA.*

ABSTRACT

In 2011, unusually large quantities of pelagic *Sargassum* washed ashore along the coastlines of eastern Caribbean islands and West Africa. Backtracking using ocean circulation models indicated that the *Sargassum* had arrived from the North Atlantic equatorial region rather than directly from the Sargasso Sea. The quantity of the *Sargassum* in the invasion events and the frequency of event occurrence created immense problems for fishery and tourism industries and presented unknown consequences for marine ecosystems. Several north Atlantic climate indices with decadal-scale oscillations reached historical maxima/minima during 2010-2011. A *Hypothesis* is developed which suggests that climate related circulation changes in the equatorial Atlantic created conditions for increased pelagic *Sargassum* retention while warm, nutrient-rich conditions aided *Sargassum* growth and bloom conditions. The invasion events, bloom dynamics, and probable transport mechanisms are examined using ocean models and satellite-tracked ocean drifters. The goal of this study is to provide a fundamental understanding of the recent pelagic *Sargassum* blooms and invasion events in order to facilitate development of prediction capabilities for the tropical Atlantic nations.

KEY WORDS: *Sargassum*, Caribbean, Africa, back-tracking, modelling

INTRODUCTION

Since 2011, unprecedented quantities of pelagic *Sargassum* have inundated coastal waters and shorelines of the tropical Atlantic, extending from Brazil to eastern and western Caribbean nations. The *Sargassum* was identified as two species (*Sargassum natans* and *S. fluitans*), both commonly found in the Gulf of Mexico, Straits of Florida and North Atlantic (Sargasso Sea), but in low quantities in north equatorial regions and the Caribbean, and unidentified in the south Atlantic. We provided an overview of this phenomenon in presentations at the 2011 and 2012 Gulf and Caribbean Fisheries Institute conferences and used model back traces (hind casts from reported stranding locations and dates) to suggest the likelihood of a sub-equatorial origin for the bloom (Franks et al. 2011, Johnson et al. 2012), with no connection to the Sargasso Sea.

In the present study we examine the probability that in normal years, small quantities of pelagic *Sargassum* from the North Atlantic is transported equator-ward along the west coast of Africa with subsequent westward spreading along the equator and entrainment in the North Brazil Current where it is carried into the Caribbean. However, an unusually strong North Equatorial Counter Current (NECC) accompanied by an unusually strong Intertropical Convergence Zone (ITCZ) event in 2010 retained much of this *Sargassum* in a region we describe as the North Equatorial Recirculation Region (NERR) (Johnson et al. 2014) where nutrients and rising sea surface temperature amplified its growth for an additional year before being transported to both the Caribbean and West Africa in 2011.The NERR is defined, herein, as lying between the South Equatorial Current (SEC) and the North Equatorial Counter Current (NECC). It is bounded on the west by the North Brazil Current (NBC) and the North Brazil Current Retroflection (NBCR) and on the east by the Guinea Current (Gulf of Guinea) (Figure 1 A, B).

Several northern tropical Atlantic climate indices (Figure 2) with decadal-scale oscillations reached historical maxima/ minima during 2010, the year preceding the first pelagic *Sargassum* influx event. Since that time, the mass quantities of pelagic *Sargassum* and the frequency of influx events in Caribbean coastal regions have compromised living marine resources, coastal habitats, local economies, fishing efforts, and community life. Other reports of pelagic *Sargassum* beachings in 2011 came from Benin, Sierra Leone and Ghana, West Africa (McDiarmid 2012), locations where such massive quantities were previously unknown (Smetacek and Zingone 2013). Pelagic *Sargassum* was also observed in rafts and weed lines off the northern coast of Brazil in 2011 (de Széchy et al. 2012), a region of uncommon occurrence. Pelagic *Sargassum* propagates by vegetative fragmentation (Lüning 1992) and requires nutrient input to sustain growth. The massive amount of pelagic *Sargassum* that appeared in the equatorial Atlantic needed several conditions to be realized for bloom and invasion:

i) An initial quantity in a suitable habitat,
ii) Confinement to the habitat for sufficient time to grow, and
iii) Solar input, warm water and nutrients for rapid growth.

