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Review

Understanding the *Sargassum* phenomenon in the Tropical Atlantic Ocean: From satellite monitoring to stranding forecast

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ABSTRACT

Since 2011, massive strandings of holopelagic *Sargassum* have occurred on the coasts of the Caribbean and of West Africa. Although open ocean *Sargassum* mats are oases of biodiversity, their stranding has a number of negative ecological, economic and health consequences. To limit these impacts, *Sargassum* needs to be collected as quickly as possible to avoid its decomposition, which requires accurate predictions of the date, location and abundance of the strandings. Two complementary approaches have been developed for this purpose: satellite remote sensing technique, to detect *Sargassum* aggregations, and modeling, to forecast *Sargassum* displacement and growth. The objective of this review is to provide a synthesis of the current knowledge related to *Sargassum* monitoring in the tropical Atlantic Ocean. To better understand the issues surrounding *Sargassum* and its monitoring, the first two parts are devoted to an overview of the ecology of the two most prevailing holopelagic *Sargassum* species, to the current issues related to their strandings, to the causes of their occurrence in the tropical Atlantic Ocean and to their seasonal and interannual variabilities. The methods used to detect *Sargassum* from satellite images and their limitations are examined. The transport and biogeochemical models developed for seasonal forecast and stranding predictions are described along with their limitations. As both detection and modeling rely on validation data to assess their accuracy, previous works providing in situ characterization of *Sargassum* are also reviewed here. The last part provides recommendations to further increase knowledge on holopelagic *Sargassum* and improve the predictions of their strandings.

1. Introduction

Sargassum is a brown algae genus that is present in all ocean basins, including 359 species (Stiger-Pouvreau et al., 2023). Two main species are present in the open Atlantic Ocean: *Sargassum fluitans* and *Sargassum natans* (Parr, 1939). They are both holopelagic, meaning they spend their entire life cycle floating on the surface, and aggregate under the effect of winds and currents to form mats (Langmuir, 1938; Ody et al., 2019). They have been observed in the north Atlantic Ocean for several centuries, with the first historical report dating back to the 15th century

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and Christopher Colombus' journey to the Americas during which the Sargasso Sea was described (Frazier, 2014; Martin, 2016; Wang et al., 2019). Their presence has also been reported in the Gulf of Mexico since the mid-19th century, through reports of strandings in the local press (Webster and Linton, 2013).

Since 2011, *Sargassum* has been growing in the tropical Atlantic Ocean, extending from the Gulf of Mexico (America) to the Gulf of Guinea (Africa) and forming what Wang et al. (2019) called the Great Atlantic *Sargassum* Belt (GASB). Open ocean *Sargassum* aggregations compose unique pelagic habitats that contribute to a diversified marine life (Coston-Clements et al., 1991; Van Tussenbroek et al., 2024) and constitute important feeding, breeding and resting areas for many species (Haney, 1986; Wells and Rooker, 2004). Their massive strandings, which can exceed ten million tonnes in certain months in the Caribbean (UNEP-CEP, 2021), pose significant biological and socioeconomic challenges by severely impacting coastal communities, public health, tourism, and fisheries (Chávez et al., 2020; Mohan and Strobl, 2024; Resiere et al., 2018; Van Tussenbroek et al., 2017; UNEP-CEP, 2021). In recent years, this emerging environmental hazard has conducted several Caribbean countries to declare national states of emergency in response to *Sargassum* influxes (Desrochers et al., 2022).

In order to limit the negative consequences of *Sargassum* strandings, the main response of local communities is to collect stranded *Sargassum* and dispose of it before decomposition (Florenne et al., 2016; Hamel et al., 2024). Therefore, it is important to predict strandings accurately in order to collect *Sargassum* shortly after deposition. The predictions of stranding are based on two methodological axes: the detection of *Sargassum* in the ocean based on satellite images (Wang and Hu, 2016) and the modeling of *Sargassum* drift, possibly including biological dynamics (Berline et al., 2020; Jouanno et al., 2021a; Putman et al., 2018).

The detection phase is performed in several steps, including atmospheric correction, cloud and land masking, and spectral reflectance indices computation. Each of these steps can be achieved using different methods, including novel techniques. Similarly, several ocean transport models have been implemented to predict *Sargassum* seasonal dynamics and strandings, based on a variety of sources for input data, and including only physical factors or also biogeochemical parameters. Despite progress in these two fields, several limitations are still persistent and major gaps in our ability to predict *Sargassum* displacement with accuracy and effectiveness remain, partly due to seasonal and interannual variations in their timing and extent and to a lack of knowledge about some processes (Jouanno et al., 2023; Marsh et al., 2022; Skliris et al., 2022; Wang et al., 2019).

A review of current knowledge clusters and gaps is therefore relevant to consolidate and improve understanding of *Sargassum* features (e.g. occurrence, dynamics, spatio-temporal variability). Several reviews already exist on the *Sargassum* topic. Arita et al. (2023) and Fidai et al. (2020) carried out systematic maps, respectively on holopelagic *Sargassum* in general and on *Sargassum* monitoring in particular. GlobalHAB and GESAMP (2024) produced a white paper on the challenges of the *Sargassum* issue. Lazcano-Hernandez et al. (2023) concentrated on the detection algorithms used in *Sargassum* observation. Devault et al. (2021a) looked at the accumulation of contaminants in *Sargassum* and its consequences for valorization. However, to our knowledge, there is a lack of review that performs a synthesis of the entire *Sargassum* monitoring process in the tropical Atlantic Ocean, from satellite images preprocessing to *Sargassum* identification and biomass estimation, to prediction of stranding by physical and biogeochemical modelings and to validation of detection and modeling using in situ data. The different methods and limitations encountered during the detection and modeling steps are thus outlined here. Current knowledge on *Sargassum* ecology, emergence and dynamics in the tropical Atlantic Ocean is also investigated to better understand stranding issues.

