ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL105545

Skillful Seasonal Forecast of *Sargassum* Proliferation in the Tropical Atlantic

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Key Points:

- A transport and physiology model of pelagic *Sargassum* has been developed
- Skillful seasonal forecast of *Sargassum* distribution can be achieved with up to 7 months in advance
- This forecast extends the current *Sargassum* observation and forecasting services

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Jouanno, J., Morvan, G., Berline, L., Benshila, R., Aumont, O., Sheinbaum, J., & Ménard, F. (2023). Skillful seasonal forecast of *Sargassum* proliferation in the Tropical Atlantic. *Geophysical Research Letters*, *50*, e2023GL105545. https://doi.org/10.1029/2023GL105545

Received 20 JUL 2023
Accepted 26 SEP 2023

Abstract

The large-scale proliferation of pelagic *Sargassum* in the Tropical Atlantic from 2011 has been the subject of increasing attention because of its negative consequences on the environment, fishing, and socioeconomic activities when stranding on coastal areas. This recurrent phenomenon presents strong seasonal and year to year variations. Anticipating the abundances and stranding on seasonal scale poses important challenges in terms of observations and modeling. We show that skillful seasonal forecast of *Sargassum* distribution can be achieved with up to 7 months in advance over the Tropical Atlantic, by integrating both transport and current knowledge on physiology of *Sargassum*. This forecast is designed to help marine stakeholders to develop mitigation and resilience strategies through anticipatory decision-making.

Plain Language Summary

The Caribbean, Gulf of Mexico, and Tropical Atlantic are facing a massive and growing proliferation of floating brown algae (*Sargassum*) since 2011, whose environmental and socioeconomic impacts are immense. Observing, modeling, and forecasting the *Sargassum* proliferation and strandings are essential for designing effective integrated risk management strategies and is a strong and pressing demand from the civil society. The present study shows that a skillful forecast can be produced up to 7 months ahead of time by building on current knowledge on *Sargassum* physiology, mechanistic modeling, and remote sensing observations.

1. Introduction

Before 2011, pelagic *Sargassum* spp. bloomed preferentially in the Sargasso Sea and in the northwestern tropical Atlantic. They now strand in large quantities on the coasts of the Greater and Lesser Antilles, Central America, and West Africa. Satellite imagery reveals that these strandings come from colossal quantities of algae drifting from the central tropical Atlantic between 0 and 15°N (Gower & King, 2020; Jouanno et al., 2021b; Langin, 2018; Wang & Hu, 2016; Wang et al., 2019). As inferred from remote sensing estimates of *Sargassum* coverage the proliferation follows a seasonal pattern with a persistence of *Sargassum* in fall-winter in the Inter Topical Convergence Zone region and a peak in boreal summer in the Western Tropical Atlantic and Caribbean Sea (Figures 1a–1d). The phenomenon appears to be a new norm while showing important fluctuations from 1 year to another (Figure 1e, Wang et al., 2019).

The massive arrivals of *Sargassum* on the beaches on both sides of the Tropical Atlantic places the countries of West Africa and the Caribbean region at the heart of regional and international concerns, because of the health, economic, and environmental risks they represent. The ability to anticipate proliferations several months in advance appears essential to help marine stakeholders to mitigate negative impacts. A key step in that direction is the development of a seasonal *Sargassum* forecast. In this study we developed a mechanistic model of the *Sargassum* populations that implements the biology and complex drift properties of the *Sargassum* aggregations and that integrates the atmospheric and oceanic predictability of the regional climate system.