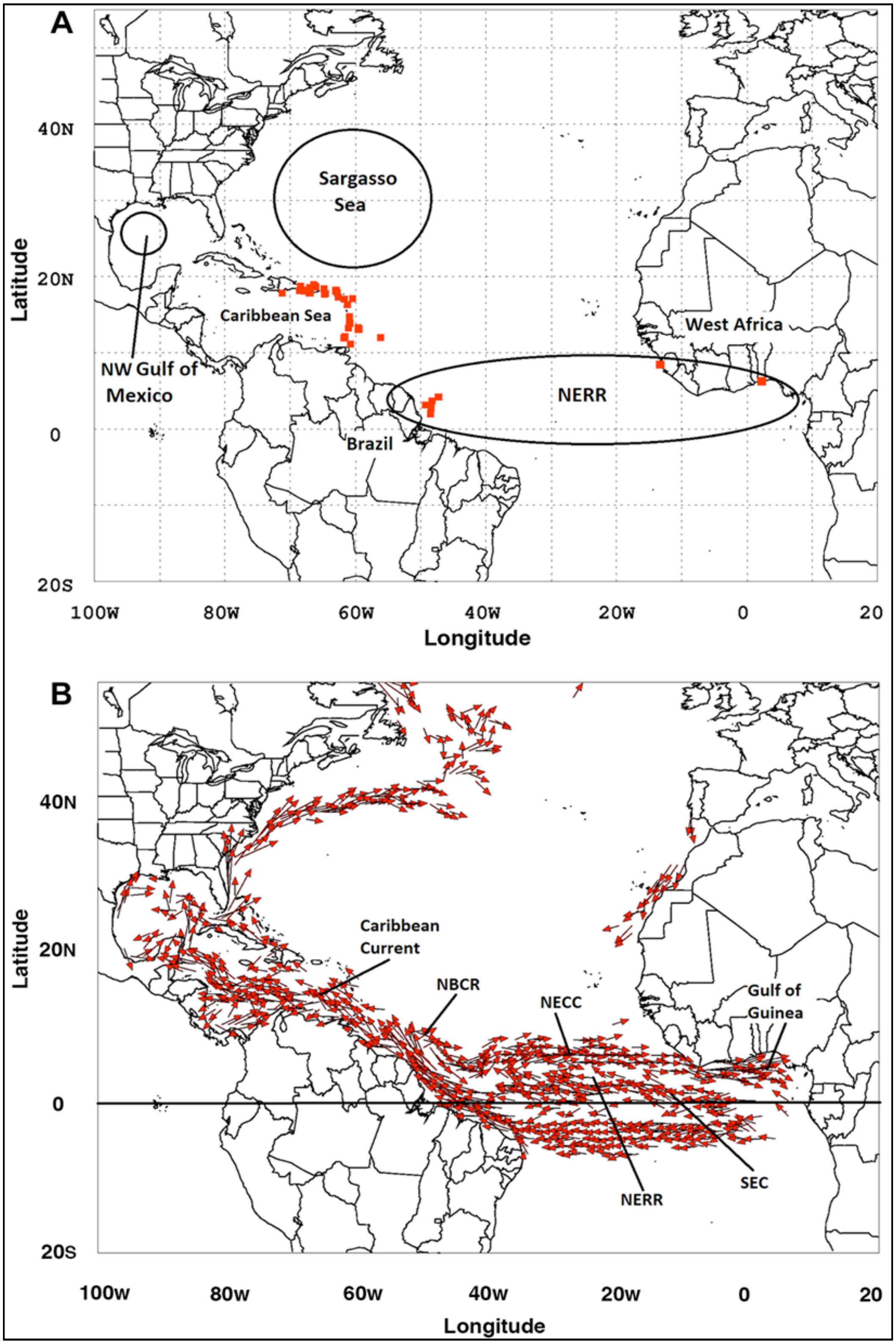

Figure 1. A. Historic locations of pelagic *Sargassum* concentrations (Gulf of Mexico and Sargasso Sea) and a new region of pelagic *Sargassum* growth and consolidation (North Equatorial Recirculation Region - NERR). B. Historical North Atlantic currents during June-October calculated from satellite tracked mixed layer drifters are plotted at locations where current vectors exceed 20 cm/s.