The paper is organized as follows. First, the ecology of holopelagic *Sargassum* is presented (Section 2). The emergence and dynamics of *Sargassum* blooms in the tropical Atlantic Ocean are then described (Section 3). The detection of *Sargassum* using remote sensing techniques is reviewed in Section 4, followed by the transport and growth modeling in Section 5. A state-of-the-art of field measurements studies is carried out in Section 6. Finally, some recommendations for future works are proposed for each topic to provide insights into the potential ways for improving *Sargassum* detection and strandings prediction.

2. Ecology of holopelagic *Sargassum*

2.1. Description

Sargassum is a genus of brown algae belonging to the *Sargassaceae* family (order *Fucales*, class *Phaeophyceae*), including 359 benthic or pelagic species (Stiger-Pouvreau et al., 2023). In the Atlantic ocean, three morphotypes of two holopelagic species dominate: *S. fluitans* III, *S. natans* I and *S. natans* VIII (Collins, 1917; Parr, 1939; Siuda et al., 2024) (hereafter referred to as *Sargassum*). These morphotypes can be distinguished mainly by the size of their blades and the presence or absence of thorns (resp. spines) on their stems (resp. bladders) (García-Sánchez et al., 2020; Parr, 1939; Schell et al., 2015) (Fig. 1).

Sargassum morphotypes have an entirely pelagic life cycle, floating at or near the surface thanks to their bladders (Parr, 1939). In the open ocean, individuals often gather in aggregations of various sizes (from a few meters to several hundreds), thicknesses (from a few dozen centimeters to several meters) and shapes (windrows, patches or combination of both), which can group together in structures several kilometers long (Goodwin et al., 2022; Ody et al., 2019; Zhong et al., 2012).

These aggregations are driven by winds, waves, and ocean currents, particularly the wind-induced Langmuir circulation (Langmuir, 1938). Although aggregations tend to form under calm conditions (Parr, 1939), they can disperse in strong winds (4 $m.s^{-1}$) (Marmorino et al., 2011; Woodcock, 1993) although Ody et al. (2019) observed horizontal disaggregation even in low winds, attributed to weakened Langmuir cells. The frontal dynamic is also important in the aggregation process on a larger scale (Zhong et al., 2012). Furthermore, vertical disaggregation can occur due to the submergence of *Sargassum* aggregations in rough seas (Ody et al., 2019; Sun et al., 2024), with descending currents above 4.5 $cm.s^{-1}$ (Woodcock, 1950). The outcome of submerged *Sargassum* (resurfacing or sinking) depends on the duration and depth of submergence, as pressure can cause the collapse of their bladders. The time-depth relationship determining buoyancy loss can be modified by *Sargassum* age, disease or encrustations of epibionts (Johnson and Richardson, 1977).

2.2. Physico-chemical factors affecting growth

Holopelagic *Sargassum* species spread by vegetative growth (Winge, 1923). Doubling times vary between 9 and 200 days depending on location, abiotic conditions, and species, although most studies reported doubling times between 10 and 30 days (Table 3 in Corbin and Oxenford (2023)). Growth rates differ among species, with *S. fluitans* III often outpacing *S. natans* I and VIII (Changeux et al., 2023; Corbin and Oxenford, 2023; Hanisak and Samuel, 1987; Magaña-Gallegos et al., 2023b), although some studies report higher rates for *S. natans* or no differences (Lapointe, 1986; Lapointe et al., 2014; Magaña-Gallegos et al., 2023a).

The observed variability in growth rates can be attributed to different experimental conditions, as multiple parameters influence algal growth, including temperature, salinity, insolation, and nutrient availability. Temperature exerts a significant effect, with a bell-shaped relationship between growth rate and temperature. Hanisak and Samuel (1987) found optimal temperatures of 24–30 °C for *S. fluitans* and 18–30 °C for *S. natans*, with a steep decline in growth rates at lower and higher temperatures and no growth below 12 °C. These findings align with more recent studies by Corbin and Oxenford (2023) and Magaña-Gallegos et al. (2023b), which report higher growth rates at

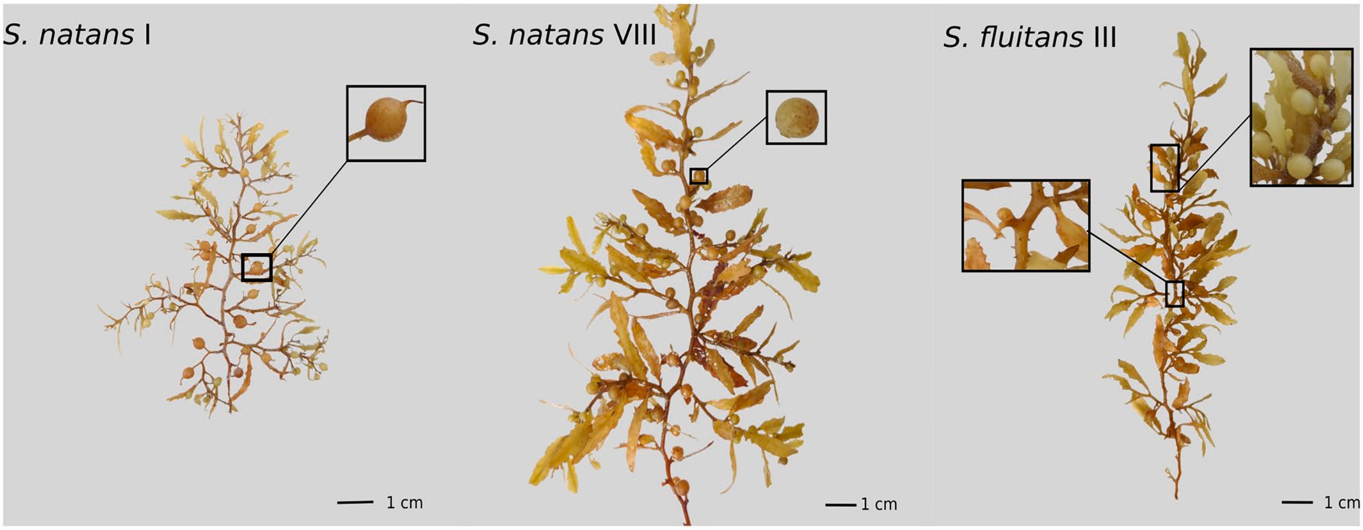


Fig. 1. Morphology of the three holopelagic *Sargassum* morphotypes present in the Atlantic Ocean. Insets zoom in on differences between the morphotypes, in particular the shape of the bladders and the presence or absence of spines on the stem and on the bladders.
From Alleyne et al. (2023a).

