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PELAGIC *SARGASSUM* PREDICTION AND MARINE CONNECTIVITY IN THE TROPICAL ATLANTIC§

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ABSTRACT: Since 2011, pelagic *Sargassum* has experienced extraordinary blooms in the Tropical Atlantic where a system of persistent but seasonally variable currents has retained and consolidated it in large masses. Although beneficial at sea, principally as a unique pelagic habitat, when *Sargassum* inundates the nearshore environment it can have catastrophic effects on tourism, fisheries, health, and local ecosystems. Providing advanced warning of arrival dates of large masses of *Sargassum* is critical for enabling preparations and planning for its removal, use, and mitigation. Predictions of arrival time and location involve satellite identification of *Sargassum* at sea together with ocean current data for forward model tracking. However, forecast ocean current data are generally valid for only 5—7 days. In this study, ocean currents from 2 models (HYCOM and OSCAR) are validated against satellite tracked drifters from the Global Drifter Program with vector correlation and with skill in replicating a drifter pathway. Various wind additions to the models are also tested. Although both models capture the surface current systems in the Tropical Atlantic, they are mediocre in performance along both boundaries. In contrast, a drifter based current data model with 0.5% wind addition had high skill levels. This skill—tested drifter—based model was then used to determine marine connectivity across the Tropical Atlantic and suggests a much broader spread of *Sargassum* in the eastern Tropical Atlantic than is presently observed by satellites, conforming to earlier hypotheses. This model forms the basis for seasonal scale *Sargassum* forecasting.

KEY WORDS: *Sargassum* distribution, forecasting, validation, drifters, ocean models

INTRODUCTION

Since 2011, large quantities of pelagic *Sargassum* spp. (*S. natans* and *S. fluitans*; hereafter referred to as pelagic *Sargassum*) have repeatedly inundated coastal locations in the Tropical Atlantic, from equatorial Brazil, throughout the Caribbean, and along West Africa from Sierra Leone through the Gulf of Guinea (Johnson et al. 2013, Franks et al. 2016a, Wang et al. 2019). Although pelagic *Sargassum* was previously known to occur periodically in this region, the sudden appearance of such massive quantities was unprecedented and suggested a new consolidation region for pelagic *Sargassum* had been established across the equatorial region of the Tropical Atlantic, and that it most likely began to bloom there around 2010 (Gower et al. 2013). The system of persistent ocean currents in this equatorial region can circulate pelagic *Sargassum* throughout the region and consolidate it on scales sufficiently large for in—situ blooming to occur under excellent growth conditions (Franks et al. 2016b). This new region has been supplying mass pelagic *Sargassum* influxes to the Caribbean and West Africa since 2011. Prior to 2011, pelagic *Sargassum* consolidation and mass blooming was unique to the sub—tropical North Atlantic (Sargasso Sea and the Gulf of Mexico [GOM]; Laffoley et al. 2011).

Individual pelagic *Sargassum* thalli propagate vegetatively and can reach up to 1 m length. They can easily entangle with other thalli and, under the right sea conditions, form large rafts of pelagic *Sargassum* which may span several kilometers and create a distinctive marine habitat (Butler et al. 1983). Conversely, currents, winds and waves are also active in breaking the loosely entangled structures apart and dispersing individual pelagic *Sargassum* strands and clumps over long distances, connecting otherwise isolated marine ecosystems with uncertain consequences.

In pelagic *Sargassum* consolidation regions offshore, the floating rafts and long lines can be of enormous ecological benefit, supporting a large and diverse marine community from epiphytes and small invertebrates to large pelagic fishes and seabirds (Laffoley et al. 2011, Huffard et al. 2014, Monroy—Velázquez et al. 2019). In recognition of its value as essential fish habitat, protection is given for the Sargasso Sea under the International Sargasso Sea Alliance (Laffoley et al. 2011). In addition, the US National Marine Fisheries Service (NMFS) implemented a fishery management plan for pelagic *Sargassum* habitat within waters of the US south Atlantic region (NMFS—NOAA 2003). Despite its ecological value when at sea, impacts on local ecosystems, human health, coastal livelihoods, and national economies throughout the equatorial Atlantic and Caribbean have been, and continue to be, extremely serious when pelagic *Sargassum* washes ashore in large masses (hereafter referred to as events; e.g. Louime et al. 2017, McLawrence et al. 2017, van Tussenbroek et al. 2017, Langin 2018, Resiere et al. 2018).

Cataloging the new distribution of pelagic *Sargassum* out-

§*This article is based on a presentation given in November 2019 at the 72nd annual Gulf and Caribbean Fisheries Institute conference in Punta Cana, Dominican Republic.*

side of its historic locations in the North Atlantic Gyre (Sargasso Sea) and GOM and prediction of its arrival along coastlines in the Tropical Atlantic and the Caribbean has become paramount (UNEP 2018[1]). Validating transport models of pelagic *Sargassum* and understanding the connectivity between consolidation areas by ocean currents is essential for accurate prediction of coastal pelagic *Sargassum* events and determination of annual and inter–annual event cycles. This is critical for informing appropriate response and adaptation measures to the pelagic *Sargassum* events, which have significant implications for small–scale fisheries, tourism and human health, as well as innovative valorization of pelagic *Sargassum* in agriculture, renewable energy, carbon sequestration, and as a raw material in a myriad of potential products (UNEP 2018[1], Desrochers et al. 2020).