The North Equatorial Atlantic

The NERR forms in summer (July through September) between the westward flowing South Equatorial Current (SEC) and the eastward flowing North Equatorial Counter Current (NECC) at about 5 - 10 ^{o} north latitude (Philander 2001). From January through May the NECC breaks down and, except for coastal currents along Africa, current flow is predominantly westward over the entire region. The NECC is coupled to the seasonally varying Intertropical Convergence Zone (ITCZ) which in turn is linked to high sea surface temperatures, rising air masses with high precipitation and weak surface wind stress (doldrums).

Pelagic *Sargassum* in the NERR characteristically arrives in small quantities from the subtropical North Atlantic along the coast of West Africa in the southward flowing Canary Current and then into the Gulf of Guinea via the Guinea Current. Per our *Hypothesis*, in boreal summer this *Sargassum* may spend some time circulating in the eastern NERR before being 'flushed' out by breakdown of the NECC resulting from southward migration of the ITCZ and winter trade winds which replace the doldrums. The year 2010, preceding the first pelagic *Sargassum* event, was historically unusual for north Atlantic conditions. The North Atlantic Oscillation (NAO) climate index reached its lowest trough while the Atlantic Meridional Mode-SST (AMM) index simultaneously reached its highest peak since 1958 (www.esrl.noaa.gov/psd/data/climateindices) (Figure 2). The weak NAO in 2010 can be linked to weakened winter Trade Winds and, hence, weak flushing of the NERR. The AMM peak is linked to the 'doldrums' and strong recirculation within the NERR, as well as being linked to the ITCZ and thereby to the NECC. Sea surface temperature (SST) in the tropical north Atlantic was at its historic highest peak in 2010. (www.esrl.noaa.gov/psd/data/climateindices). In 2010, conditions were favorable for a stronger than usual summer recirculation of pelagic *Sargassum* within the NERR and weaker than normal winter removal.

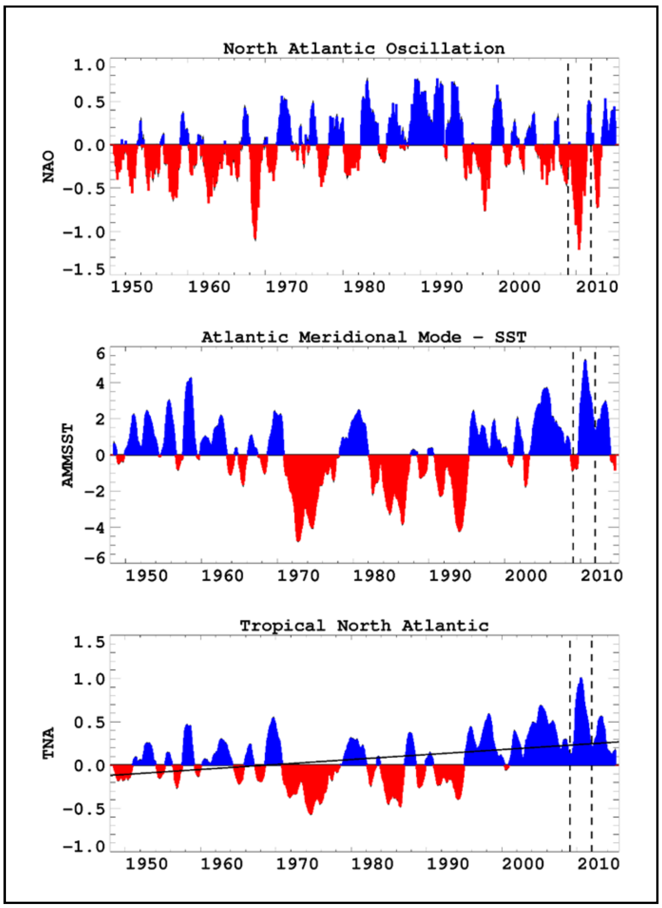

Figure 2. Atlantic Climate Indices. (A) North Atlantic Oscillation (NAO; sea-level air pressure gradient between the Icelandic low and Azores high), smoothed over 12 months. (B) Atlantic Meridional Mode (AMM; coupled Atlantic equatorial wind and sea surface temperature (SST)). Data from http://ww.esrl.noaa.gov/psd/data/climateindices.