This forecast extends the current *Sargassum* observation and forecasting services (Marsh et al., 2022; Triñanes et al., 2021; Wang & Hu, 2017), and is freely available at https://www.legos.omp.eu/sargassum/. While there are several companies or national agencies that provide short-term forecasts or inundation reports (*Sargassum* Inundation Risk weekly reports by the National Oceanic and Atmospheric Administration [https://cwcgom.aoml.noaa.gov/SIR]; monthly outlook bulletin by the University of the West Indies [https://www.cavehill.uwi.edu/

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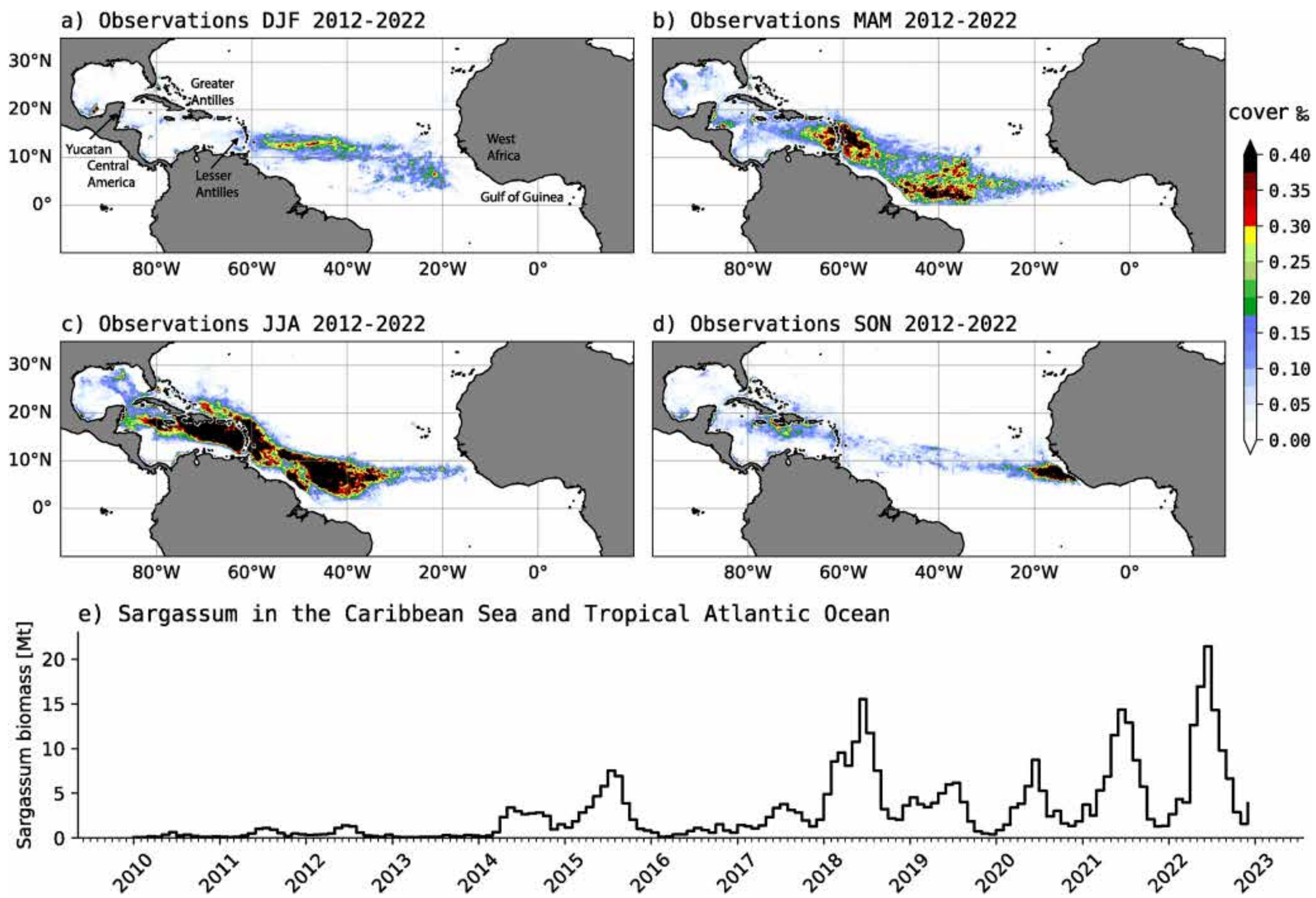