There has been much effort expended over the last few years to understand pelagic *Sargassum* arrival and transport throughout the Wider Caribbean (e.g., Wang and Hu 2016, Brooks et al. 2018, Putman et al. 2018, Wang et al. 2018, 2019, Johns et al. 2020). New and experimental products have been developed, which provide valuable insight into the comparative presence of pelagic *Sargassum* blooms across the Caribbean and GOM, and visual assessment of the probability of inundation (e.g., Webster and Linton 2013, Hu et al. 2016, Wang and Hu 2017, Arellano–Verdejo et al. 2019). Some of these products are freely accessible (e.g., USF's Optical Ocean Laboratory, Satellite–based Sargassum Watch System (SaWS) [https://optics.marine.usf.edu/projects/SaWS.html], NOAA's Atlantic Oceanographic and Meteorological Laboratory Ocean Viewer [https://cwcgom.aoml.noaa.gov/cgom/OceanViewer/]). Other initiatives are striving to provide more accurate forecasting. Examples of high resolution, short–term forecasting include Maréchal et al. (2017), Sutton (2019) and Bernard et al. (2019). To date however, there are few examples of longer–term (seasonal) forecasting of pelagic *Sargassum* arrival. Johnson and Franks (2019) have used climatologies from different ocean current data sets, together with 7–day composite satellite images of the Alternative Floating Algae Index (AFAI), to provide a 'threat level' forecast of pelagic *Sargassum* in the Eastern Caribbean. As they point out however, the considerable variations in models used for tracking pelagic *Sargassum* and lack of model validation and skill assessment contributes significantly to the present low level of forecasting precision.

[1]UNEP. 2018. Sargassum outbreak in the Caribbean: Challenges, opportunities and regional situation. UNEP(DEPI)/CAR WG.40/ INF8 Sargassum White Paper. Meeting of the Scientific and Technical Advisory Committee (STAC) to the Protocol Concerning Specially Protected Areas and Wildlife (SPAW) in the Wider Caribbean Region, Panama City, Panama, 5 – 7 December 2018, 16 p. http://gefcrew.org/carrcu/SPAWSTAC8/Info–Docs/WG.40_INF8–en.pdf

Despite the ongoing efforts, UNEP (2018[1]) highlight the current gap between researchers developing pelagic *Sargassum* identification and forecasting methods, and national and regional agencies challenged to deal with the problem. Indeed, the communication of reliable long–term (years) and medium–term (months) forecasts of pelagic *Sargassum* arrivals to stakeholders is critical for the Caribbean region for adaptation and innovation to this new climate hazard and opportunity (Cox and Oxenford 2019).

In this study, we evaluate the performance of 2 ocean current models and a climatological drifter–based dataset in the complex equatorial region of the Tropical Atlantic as a foundation to longer–term prediction of pelagic *Sargassum* events. We then use the best performing current dataset to (1) examine connectivity of pelagic *Sargassum* between eastern and western equatorial Atlantic consolidation areas and the Western Tropical Atlantic, and to (2) provide the first medium–term forecasts of pelagic *Sargassum* events in the Eastern Caribbean by tracking from identifications in regional satellite imagery. Further, we address the communication gap by using our predictions to provide island–scale information and guidance to the Eastern Caribbean islands' fisheries and tourism stakeholders via the publication and distribution of the *Sargassum* Sub–Regional Outlook Bulletin.

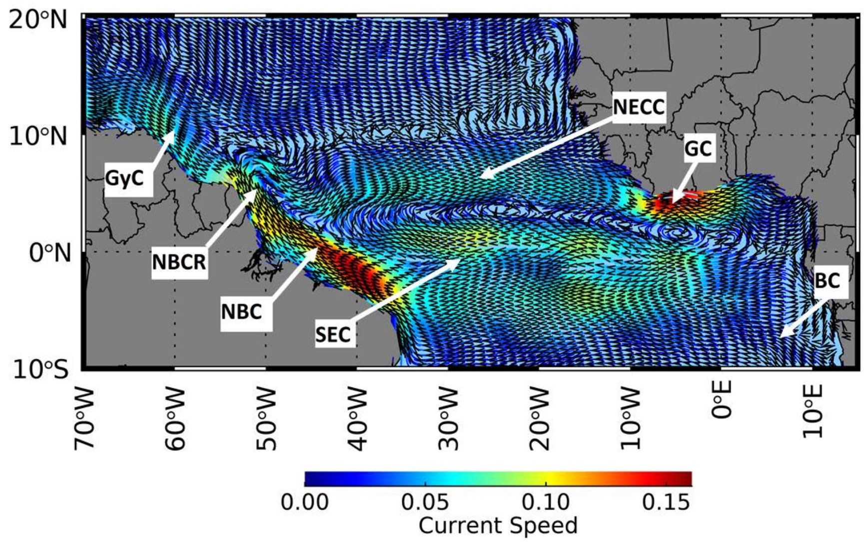

FIGURE 1. *Ocean surface current streamlines showing study area. Noted currents are Guyana Current (GyC), North Brazil Current Retroflection (NBCR), North Brazil Current (NBC), South Equatorial Current (SEC), Benguela Current (BC), Guinea Current (GC), and North Equatorial Counter Current (NECC).*

Materials and Methods

Three sets of archived gridded ocean currents (tracking–currents) obtained from HYCOM, OSCAR and a climatological drifter dataset were evaluated for use in pelagic *Sargassum* prediction and connectivity across the Tropical Atlantic between 10°S and 20°N latitudes (Figure 1). First, modeled ocean currents from HYCOM and OSCAR were statistically compared to drogue–off drifter currents over the period 2013–2014 as a means of validating these models. Secondly, the models and the climatological drifter dataset were skill—assessed against a drifter pathway right across the equatorial Atlantic to examine their performance in emulating the track. The datasets used are described in detail here, followed by the steps taken to evaluate performance.

Satellite tracked drifters

Satellite tracked drifters (also referred to as mixed layer drifters) from the Global Drifter Program (GDP, formally SVP, https://gdp.ucsd.edu/ldl/svp/) have been deployed around the globe since 1979 and consist of a low—windage surface satellite transmitter (35 cm spherical hull) tethered by a thin cable to a semi—rigid Holey—Sock drogue centered at 15 m depth. Archived data records (https://www.aoml.noaa.gov/phod/gdp/) contain longitude/latitude, date/time and calculated current components (u—east, v—north). Data are quality checked and spline fit to 6—h intervals (Lumpkin and Pazos 2007). The metadata set associated with each drifter ID contains a drogue—off flag, noted at the location and time when drogue loss occurs. Although GDP drifters were designed to last in excess of 400 d, loss of drogue is common before loss of battery. The drifting transmitter buoy (drogue—off drifter) then becomes a reasonable representation of surface currents providing that windage on the drifting buoy is considered. For example, global statistics of slippage for these drogue—off drifter buoys has been determined at 1% ± 0.5% of wind speed at 10 m height (Pazan and Niiler 2001).