temperatures between 25 °C and 28 °C, particularly for *S. fluitans*. However, *S. natans* appears to exhibit greater tolerance to lower temperatures.

The optimal salinity for growth ranges from 36 psu to 42 psu, with a reduction in the growth rate of approximately 50 % at a salinity of 30 psu and no growth below 18 psu (Hanisak and Samuel, 1987). Pelagic species are stenohaline compared to benthic ones and thus are more sensitive to salinity variations encountered in estuaries or coastal areas (Hanisak and Samuel, 1987). However, as highlighted in Schell et al. (2024), while studies agree that optimal temperature and salinity for growth are dependent on morphotypes, there is considerable disagreement about the specific patterns and optimal values.

Insolation also impacts the growth rate, with a compensation point ranging from 25 to 85 $\mu E.m^{-2}.s^{-1}$ and a saturation point ranging from 200 to 1000 $\mu E.m^{-2}.s^{-1}$ (Hanisak and Samuel, 1987; Lapointe, 1995). Pelagic species exhibit higher saturation points than benthic species, indicating adaptation to high light conditions (Hanisak and Samuel, 1987; Lapointe, 1995; Vásquez-Elizondo et al., 2024).

The availability of nutrients, particularly nitrogen (N) and phosphorus (P), limits growth rates in *S. fluitans* and *S. natans* (Lapointe, 1986, 1995). This limitation is more marked in oceanic waters than in neritic ones, leading to a higher growth rate in the latter (Lapointe, 1995; Lapointe et al., 2014). Several sources of N and P could contribute to *Sargassum* aggregations growth, including metabolic activities (e.g. bacterial mineralization of dying *Sargassum*, fishes excretions) (Culliney, 1970; Lapointe et al., 2014), nitrogen fixation by epiphytes (Carpenter, 1972; Hanson, 1977; Phlips et al., 1986) and larger-scale inputs, such as vertical mixing, upwellings, river discharge or atmospheric deposition (Johns et al., 2020; Lapointe et al., 2021; Oviatt et al., 2019; Skliris et al., 2022; Wang et al., 2019). Magaña-Gallegos et al. (2023a) observed no change or even a decrease in growth rates with the addition of nutrients, attributed to either a persistent P-limited environment or to the shading by epiphytes or algae which decreases insolation and photosynthesis. Leemans et al. (2025) also proposed an iron growth limitation.

Finally, Magaña-Gallegos et al. (2023b) suggested seasonal variations in growth rate, potentially related to either internal life cycle, storage of nutrients in vacuoles or temperature-nutrient interactions, as Wu et al. (2022) highlighted for *Sargassum horneri* whose tolerance to high temperature decreases with a high level of N.

The growth and consequently the quantity of *Sargassum* are therefore strongly linked to physico-chemical factors and can change drastically depending on environmental conditions. It is of importance for detection, as *Sargassum* can be observed only if it is sufficiently abundant and aggregated (Section 4). It also suggests the relevance of including these factors when modeling *Sargassum* dynamics (Section 5).

The dependence of growth rates on these parameters also raises questions about the possible evolution of *Sargassum* in the context of climate change and increasing sea surface temperature (hereafter SST). Marsh et al. (2023) suggest that the abundance, spatial and temporal distribution and composition of populations of *Sargassum* may be affected, with lower growth rates or higher mortality rates in the tropics, proliferation poleward, earlier and more prolonged blooms and shifts in community composition based on the optimal temperature range of the morphotypes. Changes in SST could also influence winds, rainfalls and mixed layer depth (MLD), thus impacting *Sargassum* drift and nutrients supply through increased runoff but reduced vertical mixing. Additionally, anthropogenic activities such as deforestation, biomass burning, fertilizer use or urban sewage have led to increased nutrient supply, particularly nitrogen, which could affect *Sargassum* evolution (Aquino et al., 2022; Lapointe et al., 2021).

2.3. *Ecological importance*

Sargassum aggregations constitute ecosystems of high trophic and ecological value in the open ocean (Fig. 2). These habitats host significantly more individuals and species compared to surrounding waters (Casazza and Ross, 2008; Martin et al., 2021; Michotey et al., 2020), with more than two hundred species of different sizes, ages, and ecologies (Coston-Clements et al., 1991; Dooley, 1972; Hoffmayer et al., 2005; Laffoley et al., 2011), including endemic ones (Hemphill, 2005; Laffoley et al., 2011). The ecosystem surrounding *Sargassum* aggregations supports both sessile and mobile fauna (e.g. Bortone et al., 1977; Butler and Stoner, 1984; Calder, 1995; Casazza and Ross, 2008; Coston-Clements et al., 1991; López-Fuerte et al., 2022; Martin et al., 2021; Mendoza-Becerril et al., 2020; Morris and Mogelberg, 1973; Van Tussenbroek et al., 2024; Weis, 1968). Furthermore, migratory species such as dolphins, eels, sea turtles, and seabirds benefit from these aggregations (Beardsley, 1967; Carr and Barkau Meylan, 1980; Haney, 1986; Kracht and Tesch, 1981; Moser and Lee, 2012; Witherington et al., 2012).