Figure 1. Seasonal cycle of *Sargassum* areal coverage (‰; a–d) in the Tropical Atlantic computed from MODIS detections from 2012 to 2022 and shown at 25 km resolution. As in Wang and Hu (2016), the areal coverage was defined as the proportion of a pixel area occupied by *Sargassum* mats. Here the pixel area is ∼25 × 25 km. Details are given in Section S1 in Supporting Information S1. (e) Monthly time series of estimated *Sargassum* biomass over the north Tropical Atlantic from 100°W to 0°E and from 0°S to 30°N.

cermes/research-projects/sargassum/outlook-bulletin.aspx]; SAMtool forecast by Collecte Localisation Satellites [https://datastore.cls.fr/products/samtool-sargassum-detection/]), seasonal forecasting initiatives are scarce. To the best of our knowledge, the only other existing publicly available long-term forecast is the one proposed by the Optical Oceanography Laboratory, which provides the probability of *Sargassum* blooms in the Caribbean and Gulf of Mexico for the next 3 months (https://optics.marine.usf.edu/projects/saws.html), built on statistically based predictions from bloom conditions in previous months and years. We show in this study that a longer-term and refined basin-scale forecast is achievable.

2. Materials and Methods: The Forecasting Strategy

Modeling and forecasting the large-scale seasonal distribution of *Sargassum* require coupling *Sargassum* transport and biological modeling. The *Sargassum* model developed for seasonal *Sargassum* forecasting relies on the strategy used to represent the distribution of other macroalgae species such as *Ulva* (e.g., Ménesguen et al., 2006; Perrot et al., 2014; Solidoro et al., 1997), with the difference that here the algae is transported by a two-dimensional advection/diffusion/reaction model to take account of its pelagic nature. The model used in this study is an evolution of the model described in Jouanno et al. (2021a). Complete description of the model is given in Supporting Information S1.

In recent years, modeling efforts mainly focused on the transport properties of *Sargassum* aggregations by offshore currents, with significant advances on the role of inertia in the drift trajectories (Beron-Vera & Miron, 2020; Brooks et al., 2019) and the importance of considering windage to properly resolve the drift of the

Sargassum aggregations (Berline et al., 2020; Putman et al., 2020). The importance of Stokes drift on seasonal transport has also been revealed (Jouanno et al., 2021a). Active research on this topic reflects the complexity of representing properly *Sargassum* transport. In a seasonal forecasting perspective, uncertainties on the forecasted ocean currents and integration times of several months add to the difficulty of accurately representing transport.

The modeling of growth and mortality characteristics is poorly constrained by observations or experiments, so this aspect is particularly challenging. The main factors that were identified as essential to take into account to represent *Sargassum* growth are internal nutrient reserves of nitrogen and phosphorus (Hanisak, 1983), dissolved inorganic nutrients (nitrate, phosphate, ammonium) in the external medium (Changeux et al., 2023; Lapointe, 1986, 1995; Lapointe et al., 2014, 2021; Magaña-Gallegos et al., 2023a, 2023b), solar radiation (Hanisak & Samuel, 1987; Lapointe, 1995), sea surface temperature (Hanisak & Samuel, 1987; Magaña-Gallegos et al., 2023b), sea surface salinity (Hanisak & Samuel, 1987), and surface wind speed (Magaña-Gallegos et al. (2023a) found that continuous movement of Sargassum is required to allow growth in ex-situ culture systems).

A full description of the model is given in Supplementary material. The choice to consider varying internal nutrient quotas (C:N:P stoichiometry) is motivated by observations suggesting that *Sargassum*, like other brown algae, is able to store some nutrients in its tissues (Hanisak, 1983; Lapointe, 1995; Lapointe et al., 2021). In situ observations have also revealed that three different morphotypes are involved in the proliferation (*Sargassum fluitans* III, *Sargassum natans* I, and *Sargassum natans* VIII e.g., Alleyne et al., 2023; Dibner et al., 2022; García-Sánchez et al., 2020; Schell et al., 2015). The eco-physiological features are species dependent, and it has been shown that *Sargassum fluitans* III, which has been the dominant morphotype over the recent years (García-Sánchez et al., 2020), grows significantly faster than the *Sargassum natans* morphotypes (Changeux et al., 2023; Corbin & Oxenford, 2023; Magaña-Gallegos et al., 2023a, 2023b). However there is no convergence of the recent studies on the temperature dependance of the different morphotypes (Corbin & Oxenford, 2023; Magaña-Gallegos et al., 2023a, 2023b) and there is no knowledge of the salinity, light, or senescence dependence of the different morphotypes. Thus, we have chosen to model a generic species of pelagic *Sargassum*. This strategy is further constrained by the fact that the satellite detections used to initialize the forecast do not allow us to distinguish the proportion of different morphotypes in the aggregates.