The following drifter data were used here: (1) data from all Tropical Atlantic drifters (comprising about 1.25 million data points) available between 1990 and 2019 (this data set is referred to herein as the 'climatology drifter—based current dataset'); (2) data from all Tropical Atlantic drifters that lost their drogues (drogue—off drifters) available between 2013 and 2014 (n = 8,398); and (3) data from drifter ID 118523 that lost its drogue in April 2013 but continued to track currents until July 2014.

A gridded set of drifter current vectors for the drifters was created by interpolation to the HYCOM grid (1/12° longitude/latitude) at 365 year—days using an inverse distance interpolator with a cut—off at 2° longitude/latitude. Spline fits over time filled most of the offshore voids, many of which were found at grid points along the equator where mixed layer drifters tend to flow around the shallow Equatorial Undercurrent (EUC).

Hybrid Coordinate Ocean Model (HYCOM)

The Hybrid Coordinate Ocean Model (Bleck 2002, http://hycom.org) is a finite difference numerical model with 1/12° longitude/latitude resolution. It is a foundation for the Global Ocean Forecasting System (GOFS). It has high vertical resolution in the mixed layer with surface currents representing the upper 1 m. One advantage of the hybrid coordinate system is its ability to transition from ocean basin to continental shelf. A second, major advantage is its use of data assimilation (altimetry especially) to phase—lock the model to real events. Rather than directly incorporating surface data into the equations of motion, assimilation is approached by providing a climatology of temperature and salinity structure and converting remotely sensed data into dynamic corrections to this climatology (Fox et al. 2002).

Global validation of the model output is done by statistical comparison with the GDP drifters described above (Metzger et al. 2017). In 2017 the GOFS 3.0 system was transitioned to GOFS 3.1 with improvements in wind—stress forcing and near surface layering. Wind stress forcing in the improved system accounts for the alteration of surface wind shear due to surface currents.

Ocean Surface Current Analyses Real—time (OSCAR)

Ocean Surface Current Analyses Real—time (OSCAR) is a NASA diagnostic model developed by ESR (Earth and Space Research; Dohan 2017) with a global surface current database. OSCAR data were obtained from NASA's Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Data Archive Center (DAAC). Mixed layer currents are calculated (Bonjean and Lagerloef 2002) with simple physical representation using satellite sensed sea surface height (altimeter), wind and sea surface temperature measurements, and interpolated to 1/3° longitude and latitude horizontal grid resolution at 5 d intervals. Dynamic improvements for equatorial regions where the Coriolis parameter goes to zero are implemented. In contrast to HYCOM, the remotely sensed forcing parameters are directly incorporated into the diagnostic model. It is globally tuned to GDP drifters described above and, hence, represents the mixed layer as 'slab' motion.

National Center for Environmental Prediction (NCEP) winds

NCEP—Reanalysis marine surface wind data were obtained from NOAA, Boulder Colorado (https://psl.noaa.gov/data/gridded/data.ncep.html). Meridional and zonal daily 10 m winds were obtained at 2.5° horizontal resolution and interpolated to the HYCOM grid (1/12°) or OSCAR grid (1/3°). For comparison experiments in parcel tracking, wind vector components from 2013—2014 were added to HYCOM and OSCAR surface currents as a percent of wind speed. Climatological winds (averages over 2010 to 2017) were also added to the gridded drifter current dataset to investigate the impact of wind—forced slippage (drifter/model—parcel motion through the water). Tests were made of wind additions to model currents of between 0.5% to 2.0% of the wind speed at 10 m.

Model validation

Modeled currents (from HYCOM and OSCAR) were interpolated to drogue—off drifter locations for statistical comparison. Currents derived from all drifters in the Tropical Atlantic between 2013—2014 that lost drogues (n = 8,398) were used in this direct vector correlation (following Kundu 1976) with model produced tracking—currents. For calculation of vector veering (angle between drifter and modeled vectors) the set was divided into northern and southern hemisphere (n = 5,413 and 2,985 respectively).

Trajectory skill assessment

It is important to assess the 'skill' of different ocean current models and ocean current datasets to determine how accurately they mimic the actual recorded track of a drifter

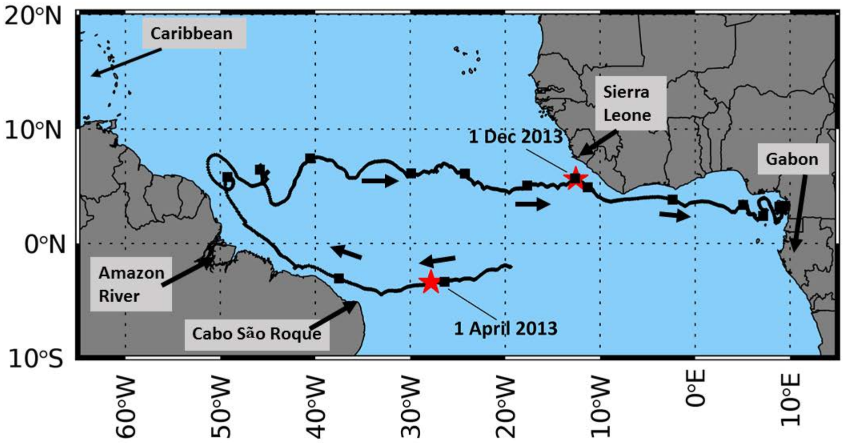

FIGURE 2. *Global Drifter Program (GDP) drifter (ID 118523, black line) that lost its drogue on 6 April 2013 and died in the Gulf of Guinea in July 2014. Red stars are end points for forward and back tracking comparisons. Black squares are at monthly intervals starting on 1 April 2013. Arrows show direction of travel.*

when both forecasting and hindcasting. This is especially true over large distances in order to validate not only the accuracy of end points but also the route taken along the way, to fully understand connectivity of marine areas. Model—based tracking can start and end at the correct locations (demonstrating connectivity between marine areas at end points) but may show little resemblance to the actual path taken and therefore misrepresent the real connectivity of marine areas. Trajectory skill assessment (Liu et al. 2014) has been developed and used to compare the relative performance of altimeter—based models in the GOM.

