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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

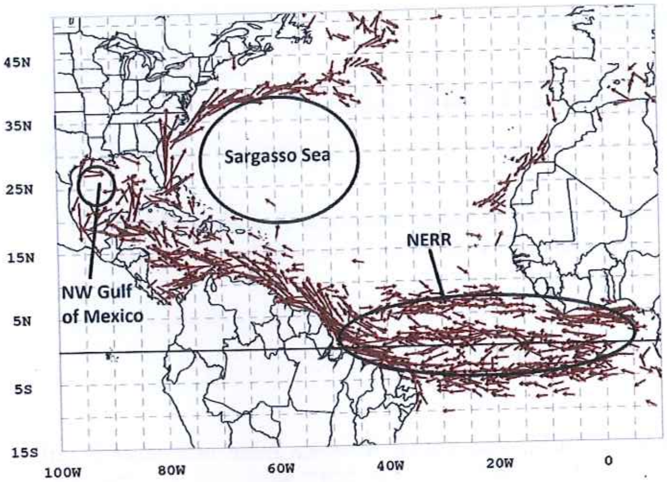


FIGURE 1. *Locations of pelagic Sargassum. Two regions where pelagic Sargassum is commonly found in abundance (northwest Gulf of Mexico and the Sargasso Sea) and a new area, the North Equatorial Recirculation Region (NERR), proposed in Franks et al. (2011). Current vectors are calculated from mixed layer 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 iter
and Akima cubic spline (Akima 1970) was used to in
late gridded model currents to the time and location
time step was set to 15 min. To accommodate the
of sub–grid scale motion, 5 parcels were released at
position with a Gaussian (mean of zero, standard dev
of one) addition of 1 km/d to the current vector an
ter–of–mass averaged for a new position. The proce
continued for 365 days from locations of pelagic *Sarg*
stranding events in 2011.

Drifting Buoys

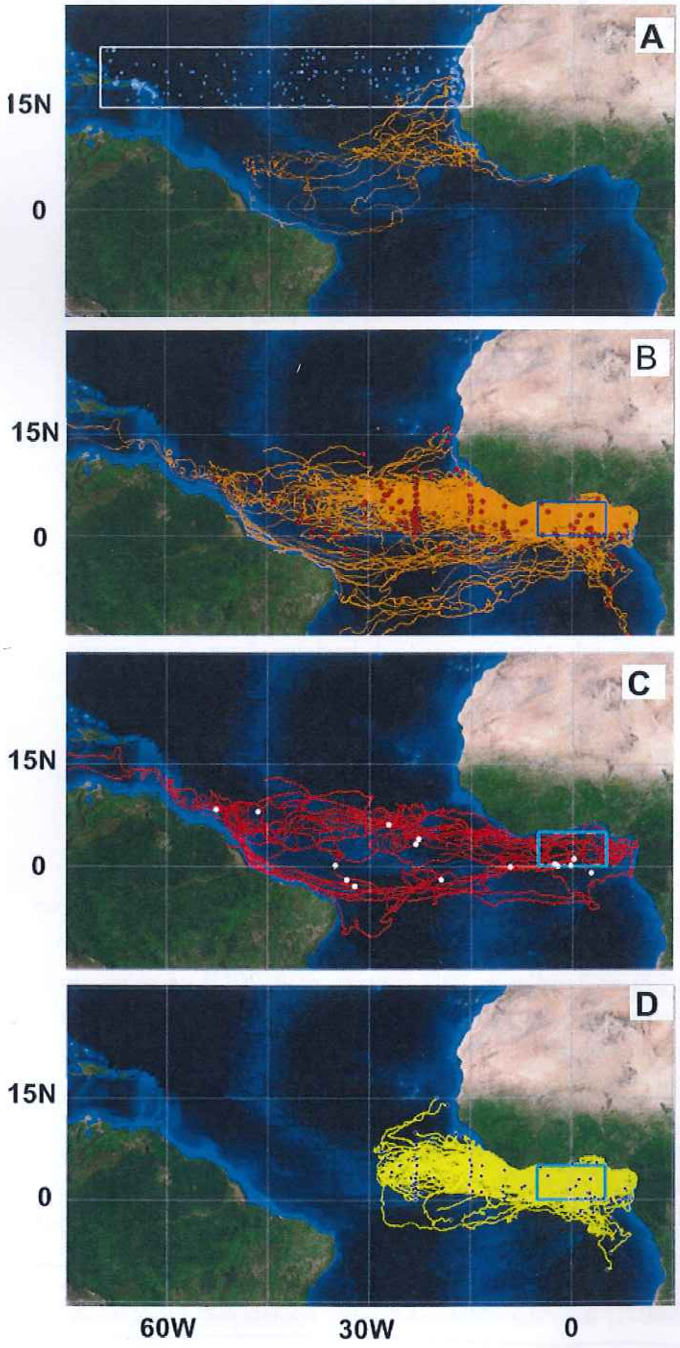
In order to isolate transport pathways that can
onstrate recirculation and consolidation in the NE
gether with reported stranding's on both sides of t
lantic, designed experiments were conducted using s
drifting buoys. Satellite tracked drifting buoys hav
deployed globally as part of the World Ocean Circu
Experiment, with records starting in 1979 and ar
at NOAA'S Atlantic Oceanographic and Meteoro
Office (http://www.aoml.noaa.gov/phod/dac/inde
Buoys are drogued to reduce wind slippage and he
reasonable simulators of surface drifting pelagic *Sar*
Buoy tracks are interpolated to 6 hourly position
currents calculated from successive positions. The d
quality controlled, archived and made available for
use (Lumpkin and Pazos 2007). In order to simulat
port pathways of the surface drifting *Sargassum* bo
and within the NERR, boxes were created at strat
cations and the pathways of satellite tracked buoys
passed through the boxes were studied.