Although lower than that of plankton, *Sargassum* productivity is not negligible (Hanson, 1977; Howard and Menzies, 1969), especially in the

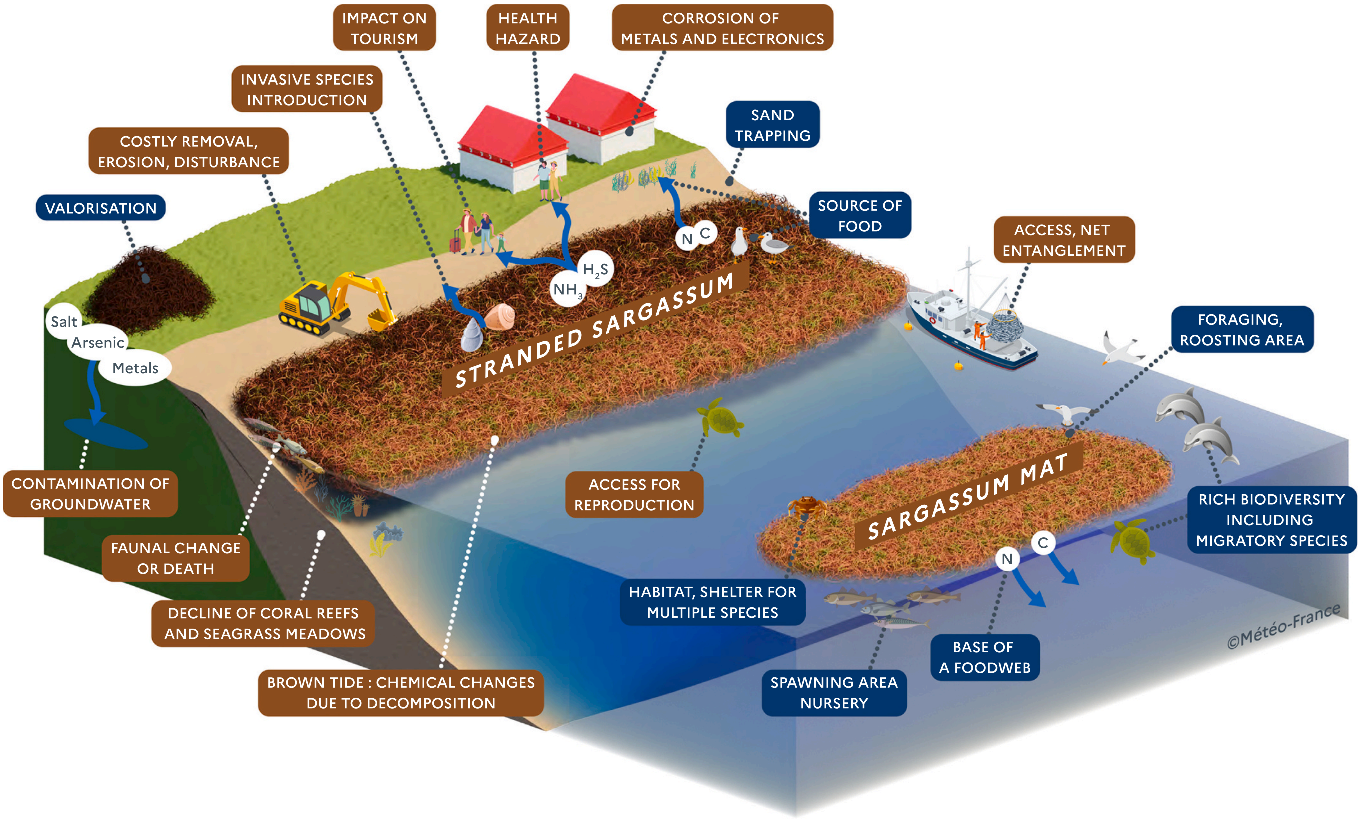


Fig. 2. Ecological value of *Sargassum* aggregations and consequences of their strandings. Blue labels: benefits; brown labels: issues; blue arrows: transmission to another compartment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

upper meter (Pérès, 1982). Associated with nitrogen-fixing cyanobacteria (Phlips et al., 1986), they release dissolved organic carbon and provide nitrogen to the community, which constitutes the base of a food web (Carpenter, 1972; Hanson, 1977; Howard and Menzies, 1969; Powers et al., 2019). These aggregations serve as important foraging areas, spawning areas, habitats for sessile fauna, roosting sites for birds, nurseries for juveniles fishes and turtles and shelters from predators and from wave mechanical action (e.g. Casazza and Ross, 2008; Dooley, 1972; Haney, 1986; Martin et al., 2021; Stoner and Greening, 1984; Wells and Rooker, 2004). Communities tend to be structured, with smaller individuals found closer to or within the aggregations (Casazza and Ross, 2008; Goodwin et al., 2022). These communities are also generally homogeneous and stable over time, likely due to the isolated nature of the aggregations and to favorable interspecific interactions (Martin et al., 2021).