In the present skill study, we used drifter ID 118523 which was launched in March 2013, dropped its drogue on 6 April 2013 and continued to drift from the equatorial channel up the coast of Brazil and back to Africa where it entered the west African coastal current in December 2013 and finally died in the Gulf of Guinea in July 2014 (Figure 2). From drogue—off to arrival off Africa the track is ~9800 km in length and 243 d in duration. This drifter track passed through much of the area where modeling is questionable, such as the equator, the Amazon outflow, the west coast of Africa and the Gulf of Guinea, and provides an excellent opportunity to evaluate skill of replication for both forward and back tracks using the ocean current models, including the gridded set of drifter tracking—currents we refer to as the climatology drifter—based current dataset. The skill assessment involved launching parcels at 10 d intervals along the drifter track and running them forwards and backwards for 60 d segments using each of the different models and the climatology drifter—based current dataset with the addition of different wind factors (slippage). Skill (S) is determined for each segment (i) from the separation distance at the end of the segment divided by the length of the drifter track segment:

Equation 1: $S_i = 1 - \Delta d_i / L_i$,

where i = 1 to n, n = total number of segments, L = length of segment, and Δd = end distance between drifter segment and simulated track. For skill assessment, S = 0 is defined as no skill and S = 1 as perfect skill. If $S_i < 0$ then set $S_i = 0$. Our measure of model skill in determining connectivity along the entire track is defined to be the mean of forward track and backward track skills for all segments.

In order to examine regional skill, segment locations along the track were separated into 3 regions, a NE Brazil section, a North Equatorial Counter Current (NECC) section and a West Africa section (Figure 3). A segment length of 60 d (~25% of entire drifter track length) was chosen after initial trial runs indicated that this was an appropriate length for providing reasonable visual separation to determine skill in different regions of the drifter track. Marine connectivity between the two locations is considered reasonable (not spurious) when the 2—way tracks coincide (e.g., Breivik et al. 2012).

Examining connectivity across the Tropical Atlantic

Connectivity between the Caribbean and the Tropical Atlantic was reexamined by using our skill assessed climatology drifter—based current dataset to backtrack from 39 pelagic *Sargassum* events (37 in the Eastern Caribbean and 2 in West Africa) reported in 2011 by Franks et al. (2016b). Multiple year backtracking from these events was done with the year—day climatology by simply adjoining 2 one—year records. Event dates were best estimates from event reports and ran from 8 April to 23 December 2011. These were backtracked to what would be the equivalent of 1 January 2010 in the climatology. This end date was chosen because of the occurrence of an historic low in the North Atlantic Oscillation index, and the suggestion by Johns et al. (2020) that a wind anomaly over the central/eastern portion of the North Atlantic during January—March 2010 could have brought sufficient quantities of pelagic *Sargassum* into the Tropical Atlantic for bloom to occur. To account for sub—grid scale turbulent diffusion, 10 parcels were launched at each event site with a stochastic current addition of 1% of the current speed.

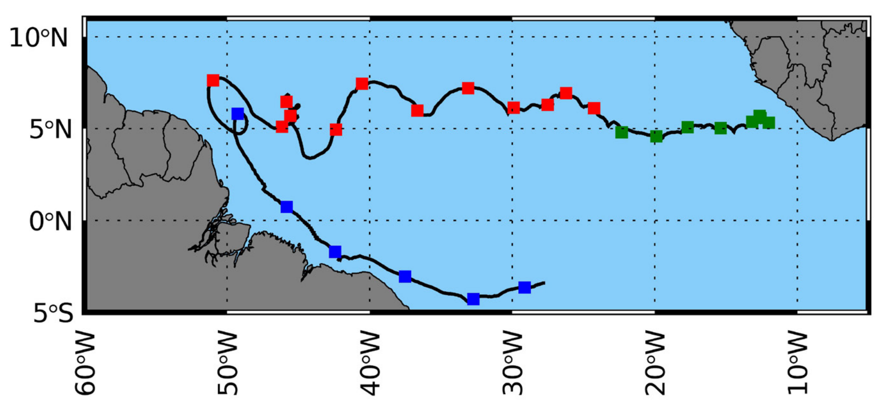

FIGURE 3. *Regional division of segments for skill assessment. Squares represent 10 d launch intervals for each 60-d segment. NE Brazil: Blue squares. NECC/NBCR: Red squares. West Africa: Green squares.*

Results

Validation of ocean current models

Modeled currents from both HYCOM and OSCAR yielded encouraging statistical comparisons (Table 1) to satellite tracked drifters that had lost their drogues (n = 8,398) but continued to record movement. The mean speed of all drogue—off drifters in the Tropical Atlantic study area for the years 2013—2014 was calculated as 0.308 m/s. This is faster than the actual mean speed of surface water flow, due to wind forced slippage of the drogue—off transmitter buoys that travel through the water (rather than simply with the water). The mean speed of HYCOM (measuring surface water) and OSCAR (measuring the average over the surface layer to a depth of 15 m) currents calculated for this Tropical Atlantic region compared favorably to the drifter data set, giving mean speeds of 0.268 m/s and 0.234 m/s, respectively. To match drogue—off drifter speeds, HYCOM had to be multiplied by 1.070% (rounded to 1%) of the wind speed, matching known slippage of these drifters and confirming that HYCOM should not need a wind addition to match surface flow. OSCAR had to be multiplied by 1.725% (rounded to 1.7%). Comparison between HYCOM GOFS 3.1 and GOFS 3.0 shows that there has indeed been a small improvement in mean speed comparison and correlated variance in speed. In summary, HYCOM GOFS 3.1 with a 1% wind addition was able to account for 52% of the variance in vector correlation (Table 1).