An operational and ensemble version of the *Sargassum* model at 1/4° horizontal resolution has been implemented and allows for the production of 7-month forecasts every month, initialized from *Sargassum* areal coverage near-real time estimates from the Moderate Resolution Imaging Spectroradiometer MODIS (Berline & Descloitres, 2021). The forecast is the result of 25-member ensembles to account for uncertainties in the predictability of the coupled ocean-atmosphere system. For each member, the surface winds and the solar radiation are obtained from members of the fifth-generation seasonal forecast system SEAS5 of the European Centre for Medium-Range Weather Forecasts (ECMWF, Johnson et al., 2019). The surface currents, temperature and salinity are obtained from ensembles of 25 regional physical ocean forecasts based on NEMOv4.0 (Nucleus for European Modelling of the Ocean, Madec & The NEMO System Team, 2023) forced with meteorological fields from the SEAS5 members. A climatology based on the biogeochemical analysis and forecast system BIO4 from Mercator Ocean International is used for nutrients as there are no available skillful biogeochemical seasonal forecasts available to the community. The 7-month limit of the *Sargassum* forecast is imposed by the length of the ECMWF's operational forecasts.

3. Skill of the Forecast

An example of *Sargassum* coverage ensemble mean prediction in January, April, and July 2021 is shown in Figure 2. This prediction has been initialized at 01 January 2021, using monthly mean *Sargassum* distribution centered on 01 January 2021. It emphasizes the key role of the central Tropical Atlantic on the seasonal proliferation toward the Caribbean and the ability of the model to represent the transport and growth of the *Sargassum* several months in advance. The mean seasonal distribution at different lead times is shown in Figures S1 and S2 in Supporting Information S1. It is close to the observed climatological seasonal cycle shown in Figure 1. The model is therefore able to reproduce the spatial structure of the "Great Atlantic *Sargassum* Belt" (Wang et al., 2019) and its seasonal variability.

Prediction performance is then inferred from MODIS *Sargassum* detections from 2012 to 2022 across the tropical Atlantic. The system produces skillful predictions up to 7 months in advance across the entire "Great Atlantic

