MODELING NONLINEAR PHYSICAL-BIOLOGICAL INTERACTIONS: EDDIES AND *SARGASSUM* IN THE NORTH ATLANTIC

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EXECUTIVE SUMMARY

The macroalgae *Sargassum*, commonly known as "gulf weed," inhabits the Atlantic Ocean and poses natural resource management challenges for coastal communities in its range. This study seeks to highlight interactions among *Sargassum* and mesoscale eddies and fronts to better predict *Sargassum*' dispersal and growth. To this end, I developed a coupled model system that spans scales from individual organisms up through the basinwide circulation of the Atlantic. The resources of Blue Waters facilitated this model development and allowed for implementation at high resolution. Model results suggest that the Gulf of Mexico (GoM) and Western Tropical Atlantic play a key role in determining *Sargassum* distribution, and highlight the need for better understanding of the reproductive strategy of this organism. The eddy field in the GoM in particular appears to both influence *Sargassum* dispersal into the greater Atlantic and alter the growth conditions experienced by *Sargassum* in the region.

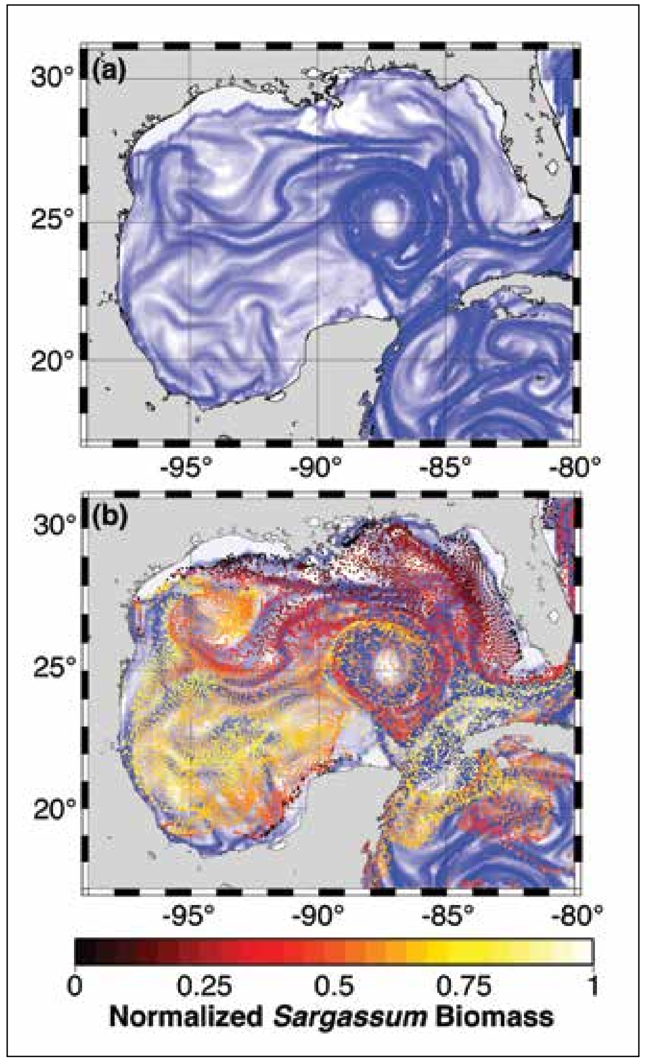

Figure 1: (a) Attracting Lagrangian coherent structure field for the Gulf of Mexico for November 6, 1993, as calculated by finite-time Lyapunov exponent from a 28-day backwards-time particle integration. (b) Normalized biomass of *Sargassum* particles, overlaid on the LCS field for the same date. Note higher biomass in the western GoM.

RESEARCH CHALLENGE

Pelagic *Sargassum* is comprised of two species: *Sargassum fluitans* and *Sargassum natans*. These are the only species of macroalgae in the world that spend their entire life cycle floating on the ocean surface. They serve as keystone species in the Sargasso Sea and throughout their range, supporting a thriving ecosystem, from invertebrates to commercial fish, in low-nutrient "ocean desert" regions [1]. Recently, increased reports of *Sargassum* wash-ups have highlighted its negative impacts. These events are associated with lost fishing and tourism revenue, as well as large clean-up costs for coastal communities on both sides of the Atlantic [2].