TABLE 1. *Summary of model validation results showing mean speed and vector correlations of model currents versus drogue-off drifters in the tropical Atlantic for the period 2013-2014 (n = 8,398). Mean speed of drifter set was 0.308 m/s. Slippage is the percent wind at 10 m added to the model. A positive veer means model vector is clockwise from drifters and a negative veer is counterclockwise. N/S is north (+) or south (-) of the equator.*

Model	Slippage	Mean Speed	Correlation	Degrees Veer
	(%)	(m/s)	(r^2)	(N/S)
HYCOM_GOFS3.1	0	0.268	0.50	2.4/-5.7
HYCOM_GOFS3.1	1.0	0.308	0.52	1.2/-2.6
HYCOM_GOFS3.0	0	0.332	0.32	-1.3/-10.3
HYCOM_GOFS3.0	1.0	0.358	0.35	-2.1/-7.5
OSCAR	0	0.234	0.77	2.9/-2.6
OSCAR	1.7	0.308	0.73	1.0/1.4
Drifters	N/A	0.308	N/A	N/A

OSCAR mean speed matched the drogue—off drifter set mean speed when a wind addition of 1.7% of the 10 m wind speed was added to modeled currents. Again, comparison of this result to the observed global slippage of drogue—off GDP drifters (i.e., 1.0% ± 0.5% of wind) suggests that a wind addition of ~0.7% can be added to OSCAR modeled currents to simulate surface water flow. Since OSCAR currents are tuned to mixed layer slab flow, this wind addition is reasonable in order to reproduce wind forced surface flow. Vector correlation amplitude is higher in OSCAR (the model can account for 73% of vector correlation variance) than HYCOM and the correlated deflection angle between OSCAR and drifter currents remains remarkably low showing little Ekman veering between the surface and the 15 m simulation by OSCAR (Table 1).

Skill assessments

Although statistical comparison of speed and vector correlation between drogue—off drifters and modeled currents was encouraging, attempts to simulate the drifter path backward and forward from points along the drifter path gave mixed results (Table 2). Sixty—day modeled segments along drifter ID 118523 path at 10 d intervals were divided into NE Brazil, NECC including the North Brazil Current Retroflection (NBCR) and West African regions by historical regional dynamics and by visual appearance of the results (Figure 4). Skill for each segment was averaged by region and by the entire track in each direction. Considering wind slippage on the drifter, results from the models (1% wind addition to HYCOM and 1.7% to OSCAR) gave a total skill (mean backwards and forwards) over all segments of S ~ 0.50. Worst skill was obtained off NE Brazil and West Africa, and best in the NECC/NBCR (Table 2).

Although not completely comparable to HYCOM and OSCAR, trajectory simulation skill was also determined for the year—day climatology drifter—based current dataset against the drogue—off drifter ID 118523. Table 2 shows the skill—

TABLE 2. *Summary of skill assessment results showing the skill in simulating drifter ID 118523 path with forward and backward tracking using different current models (HYCOM GOFS3.1 and OSCAR) and the climatology drifter-based current dataset with different levels of slippage applied. Results show mean skill levels (S) for all 60 d segments within each geographic region (NE Brazil, NECC/NBCR, W Africa) and an overall mean for each model variation. Slippage is the percent wind speed at 10 m height added to the model and the gridded drifter climatology. n - the number of 60 d segments; NECC - North Equatorial Counter Current; NBCR - North Brazil Current Retroflection.*

Model	Slippage	Skill level (S) NE Brazil	NECC /NBCR	W Africa	Overall mean
HYCOM forward	0	0.67	0.70	0.59	0.66
HYCOM back	0	0.56	0.79	0.34	0.60
HYCOM forward	1.0	0.09	0.75	0.55	0.49
HYCOM back	1.0	0.77	0.55	0.11	0.49
OSCAR forward	0	0.41	0.68	0.22	0.48
OSCAR back	0	0.56	0.79	0.34	0.60
OSCAR forward	1.7	0.35	0.61	0.40	0.50
OSCAR back	1.7	0.41	0.54	0.52	0.51
Drifters forward	1.7	0.70	0.69	0.60	0.66
Drifters back	1.7	0.77	0.55	0.68	0.64
Drifters forward	0.7	0.68	0.84	0.47	0.76
Drifters back	0.7	0.80	0.82	0.89	0.84
Drifters forward	0.5	0.63	0.86	0.62	0.75
Drifters back	0.5	0.80	0.82	0.89	0.84
Drifters forward	0	0.90	0.87	0.75	0.84
Drifters back	0	0.87	0.82	0.92	0.86