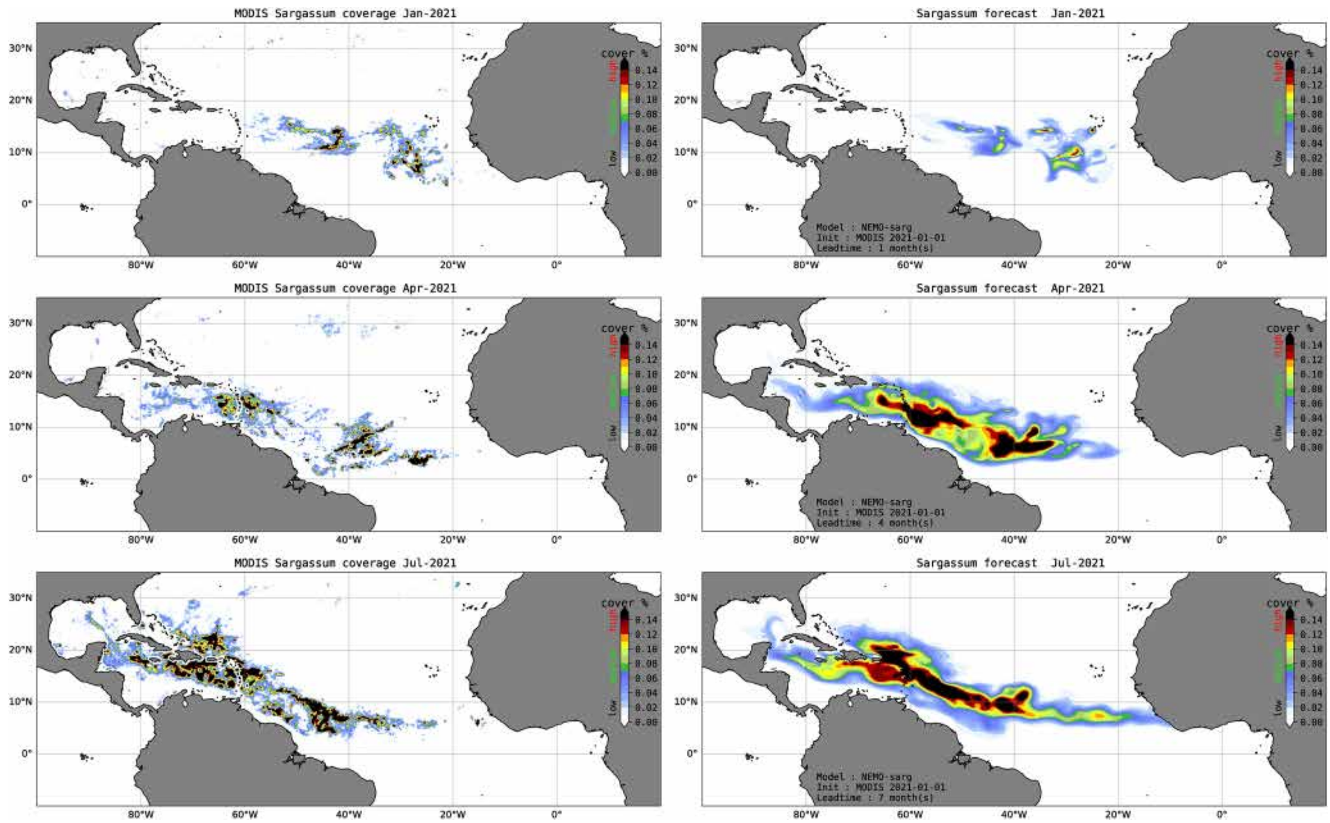

Figure 2. Illustration of the forecasts and ability of the system to predict the large-scale distribution of *Sargassum* with 1–7 months in advance. On the left: monthly observations of *Sargassum* areal coverage (%) obtained from MODIS in January, April, and July 2021. On the right: forecast of *Sargassum* coverage (%) initialized in 1 January 2021 and shown as monthly averages for 0.5-month lead (January 2021), 3.5-month lead (April 2021), and 6.5-month lead (July 2021) forecasts. The forecast is an average of an ensemble of 25 simulations, explaining why the simulated fields are much smoother than the observed field.

Sargassum Belt" as revealed by anomaly correlation coefficient (ACC, see Supporting Information S1 for definition) in Figure 3. The skill is particularly high around the Lesser and Greater Antilles, while lower near West Africa. Interestingly, the *Sargassum* forecast system significantly outperforms alternative simpler approaches, such as considering a climatological forecast, for most of the domain (the black dots in Figure 3 indicate that the forecast skill exceeds the skill of a climatological forecast).

The time series of observed and predicted *Sargassum* biomass for the tropical Atlantic and for different regions of interest are shown in Figures S3 in Supporting Information S1 at different lead times from 0.5 to 6.5 months. In line with the skill, they confirm the ability of the model to anticipate interannual anomalies over a stated number of years, including the peaks of 2015, 2018 or 2021, with a performance that varies by region. Indeed, the skill varies according to the region and the target forecast month (Figure 4). For most regions, skill peaks for July-August forecasts, with remarkably high skill even at 6.5 months ahead. Conversely, lower skill is obtained in winter-spring. As shown in Figure 1e, *Sargassum* abundance in the basin shows a pronounced seasonal cycle with increasing *Sargassum* biomass from January to July and decreasing *Sargassum* biomass from September to December. The seasonal nature of the skill is interpreted as a measure of the model's ability to accurately represent the growth phase of *Sargassum*, with somewhat more difficulty in representing the decay phase. Higher scores are obtained for the Lesser and Greater Antilles, while weaker scores are obtained for the eastern tropical Atlantic and the Gulf of Guinea. As eastern tropical Atlantic and the Gulf of Guinea are particularly cloudy, discrepancies between forecasts and observations highly likely include inaccuracies in remote sensing estimates.