Nutrients available for pelagic *Sargassum* growth in the NERR come from Amazon and Congo River outflows, along with West African and equatorial upwelling (Figure 3). In addition, atmospheric mineral dust (Bristow et al. 2010) from the Bodélé Depression in Chad, West Africa can be readily seen in satellite images over the NERR. In summer, African dust spreads westward over the northern portion of the NERR, while in winter it spreads over the Gulf of Guinea and across the Atlantic to the Amazon River Basin. This dust contains elements and micronutrients, including nitrogen, phosphorous and iron, which are deposited onto the ocean surface in the equatorial Atlantic with the potential as fertilizer (Bristow et al. 2010) for nutrient-enhanced *Sargassum* growth.

> *The Hypothesis being built suggests climate related variations in equatorial Atlantic circulation (2010 - 2011 were exceptional years for strong recirculation in the NERR and weak flushing), in association with nutrient enrichment, resulted in conditions supportive of vigorous pelagic Sargassum growth, mass blooming, consolidation and transport into the Caribbean.*

RESEARCH OVERVIEW

The following is a general overview of our research on the massive *Sargassum* bloom and transport mechanisms in support of our stated *Hypothesis*:

Model and Parcel Tracking

When reports of the first massive invasions in 2011 were posted by online media and by email to the Gulf and Caribbean Fisheries Institute (gcfinet@listserv.gcfi.org), it became clear that this was a broad-scaled and highly unusual event. A web site for posting locations and dates was then established by the University of Southern Mississippi, Gulf Coast Research Laboratory (http://www.usm.edu/gcrl/sargassum). Reported sightings were of beach strandings, as well as at-sea mats and lines observed by aircraft. Internet searches found that large quantities of pelagic *Sargassum* had also washed ashore in Ghana and Benin in West Africa (McDiarmid 2012). In addition, pelagic *Sargassum* was found off the coast of northeast Brazil (de

Széchy et al. 2012) by reconnaissance aircraft with documentation and species identification made after subsequent shipboard sampling. These locations and dates served as starting locations and dates for backtracking, applying surface currents from an ocean model in order to estimate origins.

Model currents used for the 2011 back-tracking came from the U.S. Navy's operational Global NCOM (Navy Coastal Ocean Model). This model (Rhodes et al. 2002) has ~1/8th degree longitude/latitude resolution with 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. In early 2013, the Global NCOM system was transitioned to the 1/12th degree Hybrid Coastal Ocean Model (Bleck 2002). The 2014 *Sargassum* event was tracked with archived data from this model whose main difference from Global NCOM is the improved horizontal resolution. Before the tracking algorithm was applied, currents were smoothed over 24 hours.

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, δt is the time step and δx is the distance traced by the parcel during the time step. The equation for δx 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 minutes. To accommodate the effects of sub-grid scale motion, five parcels were released at each position with a Gaussian (mean of zero, standard deviation of one) addition of 1km/d to the current vector and center-of-mass averaged for a new position. The process was continued for 365 days.

Although data assimilation of satellite altimetry has been extremely valuable in phase-locking oceanographic models with real-time events, the method involves spatial smoothing (Ko and Wang 2014) to remove errors, which leads to uncertainty in location of modeled currents. Considering the chaotic (sensitive to initial conditions) nature of Lagrangian tracking, uncertainty in the position of the current with respect to initial *Sargassum* location can lead to amplified uncertainty in tracking, especially over long time periods and large distances. Uncertainties in timing can also be affected by difference between invasion and report, further leading to errors in tracking.

In addition, model tracking reliability is hampered by sub-grid scale turbulence (Griffa et al. 2004) which in the finite-difference model is incorporated into turbulent diffusion coefficients and hence, smoothed. This short wavelength motion is commonly reclaimed in the conversion between Eulerian (model) and Lagrangian (drifter and modeled *Sargassum* tracks) flow representations using a Lagrangian Stochastic Model (LSM), also called a random flight model (Wilson and Sawford 1996). It is noted that this addition to the model does not change the model's energy balance. In forward tracking it does provide a method of mimicking dispersion from a single source. Alternatively, it can be viewed as a means of estimating uncertainty in the computed Lagrangian trajectory. In backtracking, it is used to estimate the trajectory uncertainty.