Specific richness and abundance increase with *Sargassum* mass, as larger and more complex habitats provide more diverse growth stages (Casazza and Ross, 2008; Dooley, 1972; Fine, 1970; Haney, 1986; Martin et al., 2021; Moser et al., 1998; Stoner and Greening, 1984; Wells and Rooker, 2004), although this relationship is not always observed (Goodwin et al., 2022; Monroy-Velázquez et al., 2019). *Sargassum* species and morphotypes also play a role in the composition of the community with differences in structure, ramification, size and density of blades and vesicles that induce habitats with different architectures and niches (Bennice and Brooks, 2016; Leite et al., 2007; Stelling-Wood et al., 2020; Ware et al., 2019). *S. fluitans*, with its numerous ramifications and dense foliation, support more diverse and abundant communities than *S. natans* (Alleyne et al., 2023a; Martin et al., 2021; Weis, 1968), although not evidenced in all studies (Stoner and Greening, 1984; Van Tussenbroek et al., 2024). *Sargassum* communities composition is also likely to change in time and space, mainly on a seasonal scale with greater abundance in spring and summer (Butler and Stoner, 1984; Dooley, 1972; Fine, 1970; Monroy-Velázquez et al., 2019) which can be related to modification in oceanographic parameters, *Sargassum* growth or increasing habitat complexity. However, day-night variations were not observed by either Casazza and Ross (2008) or Dooley (1972). Aggregation age can also influence community composition, as changes in antibacterial activity can lead to a bacteria – fauna – algae succession, possibly strengthened by interspecific interactions (Conover and McN. Sieburth, 1964; Stoner and Greening, 1984). Geographical location, including distance from the coasts, can also impact the structure of communities due to differences in physico-chemical conditions or increased foraging pressure from fishes and seabirds (Bortone et al., 1977; Monroy-Velázquez et al., 2019; Niermann, 1986; Van Tussenbroek et al., 2024; Wells and Rooker, 2004).

2.4. Stranding and consequences

While *Sargassum* aggregations are valuable ecosystems in the open ocean, their massive strandings on the Caribbean and West African coasts since 2011 have raised significant concerns. Although small-scale strandings can be beneficial or have minor impacts, massive influxes near or on shore can be harmful (Fig. 2).

From an ecological point of view, stranded *Sargassum* can provide food for animals, be a source of nutrients and organic matter for dune vegetation and of carbonate sediment via its calcareous epiphytes (Salter et al., 2020). Additionally, *Sargassum* can contribute to sand accumulation by trapping sand or promoting vegetation growth (Chávez et al., 2020; Williams and Feagin, 2010).

However, numerous studies report deleterious consequences. When *Sargassum* aggregations accumulate in bays or on beaches, they undergo decomposition, leading to “brown tides” due to dissolved organic matter and the production of leachate. The surrounding waters undergo chemical changes, including hypoxia or anoxia due to bacterial activity, decrease in pH and redox potential, increase in turbidity, temperature, and nutrient load (Liu et al., 2024). As less light is available for photosynthesis, eutrophication of the aquatic environment occurs. Toxic gases such as ammonia (NH_3) and hydrogen sulfide (H_2S) are released (Chávez et al., 2020; Hendy et al., 2021; Van Tussenbroek et al., 2017). All these changes can alter faunal behavior (Antonio-Martínez et al., 2020), shift trophic niches (Cabanillas-Terán et al., 2019) or lead to mortality (Cruz-Rivera et al., 2015; Rodríguez-Martínez et al., 2019). Nearshore communities are modified, with the decline of seagrass beds or coral reefs and their associated fauna in favor of faster-growing communities such as ascidians or algae (Franks et al., 2011; Hendy et al., 2021; Van Tussenbroek et al., 2017) or of bare sand (Bartlett and Elmer, 2021), leading to geochemical changes in sediments (e.g. loss of rhizomes and decrease in below-ground biomass) (Chávez et al., 2020). The ecosystems also provide several services (Barbier et al., 2011) that can thus be compromised, in particular if the phenomenon becomes a regular occurrence, negatively affecting their resilience (Van Tussenbroek et al., 2017). *Sargassum* strandings can introduce invasive species, pathogenic bacteria (e.g. *Vibrio* species) or microplastics, posing risks to local communities and ecosystems (Aldana Arana et al., 2024; Mendonça et al., 2024; Michotey et al., 2020; Tapia-Fuentes et al., 2023; Theirlynck et al., 2023; Van Tussenbroek et al., 2024). On beaches, *Sargassum* can affect turtle reproduction by limiting access to reproductive areas, preventing egg laying, or by modifying temperature, affecting sex ratio or leading to the death of embryos (Azanza Ricardo and Pérez Martin, 2016; Chávez et al., 2020; Gavio and Santos-Martinez, 2018; Maurer et al., 2015). Beach cleaning to remove *Sargassum*, often involving mechanical methods, is also harmful to the environment, compacting the sand, removing the sand along with the algae and accentuating erosion, in turn affecting the reproduction of sea turtles (Chávez et al., 2020). If done close to an aquifer, *Sargassum* storage is likely to impact water quality by contaminating groundwater with nutrients, salt, metals, arsenic or toxic substances released by microplastics (Chávez et al., 2020; Devault et al., 2021b; Rodríguez-Martínez et al., 2020; Tapia-Fuentes et al., 2023).

The emanations of hydrogen sulfide and ammonia from *Sargassum* decomposition can pose health risks to the local population. The effects of acute exposure to these gases are multiple, from headache, dizziness, nausea, and irritation of the skin, eyes, and mucous membranes to pulmonary, neurological, or cardiovascular lesions. During the first eight months of 2018, >11,000 cases of acute exposure were reported in the French Antilles (Resiere et al., 2018). Exposition to high concentrations can also induce paralysis, asphyxia or death. However the effects of chronic exposure on human health are not entirely understood (Bartlett and Elmer, 2021; De Lanlay et al., 2022; Merle et al., 2021; Oyesiku and Egunyomi, 2014; Resiere et al., 2018, 2020, 2021; Rosellón-Druker et al., 2023; Valdez et al., 2012). Few studies also report skin irritation on contact with *Sargassum* which may be attributed to toxins contained in the nematocysts of hydrozoans fixed on the algae (Bartlett and Elmer, 2021; Mendoza-Becerril et al., 2020).