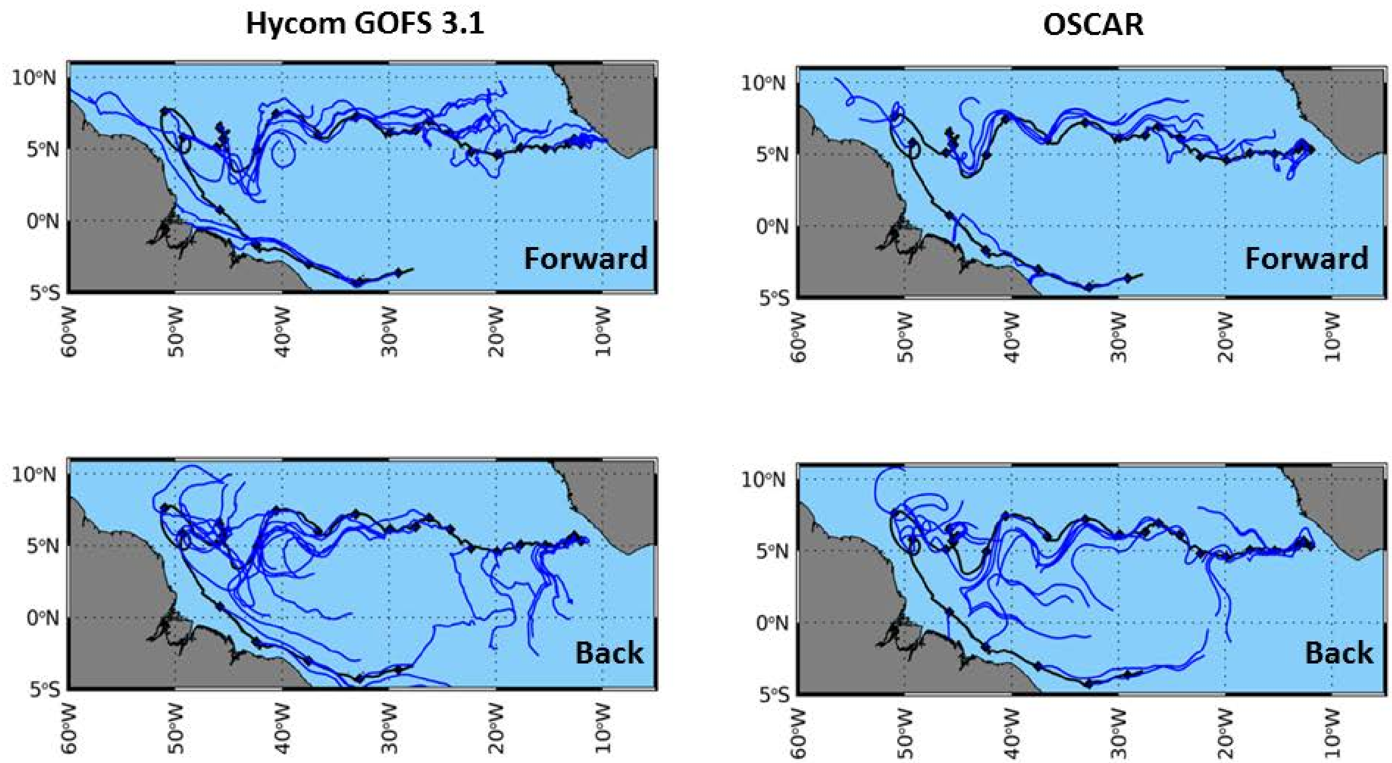

FIGURE 4. *Model current trajectory segments shown together with drogue-off drifter (ID 118523) track. Segments launched at 10 d intervals (black diamonds) along the drifter track and tracked in the models for 60 d. Left: HYCOM GOFS3.1 model with 1% wind addition. Right: OSCAR model with 1.7% wind addition. Upper: Forward tracking. Lower: Back tracking.*

level calculated using wind additions to the drifter currents between 0% and 1.7% of climatological wind speed. Mean skill for all sets was S ~ 0.77; range 0.64—0.86 (considerably higher than for the HYCOM and OSCAR models), and with low variability, especially among datasets with wind addition of 0.7% or less. Like HYCOM and OSCAR tests, daily positions of 60 d segments at 10 d intervals along the track are shown (Figure 5). This substantially higher skill from trajectory tracking using a drifter—based current product with a small wind addition (0 – 0.7%) suggests its greater accuracy for long range predictions and determination of marine connectivity between the pelagic *Sargassum* consolidation areas in the Tropical Atlantic.

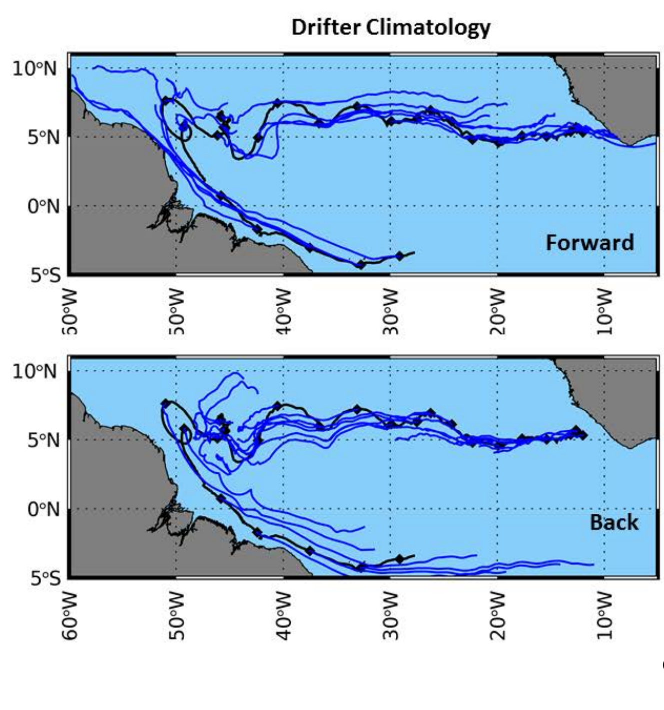

FIGURE 5. *Forward (upper) and back (lower) tracked segments using climatology drifter-based currents with 0.5% wind addition. Black line is drifter path and diamonds are skill segment starts at 10 d intervals.*

Examining connectivity across the Tropical Atlantic

Connectivity between the Caribbean and the Tropical Atlantic was demonstrated by backtracking from pelagic *Sargassum* events in 2011 using our skill—assessed current product (the climatology drifter—based current dataset with 0.5% wind addition; Figure 6a). The modeled tracks also show 2 likely pelagic *Sargassum* consolidation areas off West Africa, one in the eastern portion of the NECC and one along the equator west of Gabon. Tracking forward from the 1 January 2010 ending sites for 2 years (Figure 6b) clearly shows not only a pelagic *Sargassum* belt extending from the Caribbean back to West Africa, but a continuation of the belt into the Gulf of Guinea and an equatorial return flow to Brazil, completing the circuit. Pelagic *Sargassum* landings are observed from about 5° S along the coast of Brazil to the Antilles Islands of the Caribbean, and along the coast of West Africa from Gabon to about 10° N (Figure 6b).

Discussion

Long—range prediction

This study has been motivated by the need to predict pelagic *Sargassum* events in the Eastern Caribbean on medium—term