RESULTS AND DISCUSSION

Backtracking pelagic *Sargassum* movements from
ing sites lead to the equatorial region (Supplementa
S3). Prior to the incursion into the eastern Caribbe
solidation of the *Sargassum* off NE Brazil is appare
the density of tracks in the model run and in local
of a validation buoy. The West Africa strandings w
traced, first to the interior of the NERR and the
equatorial region where the tracks joined the easter
bean tracks. To check these findings, back traces ca
for a few strandings that occurred in early 2014 (Su
tal Figure S4) in the eastern Caribbean confirmed
nection with the equatorial region.

Transport connections between the Sargasso Se
Atlantic and the NERR (Figure 1) are a major issue
phering if the *Sargassum* incursions into the Tropic
tic arrived *en masse* or bloomed in the area from
This issue can be addressed using historical drifti
A virtual box (Figure 2A) was created across the
from 13.9°N to 16°N, where *Sargassum* from the
Sea would have to cross to reach the NERR (≤ 7
tude). Buoy identification numbers were obtain

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 pathw
connection between the NERR and the S
Atlantic, and that drifter retention in the
periods longer than a year is possible.



A second buoy experiment was cond
address surface circulation and resulting S
tion throughout the NERR along with co
areas of retention/consolidation within
Sargassum growth could occur. This was
er virtual box experiment in the Gulf o
2B). The tracks of all buoys (170 total) tha
this box showed 2 patterns of particular i
connects the Gulf of Guinea with the rec
eastern NERR found in the above experi
ing considerable time in the eastern NER
buoys grounded along the African coast f
to the Gulf of Guinea. The second path
the South Equatorial Current (SEC; Sup
S2B) to the coast of northeast Brazil and
the Caribbean, or back to the eastern NER
during boreal summer. In both pathway
transport pattern is clockwise.

In order to isolate the 2 patterns and de
consolidation areas, buoys that went thr
Guinea virtual box were further separate
also drifted west of 45°W (Figure 2C, red
that remained east of 30°W (Figure 2D,
teen of the buoys were entrained in the
February, arriving along the coast of north
North Brazil Current (NBC) the followi
(Figure 2C). Some of these grounded al
northeast Brazil, some entered the Caribb
turned eastward in the North Brazil Curr
(NBCR), crossing the entire Atlantic to th
A total of 111 other buoys cycled between
ea and the eastern NERR (Figure 2D),

FIGURE 2. *(A) Experiment using satellite tracked
buoys to determine level of connection between the
circulation Region (NERR) and the North Atlantic gy
Sea). Blue dots are locations of first-calculated curre
location). Only 6 of the 305 buoys entered the NE
along the coast of Africa. Orange dots indicate track
Experiment using satellite tracked mixed-layer driftin
potential pelagic Sargassum consolidation areas a
Identification numbers of all drifting buoys that pass
blue box in the Gulf of Guinea were obtained and th
buoys plotted from locations of first-calculated current
port. C. Separation of all drifting buoys from the abo
2B) that passed through the Gulf of Guinea virtual
west of 45°W. White dots are locations of first-cal
demonstrates entrainment (in January and February)
rial Current in the Gulf of Guinea and westward tran
coast of Brazil. D. Separation of all drifting buoys f
ment (Figure 2B) that passed through the Gulf of G
remained east of 30°W. Black dots are locations of fi*