Finally *Sargassum* strandings also have economic consequences, affecting fishing, boat circulation, coastal property value, tourism, and thus employment (Bartlett and Elmer, 2021; Bini, 2015; Fraga and Robledo, 2022; Mohan and Strobl, 2024; Rosellón-Druker et al., 2023; Sansu, 2024; UNEP-CEP, 2021). Schling et al. (2022) estimated an approximate decrease in the gross local product of 11.6 % on Mexican beaches due to *Sargassum* strandings. Bini (2015) estimated an average decrease in the turnover of Guadeloupean companies in the first quarter of 2015 ranging from €10,828 for fishing companies to €67,272 for catering companies. The study also reported an average reduction in the number of days at sea for fishermen of 22 days. Sansu (2024) indicated a diminution of the sale price of properties in zones exposed to *Sargassum* strandings of at least 25 % in the French Antilles. Hydrogen sulfide emissions also have economic impacts through corrosion of copper cables and electronic equipment (Rosellón-Druker et al., 2023; Valdez et al., 2012). Clean-up activities are also a considerable expense (Desrochers et al., 2022; Franks et al., 2011; Smetacek and Zingone, 2013), up to US$1 million per kilometer of coast (Rodríguez-Martínez

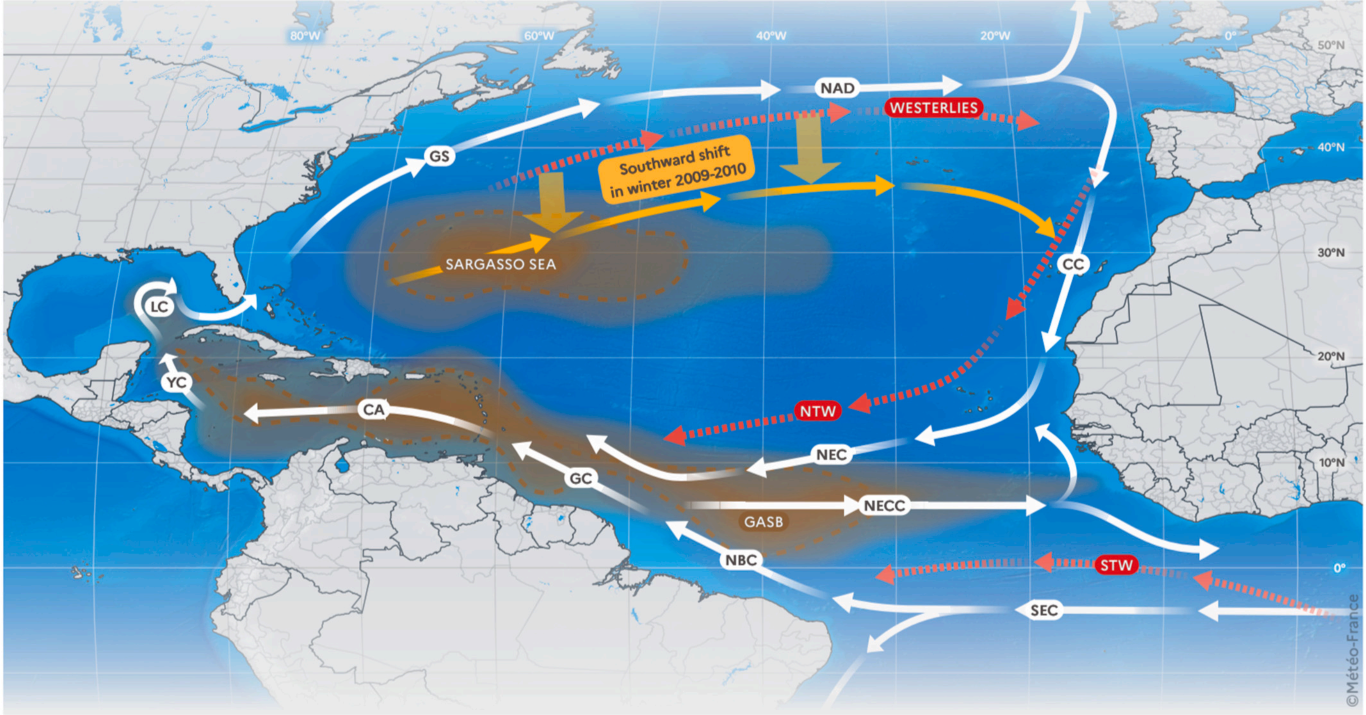


Fig. 3. *Sargassum* situation in the North Atlantic since 2011. White arrows represent surface ocean currents; red arrows represent winds; orange arrows represent the southward shift of surface currents and winds during the winter 2009–2010. CA: CAribbean current; CC: Canary Current; GASB: Great Atlantic *Sargassum* Belt; GC: Guiana Current; GS: Gulf Stream; LC: Loop Current; NAD: North Atlantic Drift; NBC: North Brazil Current; NEC: North Equatorial Current; NECC: North Equatorial Counter Current; NTW: North Trade Winds; SEC: South Equatorial Current; STW: South Trade Winds; YC: Yucatan Current. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2023) and reaching US$120 millions across Caribbean in 2018 (Beckles, 2015). The French government has estimated its expenditure related to *Sargassum* at €53.9 millions over the period 2015–2023, including research, collect and storage (Chamiot Prieur and Lamprea, 2024). Although several valorization pathways are being explored (e.g. use as fertilizer, in pharmaceutical product, or biogas production), these approaches face several limitations. The challenges include predicting the timing, location, and scale of strandings, the chemical composition of different *Sargassum* species, the presence of toxic elements such as arsenic, the costs of collection and transportation, and suitable storage locations (Dassié et al., 2022; Desrochers et al., 2022; Devault et al., 2021a; Milledge and Harvey, 2016; Ortega-Flores et al., 2023).