4. Conclusion and Discussion

The causes and drivers of the basin scale proliferation and variability are certainly multi-factorial and have not been yet fully rationalized or unified to date (Johns et al., 2020; Jouanno et al., 2021a, 2021b; Oviatt et al., 2019;

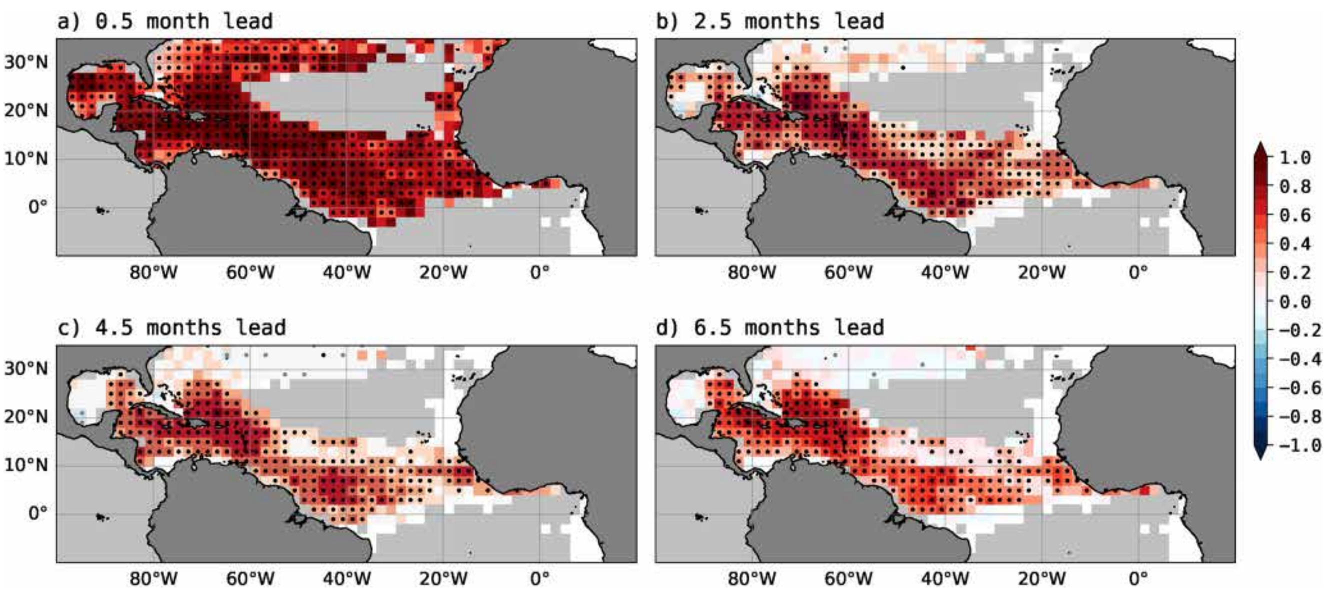

Figure 3. Prediction skill in reproducing observed variations of monthly *Sargassum* biomass anomalies, as measured by the monthly Anomaly Correlation Coefficient (ACC) between observed and predicted *Sargassum* biomass at 0.5-, 2.5-, 4.5-, and 6.5-month lead-time. Circles indicate significant ($P < 0.05$) prediction skill, with black circles indicating that the forecast skill exceeds the skill of a climatological forecast built from monthly averages of *Sargassum* satellite detection from 2012 to 2022. Due to the discrete nature of the *Sargassum* distribution in the observations and in the model, the observations and model outputs were degraded to 2° resolution before calculating the ACC. Areas with less than 3 monthly *Sargassum* detections over the period 2012–2022 are indicated by gray shading.