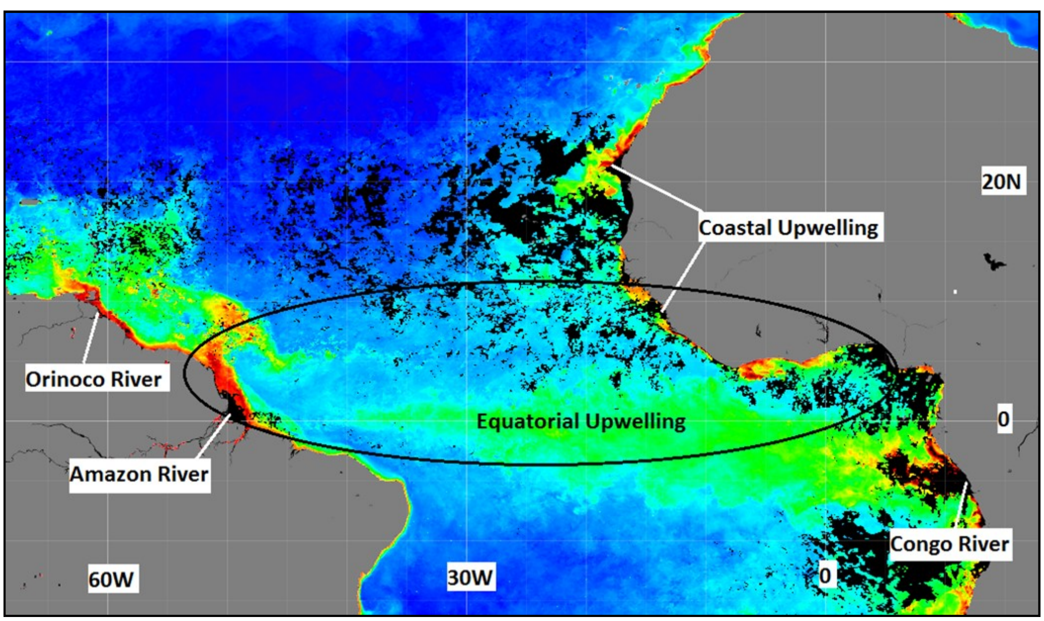

Figure 3. Image of chlorophyll-a from August 2011 showing multiple sources of nutrient input into the tropical Atlantic. Source: MODIS/Aqua - Oceancolor.gsfc.nasa.gov.

Modeled backtracks for the 2011 invasion based on reported stranding observations (Figure 4), clearly point to a low-latitude (equatorial) origin of the bloom (at least within the year prior to invasion), rather than advection from known pelagic *Sargassum* concentrations in the Gulf of Mexico and Sargasso Sea (Figure 1A). Lacking evidence of transport from other sources, we suggest that the *Sargassum* bloomed in the NERR prior to consolidation and invasion. Examining the ensemble of tracks, it can be noted that local recirculation of the modeled parcels appears to have occurred off the northwest coast of Brazil in the area of the NBCR, and it is suspected that consolidation into mats and lines took place here before invasion. It should be noted that the 2011 African invasion locations tracked back to this region before returning to the same equatorial area as observed in the Caribbean invasion tracks. Attempts at backtracking for more than one year did not result in any clear connection with the North Atlantic, e. g., Sargasso Sea. In 2014, another massive pelagic *Sargassum* influx occurred in the Caribbean (Gavio et al. 2013) concurrent with reports of a similar re-occurrence along West Africa shorelines (Mensha 2014), and in 2015 mass pelagic *Sargassum* beachings continued on both sides of the Atlantic.

Satellite Tracked Drifters

For comparison with our modelled trajectories, drifting buoy data were obtained from the National Oceanographic and Atmospheric Agency (NOAA) (Lumpkin and Johnson 2013). Included in the data stream were the buoy locations (longitude, latitude), dates and calculated currents (east/west and north/south components). The data were quality checked and interpolated to six hourly intervals before archiving (Lumpkin and Pazos 2007). Drifters consist of a surface buoy which transmits locations to satellites at regular intervals together with a drag element centered at ~15 m depth to mitigate direct wind effects. The configuration is designed to follow horizontal displacement of water parcels in the oceanic surface mixed-layer. Successive locations and times provide a direct measure of currents. Globally, over 2.7 million determinations of currents are available, going back to 1979. These drifter currents and trajectories are an important means of comparing currents and pelagic *Sargassum* transport trajectories from the finite-difference model.