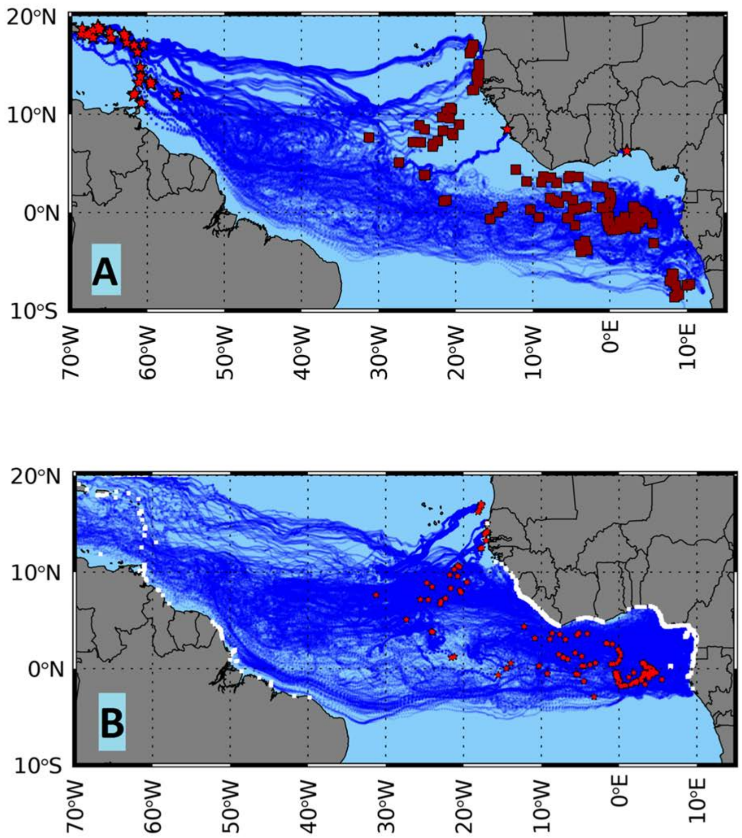

FIGURE 6. *Simulations of pelagic Sargassum tracks in the Tropical Atlantic using the skill-assessed climatology drifter-based dataset with 0.5% windage. A. Shows back-tracks of 10 parcels launched at each of 39 pelagic Sargassum event sites from 2011 with a stochastic dispersal. Red stars are start locations; purple squares are ending locations on the climatological equivalent of 1 January 2010. Daily points are plotted along tracks as small blue dots. Note clustering of endpoints in two locations off Africa. B. Shows forward tracks from the 1 January 2010 end locations (purple squares in Figure 6A). White squares are groundings of some parcels showing the likely distribution of pelagic Sargassum events in the tropical Atlantic. Density of daily points (blue dots) show likely paths of pelagic Sargassum transport. Note pelagic Sargassum belt extending along the coast of Africa from Sierra Leone through the Gulf of Guinea with an equatorial return path.*

(seasonal) and long–term (annual) scales (UNEP 2018[1], Cox and Oxenford 2019). Prediction requires: (1) satellite identification of pelagic *Sargassum* (Wang and Hu 2016, 2017) in the Atlantic, and (2) forward tracking to the date of arrival using modeled ocean currents. This presents a number of challenges. First, the limited optical satellite coverage in the cloud covered pelagic *Sargassum* source regions of the equatorial and eastern tropical Atlantic is a primary hindrance to longer range forecasts, presently limiting predictions to a 3 month time scale. Second, ocean currents from different models used to date produce significantly different trajectories when applied to forward and back tracking (Johnson and Franks 2019) in this dynamic ocean region creating uncertainty in both arrival time and identification of source region.

Here we have focused on the second challenge by using GDP surface buoys that have lost their drogues to compare with simulated trajectories using ocean currents generated by a finite difference model (HYCOM—GOFS 3.1) and a diagnostic model (OSCAR) in an attempt to validate their usefulness in tracking pelagic *Sargassum.* Two principle assumptions have been made: (1) that pelagic *Sargassum* in rafts and lines large enough to be identified in optical satellite imagery are transported at the same speed as the upper meter of water, and (2) that drogue—off GDP drifters slip in comparison to the upper meter of water at ~1% of the wind speed at 10 m height (Pazan and Niiler 2001). With these conditions, HYCOM was found to match mean surface current speed with no wind addition. This should not be surprising since extensive validation efforts (Metzger et al. 2017) have been employed to develop, validate and verify GOFS for Naval operational nowcast/forecast using GDP drifters. However, HYCOM could only account for 52% of the vector correlation variance. OSCAR required ~0.7% wind speed addition to its currents at 15 m depth to match mean surface current speed and explained 73% of the variance. In both cases correlated angle of veering between model and drifter vectors was small.

Calculated skill in following the path of a drogue—off drifter over 8 months and 9,800 km was only moderate for both HYCOM and OSCAR (S ~ 0.5, with 0.0 being no skill and 1.0 perfect skill), even when appropriate wind addition was incorporated to match drogue slippage. It should be noted, however, that the drifter passed through a wide variety of complex dynamic current regimes. It traversed from south of the equator in the South Equatorial Current (SEC) through bifurcation at Cabo Sao Roque Brazil, across the mouth of the Amazon during peak outflow in May (Dai and Trenberth 2002). Then, it moved into the North Brazil Current Retroflection (NBCR) where it circled for several loops, and finally into the NECC where it encountered long waves of length appropriate to Rossby waves emanating from the coast of Africa. It is interesting to note here that both HYCOM and OSCAR appear to simulate the oceanic first mode Rossby wave motions (Chelton and Schlax 1996) of the drifter in the NECC with significant north/south excursions at ~500—800 km wavelengths. Before the drifter reached the coast of Africa, however, seasonal reversal of the NECC began (November) with concomitant slowing and change in motion of the drifter. Poorest skill from the models occurred along the western boundary (off NE Brazil) and off west Africa within the complex seasonal reversal of the NECC.

Combined results from vector correlations and skill analysis suggest that the wind driven component of surface currents is captured by HYCOM and with wind addition to OSCAR, but the geostrophically balanced current component may be underrepresented. Away from frictional boundary layers, steady state surface currents can be approximated by a wind driven component plus a geostrophic component. The latter is dominated by Sea Surface Height (SSH) gradients balanced by Coriolis. However, in equatorial regions, the Coriolis force goes to zero as do SSH gradients in a balanced flow. Since both HYCOM and OSCAR rely on satellite altimeter measured SSH for determination of the geostrophic surface currents, it should not be surprising that both models would be sensitive to noise in the weak SSH signal (Bonjean and Lagerloef 2002). Furthermore, in equatorial regions, optical satellites are clearly compromised by water vapor and African dust (Foltz and McPhaden 2008) as well as by cosmic ray interference with their sensors. These same factors create noise in altimetric satellites which, together with low SSH gradient signals, reduce the ability of models to simulate surface currents in this region.