Skliris et al., 2022; Wang et al., 2019). Despite the limited understanding of a phenomenon that needs to be further explored, the present study shows that a skillful forecast can be produced up to 7 months ahead of time (see Figure 3) by building on current knowledge on *Sargassum*, mechanistic modeling and remote sensing observations. Given the pressing need for forecasting the *Sargassum* arrival, the skillful predictions described here represent a key step for anticipating decision-making by marine stakeholders and improving the resilience of coastal communities in the tropical Atlantic.

Although the forecast is limited to 7 months due to the duration of the SEAS5 seasonal forecasts from ECMWF, the high scores obtained for 6.5-month predictions suggest that the system has the potential to produce meaningful longer-term forecasts. It is worth mentioning that because of its resolution (1/4°) and although some parametrization of *Sargassum* stranding is considered, the system missed the coastal hydrodynamic processes likely to govern stranding mechanisms at the coast, operating at the scales of bays, lagoons and open beaches. Strandings on the coast are expected to be controlled and organized in relation to the local reality of hydrodynamics forcing and the coastal geography (complex bathymetry, indentation of coastline, topographic winds). Further efforts are required to develop and qualify downscaling strategies at the scale of the coast.

Forecast accuracy can still be improved. One key aspect that should be addressed and improved is the predictability of the biogeochemical content of the ocean. Here we force the forecast with a seasonal climatology of nutrients, but part of the year-to-year fluctuations of *Sargassum* coverage may involve interannual anomalies of the biogeochemical environment (Skliris et al., 2022) that should be considered in future versions of the system. Knowledge of the large-scale distribution of *Sargassum* is also absolutely essential to accurately predict the seasonal development of the phenomenon. In particular, uncertainties in the Inter-Tropical Convergence Zone region where the number of days with useable MODIS images is low, may weaken the skill of the forecast. Yet this area is key to the year-to-year maintenance of the phenomenon and to the seasonal development of the bloom (Berline et al., 2020; Gower & King, 2020; Gower et al., 2013; Johns et al., 2020; Jouanno et al., 2021a, 2021b; Wang et al., 2019). There is thus a step to cross in terms of observability in this region, for example, using multi-sensor approach.

In addition, a realistic representation of *Sargassum* growth and mortality would be essential to achieve seasonal or longer-term predictions. A better understanding of the factors controlling *Sargassum* growth and mortality is an important challenge for the scientific community, mainly because of the difficulty of growing these pelagic