An historical representation of boreal summer surface currents in the north Atlantic was made from satellite tracked drifter data to aid in description of the setting. Mixed-layer currents from June - October in all years from 1979-2013 were binned at 1° longitude/latitude grid points using an algorithm from optimal interpolation (Bretherton et al. 1976, Johnson et al. 2009) for weighting according to distance of drifter measured current vector from each point. Weight = $\exp(-d_i^2/r_e^2)$, where d_i is the distance from grid point to current vector and r_e is a squared e-folding distance chosen to be 0.3 degrees longitude and latitude with a cut-off distance of 0.6 degrees.

Drifter tracks were further used to establish patterns of seasonal circulation in the NERR which are visually compared to patterns of *Sargassum* movements as determined by the model data. These data not only validated patterns, but guided model experiments. From both backtracking to source regions and forward tracking from these regions, together with comparison to drifters, the region of origin of the invasions can be established in a reasonable manner.

As a check on the model tracking, a satellite tracked drifting buoy was identified that crossed the Atlantic along the equatorial region and terminated in the eastern Antilles in April 2011, about 1.5 months before the *Sargassum* invasion began there. The entire track of this drifter exhibited a striking resemblance to the year-long modeled *Sargassum* backtracks for 2011, giving a measure of confidence that the modeled currents and tracking results are valid on these large scales. Extrapolating backward along the drifter (and model) tracks, it suggested that the parcel of water associated with this drifter passed through the Gulf of Guinea.

An experiment was designed using the model currents to track forward-in-time possible routes taken by pelagic *Sargassum* in the NERR and time scales associated with

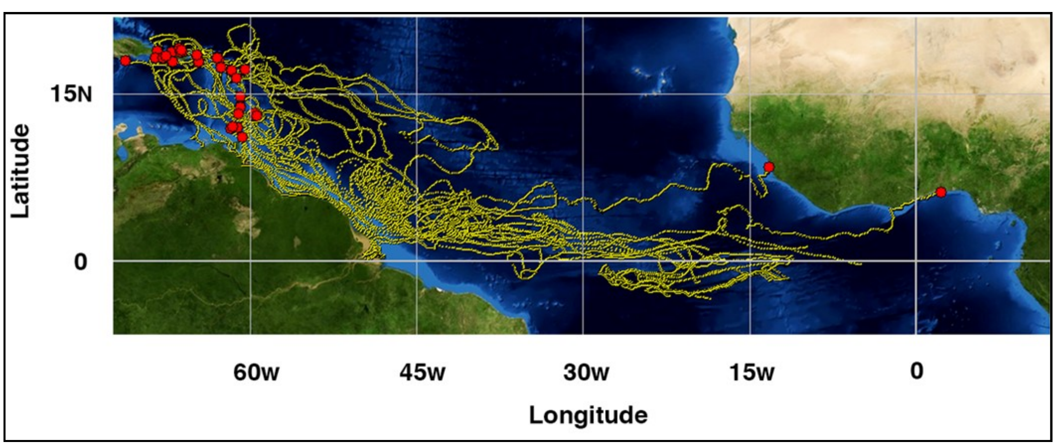

Figure 4. Model back tracks (yellow lines; dots at 6 hr intervals) from sites where pelagic *Sargassum* beaching took place in 2011 (red squares) and covering a period of one year prior to beaching date. Note all tracks go to the equatorial region (including two from West Africa) with no connection northward to the Sargasso Sea.

the invasive *Sargassum* events. Three points spread along the equator in the Gulf of Guinea served as starting locations for forward-in-time tracking. Results of this experiment showed similar circulation features found in drifter measurements:

i) A recirculation pattern connecting the Gulf of Guinea with the central NERR, and
ii) A southern route across the equatorial Atlantic with either a split into the Caribbean or a return to the NERR. As in the drifter experiment, the connection between the eastern and western equatorial Atlantic occurs in boreal winter, with arrival in the Caribbean the following spring.