Although beyond the scope of this study, it is suspected that Rossby and internal Kelvin waves, which play a large role in distributing energy, may not be well represented in altimetric forced models of the equatorial region. Rossby waves are ubiquitous throughout the oceans and are the result of transient adjustments to changes in atmospheric forcing (Chelton and Schlax 1996). Kelvin waves also redistribute energy but along boundaries, including coastlines and the equator (Djakouré et al. 2017[2]). Along the coast of west Africa where the coastline turns sharply, coastal Kelvin waves shed energy into westward propagating Rossby waves (Shriver et al. 1991). This complex system of energy redistribution can manifest itself in strong transient currents with relatively weak SSH gradients, difficult to accurately detect. A further difficulty is the limited representation of river outflow in the models in this equatorial region that receives outflow from 2 of the world's largest rivers, the Amazon River in the west and the Congo River in the east.

In contrast, a gridded climatological ocean current model based on GDP drifters with 0.5% wind addition had a high skill in forward and backward track comparisons with a drogue—off drifter across almost 10,000 km of the tropical Atlantic. Although regional improvements are needed, particularly within the Amazon outflow and in the Gulf of Guinea, and the question of pelagic *Sargassum* slippage is unclear, this gridded dataset is an improvement for long—range predictions of pelagic *Sargassum* arrival in the Caribbean and for marine connectivity studies.

Interpretation of satellite imagery to identify and visualize pelagic *Sargassum* has been an important breakthrough over the past decade (Gower et al. 2013, Wang and Hu 2016, 2017, Wang et al. 2019). However, cloud cover, optical noise and image resolution have inhibited detection of pelagic *Sargassum* by satellites in much of the region. As such, distribution of pelagic *Sargassum* along the equator and the Gulf of Guinea has generally not been recognized, although historical surface currents suggest that this is an important component of the distribution and recirculation of pelagic *Sargassum* (Franks et al. 2012, Johnson et al. 2013, Franks et al. 2016a, b). Furthermore, confirming connections between pelagic *Sargassum* events in the Eastern Caribbean and regions of consolidation and blooms in the tropical Atlantic have been hampered, not only by the constraints of satellite identification, but by uncertainty in ocean current model accuracy over long distance paths through complex ocean dynamic regions.

In this study we have used our skill—assessed gridded climatology drifter—based current dataset for back—tracking from previously reported pelagic *Sargassum* events in the Eastern Caribbean to consolidation regions. As such, our results support the hypothesis of Franks et al. (2016b), based on HYCOM model tracks and drifter pathways, of 2 major consolidation areas in the tropical Atlantic. These areas include one in the west in the area of the NBCR and one (not generally recognized in most studies) broadly spread in the eastern tropical Atlantic along and offshore the coast of West Africa from Sierra Leone through the Gulf of Guinea. From the present study, the eastern consolidation area may be better represented as 2 core areas, one off Sierra Leone and one west of Gabon along the equator. Forward—tracking for 2 years from these eastern endpoint locations produced a clustering of daily track points which extends across the NECC from the NBCR and then down the coast of West Africa and into the Gulf of Guinea. There is also a narrow strip of clustered points in the equatorial channel that connects the eastern consolidation area with spring pelagic *Sargassum* events (Franks et al. 2016b) in the southern Lesser Antilles. The distribution of consolidation areas together with the general regional circulation pattern suggests that oscillation of pelagic *Sargassum* between eastern and western areas gives rise to multi—year fluctuations in arrivals in the Caribbean and is important to annual and inter—annual scale predictions. This forward tracking also indicated grounding locations along the coasts of West Africa, South America and the entire Antilles island chain that align with pelagic *Sargassum* events reported from these locations (e.g., NE Brazil: de Széchy et al. 2012, Sissini et al. 2017; French Guiana: Florenne et al. 2016; Antilles islands: Franks et al. 2012, McLawrence et al. 2017; West Africa: Solarin et al. 2014, Komoe et al. 2016).

Communicating pelagic *Sargassum* forecasts

While this study has made significant progress in improving the ability to predict pelagic *Sargassum* arrival in the Eastern Caribbean from its new source region in the tropical Atlantic, several constraints remain that still hinder accurate forecasts, especially over time frames greater than 3 months. Principle among these are: (1) the capability to detect and quantify pelagic *Sargassum* by satellites, particularly in the equatorial and eastern tropical Atlantic, including the Gulf of Guinea; (2) lack of information on the growth and mortality of pelagic *Sargassum* as it travels, that will influence whether the biomass changes significantly between tracked start and end points; and (3) a lack of validation efforts across the tropical Atlantic of wind induced slippage on models versus actual pelagic *Sargassum* mats in situ.

Growth and mortality rates are highly complex and likely to be regionally variable in the tropical Atlantic. Although satellite estimates are important (e.g., Gower and King 2013), consolidation and dispersal along with seasonal cloud cover can readily mimic growth and mortality making it difficult to establish the intensity of pelagic *Sargassum* events in predictive models. Estimating wind influence on models (e.g., Putman et al. 2020) in order to mimic pelagic *Sargassum* drift will most likely be dependent on *Sargassum* mat structure as well as on regional conditions such as water depth, thermocline depth, and wind fetch.

Despite recognition of the relatively low precision of pelagic

Sargassum predictions to date, we are responding to the call for increased communication between researchers developing pelagic *Sargassum* prediction methods and stakeholders faced with the consequences of pelagic *Sargassum* events. In this effort a skill—assessed climatology drifter—based current dataset is used to provide medium—term (3 month) predictions of pelagic *Sargassum* events to the Eastern Caribbean sub—region. These predictions are being communicated via a quarterly product (Sargassum Sub—regional Outlook Bulletin, https://www.cavehill.uwi.edu/cermes/projects/sargassum/outlook—bulletin.aspx) designed to convey island—scale forecasts and sector—specific implications to tourism and fisheries stakeholders (Cox and Oxenford 2019). By simplifying scientific jargon so that stakeholders can easily understand and benefit from the forecasts, we anticipate that the bulletin will facilitate wider access to specifically tailored early warning information, thus allowing better decision—making by key socio—economic sectors in the Eastern Caribbean islands. We also anticipate that ongoing research and ground—truthing efforts to address the present constraints will improve the precision of these forecasts over time.

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