Sargassum has many air bladders which provide buoyancy, and this causes colonies to accumulate along convergent eddies and fronts. These features not only affect the regional surface flow, but also can induce vertical velocities that can alter the nutrient availability in the surface waters where *Sargassum* grows. Mesoscale eddies can persist at monthly time scales, long enough to impact *Sargassum* biomass based on measured growth rates [3]. This study examines the physical and physiological impacts of mesoscale features on pelagic *Sargassum*.

METHODS & CODES

This research uses a system of four coupled models to simulate *Sargassum* growth and interactions with ocean circulation features. A Hybrid Coordinate Ocean Model (HYCOM) [4] domain was implemented at 1/12° (< 10m) resolution over a domain that encompasses the known *Sargassum* distribution, from 15°S to 64°N and 100°W to 15°E. This model has 28 hybrid vertical layers which capture the 3-D ocean circulation and their resolution is concentrated in the upper 200m to better simulate vertical velocities associated with surface eddies. Coupled to the HYCOM model is a biogeochemical model adapted from the work of Fennel [5], which includes nitrogen and phosphorus, as well as phytoplankton, zooplankton, and detritus to effectively capture the dynamics of biologically-mediated nutrient cycling in the upper ocean.

Sargassum colonies are modeled using a combination of Lagrangian particle and individual-based physiology models. I have modified the HYCOM Lagrangian particle code to allow for particle buoyancy to better simulate *Sargassum*. The particle code has also been improved to allow both forward- and backward-time integration as well as inertial effects, and interpolates the physical and biogeochemical conditions from the first two models along each particle trajectory. The *Sargassum* physiology model was developed for this study and is run within every individual Lagrangian particle. It uses light, temperature, and nutrient availability to determine growth rate, and because each colony is tracked it can also account for age and reproductive strategy. Vegetative propagation is simulated by initializing a new *Sargassum* propagule in place when a colony dies to age-related causes in regions where conditions are otherwise favorable. The *Sargassum* biomass distributions generated by the 4-model suite were validated against monthly satellite climatologies derived from observations over a 10-year period [6].

RESULTS & IMPACT

This multi-scale modeling effort gives an unprecedented view of basin-wide *Sargassum* biomass and mesoscale biological-physical interactions. Particle seeding and Lagrangian trajectory analyses examined a total of 17 sub-regions of the model domain, with an average area of 1.3x10^6 km^2, and found evidence for two potential "seed" regions that exert disproportionate influence on the *Sargassum* seasonal cycle in the Atlantic. When *Sargassum* particles are seeded in the Gulf of Mexico and the Western Tropical Atlantic near the mouth of the Amazon River the seasonal distribution of biomass has a 30% reduction in RMS error as measured against the satellite observations. The inclusion of *Sargassum's* vegetative reproductive strategy also improved model accuracy, reducing model bias to within 1.5% of the mean observed biomass.

Lagrangian Coherent Structure (LCS) analysis was used to accurately determine the boundaries of mesoscale eddies and fronts via the finite-time Lyapunov exponent field (Fig. 1a). *Sargassum* particles aggregate along attracting LCS as expected, and biomass is influenced by these structures (Fig. 1b). Because the colonies tend to stay at eddy boundaries, they are spared the low-nutrient conditions in the interior of the large, convergent eddies that pinch off from the Loop Current. Buoyant particles tend not to cross LCS lines, and the differential eddy activity in the western and eastern Gulf of Mexico also helps maintain the *Sargassum* population in the western GoM where the potential for growth is high and biomass can accumulate. This improved understanding should help us better predict the potential for *Sargassum* growth based on local oceanographic conditions.

WHY BLUE WATERS

The resources of Blue Waters have made the scale and scope of this project possible. High-resolution ocean circulation modeling alone has a high computational cost. By utilizing Blue Waters, I accomplished the high-resolution ocean circulation modeling as well as coupling it with ocean biogeochemistry, Lagrangian particles, and individual organism physiology at temporal and spatial scales that span orders of magnitude. The professionalism of the NCSA staff has also been key to the success of this project. Their responsiveness and expertise made implementing and running this code on Blue Waters as straightforward as possible.

Maureen T. Brooks is in the fourth year of her Marine-Estuarine-Environmental Sciences Ph.D. program, working under the direction of Victoria Coles at the University of Maryland Center for Environmental Science Horn Point Laboratory. She plans to complete her degree in 2018.