3. The emergence and dynamics of *Sargassum* blooms in the tropical Atlantic

3.1. Origins

To date, the main hypothesis on the origin of the GASB has been documented by Johns et al. (2020) and confirmed by Jouanno et al. (2025). The unprecedented *Sargassum* inundations in the tropical Atlantic can be traced back to their origins in the Sargasso Sea (Fig. 3). A particularly intense negative anomaly in the North Atlantic Oscillation (NAO) during the winter of 2009–2010 played a key role in driving the southward shift of the westerlies. The center of the subtropical gyre, characterized by low velocities, shifted southward, and the flow that feeds the Canary Current (CC) originated from a more southerly region, including the Sargasso Sea. Resulting anomalous eastward surface currents appeared from the Sargasso sea dragging *Sargassum* aggregations along. As the NAO anomaly subsided, the Canary Current carried the *Sargassum* southward along the West African coast where they entered the tropical Atlantic oceanic system.

The physico-chemical conditions prevailing in the tropical Atlantic are favorable for the growth and survival of *Sargassum* (see Section 2.2), leading to the maintenance of *Sargassum* in the GASB in much larger quantities than in the Sargasso Sea (Jouanno et al., 2025). Limitations to this hypothesis remain to be overcome, particularly with regard to the differences in morphotype diversity between the Sargasso Sea and the GASB (Godínez-Ortega et al., 2021; Schell et al., 2015).

3.2. Seasonal variability

The *Sargassum* population in the tropical Atlantic undergoes spatial and quantitative changes throughout the year driven by a complex and seasonal interplay of oceanic currents, winds and nutrient inputs (Figs. 4 and 5). The InterTropical Convergence Zone (ITCZ), a zone of converging trade winds, aggregates *Sargassum* during March and April whose growth at the surface is sustained by vertical fluxes of nutrients (Johns et al., 2020; Jouanno et al., 2025). During the northward shift of the ITCZ (May to September), *Sargassum* aggregations move north and drift westward and eastward across the Atlantic as they cross the North Equatorial Current (NEC) and the North Equatorial Counter Current (NECC), ultimately reaching the Caribbean Sea, Gulf of Mexico and the West African coast, causing the strandings on the exposed coastal areas (Berline et al., 2020; Franks et al., 2016, 2011; Johns et al., 2020; Putman et al., 2018; Wang et al., 2019; Zhang et al., 2024) (Fig. 4).

Different sources of nutrients could affect their growth during this migration (Fig. 5): vertical fluxes due to wind mixing and Ekman

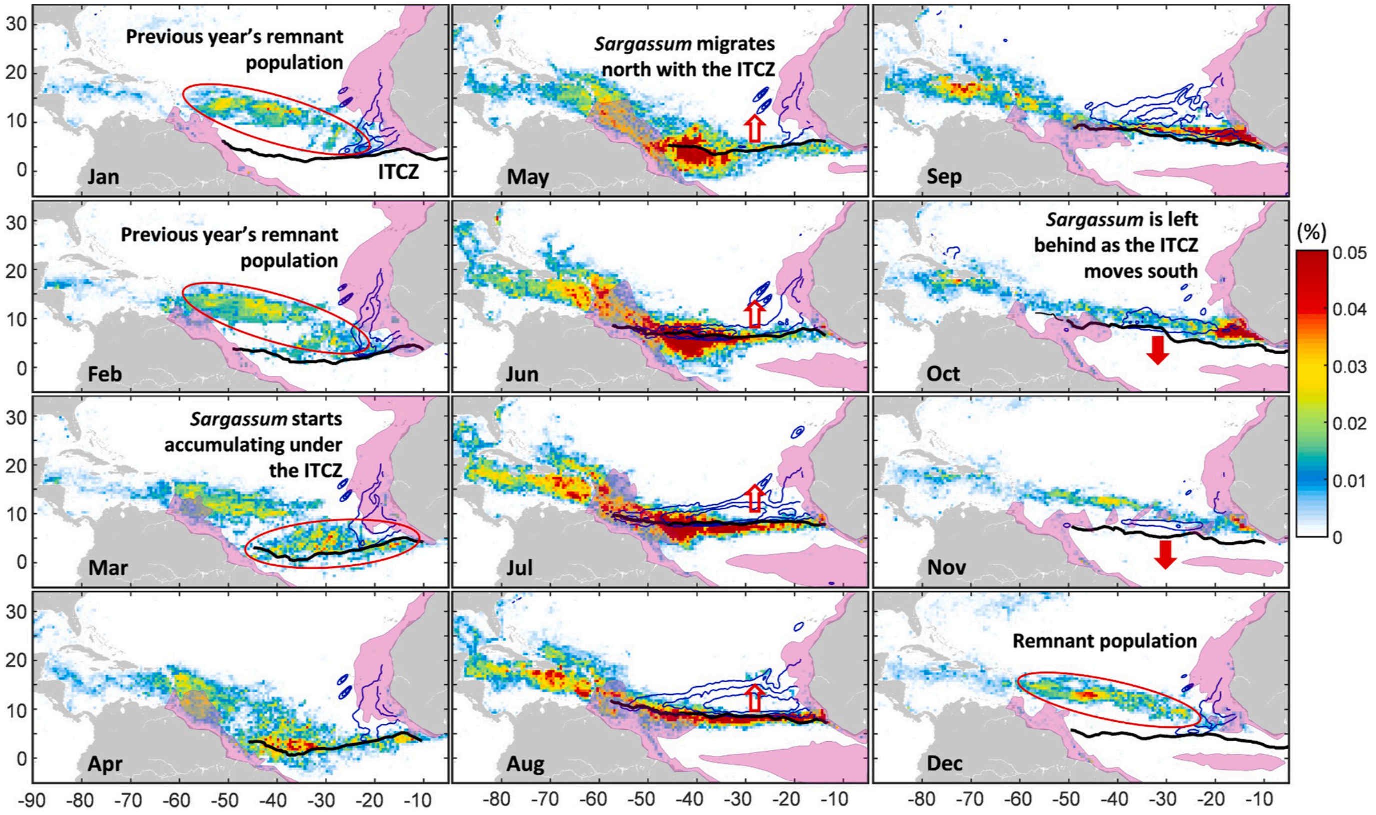


Fig. 4. Evolution of *Sargassum* density over the course of a year. Color bar: *Sargassum* spatial coverage averaged monthly over 2010–2018; black line: InterTropical Convergence Zone; blue line: Ekman pumping (0.1, 0.2 and 0.3 m·d^{-1}); red arrow: ITCZ migration; red oval: remnant population; purple filled-in areas: Chlorophyll concentration above 0.2 mg·m^{-3}, corresponding to plumes of rivers or upwellings and to phytoplankton blooms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
From Johns et al. (2020).