DISCUSSION

The geographic scope and impact of the recent pelagic *Sargassum* influx events are without equal. Massive quantities of pelagic *Sargassum* in nearshore waters and along coastlines of many Caribbean islands continue to present serious challenges to artisanal fishers and fishing communities, marine resource managers, tourism entities, and local residents (Franks et al. 2011, Blue Ocean Network 2011). Fishers unable to deploy their vessels from shore through thick aggregations of *Sargassum* or avoid entanglement of fishing gear experience dire economic hardship. Nesting site disturbance and hatchling survival are paramount among sea turtle issues. The odor from immense accumulations of decomposing *Sargassum* along shorelines and resort beaches forced some businesses to close. Pelagic *Sargassum* functions as essential habitat that provides food and shelter for various life stages of numerous marine organisms, including commercially important fishes (Wells and Rooker 2004; Hoffmayer et al. 2005) and endangered species of sea turtle (Witherington et al. 2012). However, marine species associated with the mass influx of pelagic *Sargassum* into the Caribbean are not well documented, and concerns for invasive species remain unaddressed.

Unknowns

Among unknowns critical to studies of pelagic *Sargassum* bloom genesis and influx are:

i) Why the occurrence this decade,
ii) Where within the NERR did the bloom originate,
iii) Is a critical mass of pelagic *Sargassum* required to initiate an immense bloom,
iv) What sources/patterns of nutrient input fueled the bloom,
v) What is the pelagic *Sargassum* growth rate in the NERR;
vi) When was bloomed pelagic *Sargassum* first 'flushed' from the NERR,
vii) What is the current distribution and biomass of pelagic *Sargassum* with the NERR, and
viii) What is the long-term prognosis for bloom events?

Research addressing gaps in knowledge will support building a fundamental understanding of recent bloom and invasion events and facilitate development of prediction capabilities important for resource management in tropical Atlantic countries.

CONCLUSIONS

In this study we have formulated a *Hypothesis* that the pelagic *Sargassum* bloom is occurring in north Atlantic equatorial regions due, in part, to alterations in ocean/atmospheric transport dynamics combined with increased water temperatures and strong nutrient enhancement. That *Hypothesis* necessitates additional study and investigation to further test its criteria. The NERR is a region in the tropical North Atlantic with pronounced seasonal circulation patterns that tend to favor retention pelagic *Sargassum* during boreal summer but move it into the Caribbean and the North Atlantic in boreal winter. Within this large scale seasonal circulation, there are areas which can confine and consolidate pelagic *Sargassum* for multiple seasons, i.e., 1) an extensive eastern area which includes the Gulf of Guinea and much of the central NERR, and 2) a western area including the NBCR and the western NECC. Parcel tracking using ocean models together with satellite tracked mixed-layer drifter observations tended to confirm the existence of these two areas and the connections between them. Satellite images during 2011 showed a remarkable line of pelagic *Sargassum* stretching eastward from the NBCR off northwest Brazil [**4**], providing evidence that the patterns discerned from the drifter and modeling efforts have validity. Our contention is that recirculation of pelagic *Sargassum* in the NERR for multiple seasons coupled with high nutrient input allowed time for mass growth and consolidation. Linkage of eastern and western retention and consolidation areas of the NERR along with increasing water temperatures and high nutrient availability appear to be at the core of pelagic *Sargassum* proliferation in the tropical Atlantic regions and the recent invasive events.

A number of studies have shown that the atmospheric tropical belt has widened (Seidel et al. 2008, Lu et al. 2009) due to global warming and related factors. Although the 2010/2011 anomalous oceanic circulation patterns appear to be directly involved in the recent intensive pelagic *Sargassum* blooms, it seems reasonable that future blooms and invasions may result from the changing atmospheric-oceanic coupling that drives equatorial dynamics.

The goal of this study was to:

i) Provide a fundamental understanding of the recent bloom and invasion in order to facilitate future development of short-term and long-term (seasonal and annual) prediction capabilities for tropical Atlantic nations, and
ii) Identify unknowns critical to understanding the bloom and invasion events.

Prediction schemes important to marine resource management and tourist industries in tropical Atlantic nations, as well as several US Gulf of Mexico and Atlantic states, will likely need to include climate indices and satellite imagery of pelagic *Sargassum* accumulations, together with a better understanding of growth rates and transport patterns within the NERR. We suggest that stronger than normal currents and higher sea surface temperatures can be expected as the earth warms, enhancing retention of pelagic *Sargassum* in the NERR and producing growth for subsequent blooms.

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