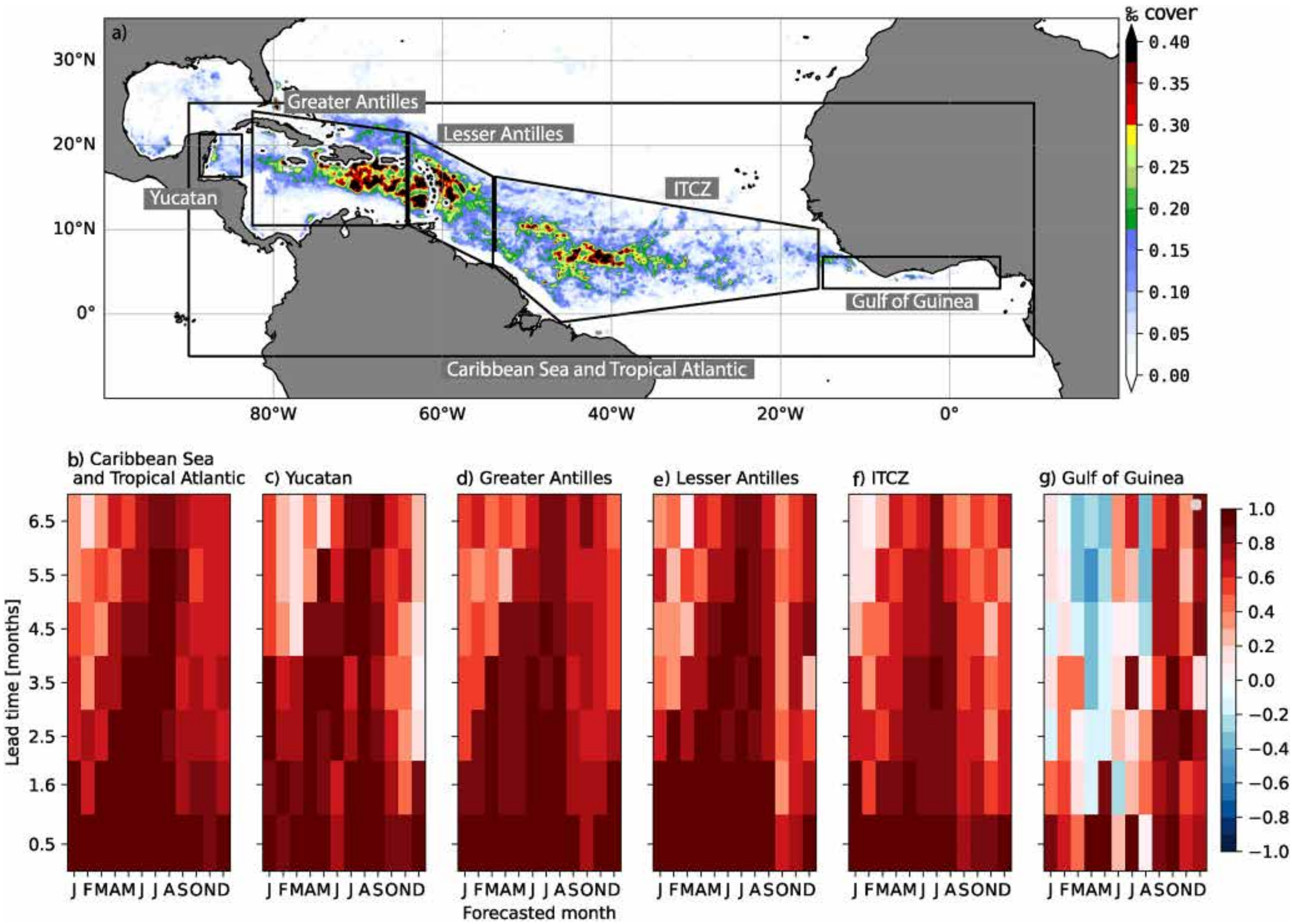

Figure 4. Mean *Sargassum* areal coverage (%) for the period 2011–2022 from MODIS observations (a) and prediction skill as a function of target forecast month for different lead-time and different regions of interest: (b) Tropical Atlantic and Caribbean, (c) Yucatan, (d) Greater Antilles, (e) Lesser Antilles, (f) Inter-Tropical Convergence Zone, and (g) Gulf of Guinea. The model and observations times series representing the evolution of the *Sargassum* biomass for the different regions are shown in Figure S3 in Supporting Information S1.

species in controlled conditions (Magaña-Gallegos et al., 2023a). Progress on this aspect will definitely help to improve *Sargassum* modeling and forecasting.

Data Availability Statement

The Seasonal Sargassum forecasts described here can be accessed at https://www.legos.omp.eu/sargassum/. The *Sargassum* areal coverage database was processed by AERIS/ICARE data center at the University of Lille and is available at Berline and Descloitres (2021). The BIO4 biogeochemical simulations are available at Mercator Ocean International (2023). SEAS5 ensembles outputs are openly available at the Copernicus Climate Change Service, and Climate Data Store (2018). The *Sargassum* model is built upon the standard NEMO code (release 4.0.1, rev 11533), provided by Madec and the NEMO System Team (2023). The NEMO code modified to include the *Sargassum* physiology and transport is available in the Zenodo archive at Jouanno and Benshila (2020).

Acknowledgments

This study was supported by the ANR project FORESEA (ANR-19-SARG-0007). Computing resources are provided by DARI under Grant GEN7298.

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