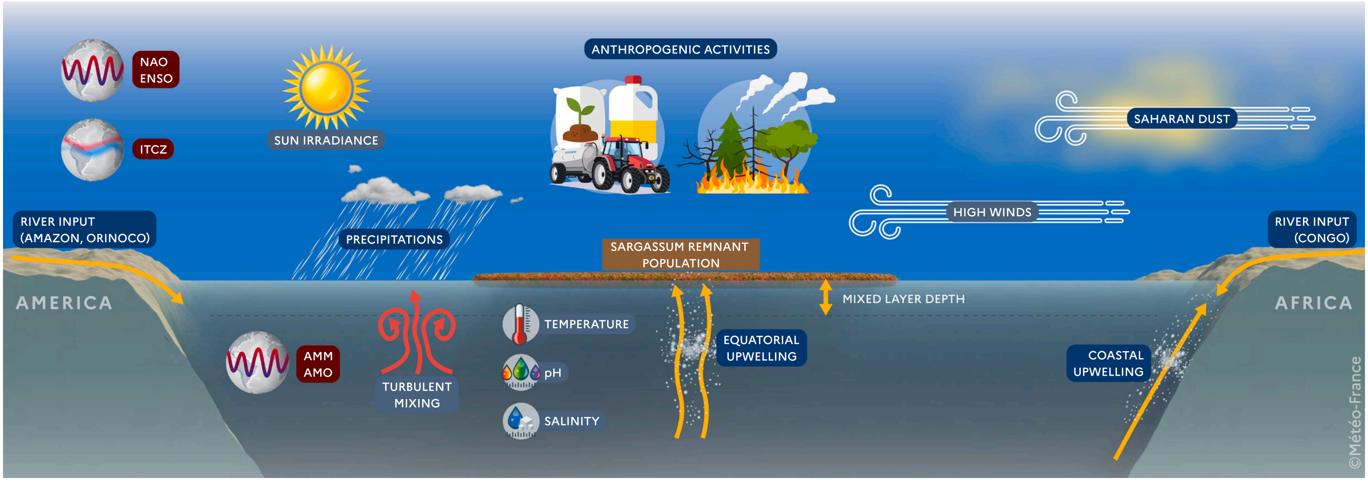


Fig. 5. Possible factors of seasonal and interannual variability in *Sargassum* abundance in the tropical Atlantic Ocean as proposed in the literature. Blue labels: factors related to nutrients; grey labels: physical factors; red labels: global atmospheric and oceanographic phenomena. AMM: Atlantic Meridional Mode; AMO: Atlantic Multidecadal Oscillation; ENSO: El Niño-Southern Oscillation; ITCZ: InterTropical Convergence Zone; NAO: NorthAtlantic Oscillation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pumping in the western tropical Atlantic (Jouanno et al., 2025) or to a deep MLD around August (Johns et al., 2020), equatorial upwellings which reach maximum intensity from June in the east to early autumn in the west (Skliris et al., 2022), African upwellings in the east (Johns et al., 2020; Oviatt et al., 2019), upwellings linked to the north Brazil current retroflection and rings in the west (Johns et al., 2020), atmospheric nitrogen fixation in the western tropical Atlantic (Jouanno et al., 2025). Lapointe et al. (2021), Oviatt et al. (2019), and Wang et al. (2019) also mentioned Saharan dust and riverine plumes as possible nutrient sources, although their contributions are rather small and subject to further investigations (e.g. contribution of the Amazon plume as discussed in Johns et al. (2020) or in Jouanno et al. (2021b, 2025)). Temperature could also explain part of the seasonal variability, with high temperatures in the western tropical Atlantic between August and October generating thermal stress and the decline of *Sargassum* (Jouanno et al., 2025) (see Section 2.2). The intra-annual variability is driven by the combination of all these factors inducing the highest observed density from April to September with a peak around June in the central equatorial North Atlantic (NA), around July in the central tropical NA and around August in the west tropical NA, related to important nutrients sources and convergence by strong winds (Skliris et al., 2022).

With the weakening of the ITCZ and its southward migration, *Sargassum* becomes less aggregated. The remaining patches can either be transported by the North Equatorial Current (NEC) leading to strandings in the Lesser Antilles (Franks et al., 2016) or serve as a seed for the following year's migration (Johns et al., 2020). During the decline phase, the remaining population is sustained by nutrient sources originating from equatorial upwellings (Skliris et al., 2022) and the Mauritania-Senegalese upwelling in the eastern basin (Berline et al., 2020; Franks et al., 2016; Johnson et al., 2020) which peaks in intensity during the winter (Skliris et al., 2022). *Sargassum* aggregations from this region can be entrained in westward transport by the NEC in December-January (Berline et al., 2020).

Different transatlantic pathways can be observed (Beron-Vera et al., 2022),which were linked to morphotypes (Alleyne et al., 2023b). *S. fluitans* III would typically follow a southern path originating near the equator, leading to strandings between March and August. In contrast, *S. natans* VIII would mainly follow a northern path, resulting in strandings between August and February. These differences may be driven by the temperature preferendum of the morphotypes along their trajectories (see Section 2.2).

3.3. Interannual variability

Beyond the variability in the transport of *Sargassum* aggregations within a year, *Sargassum* distribution exhibits a notable interannual variability (Fig. 6, Wang et al., 2019). The first major bloom events occurred in 2011, followed by a general upward trend, with notable peaks in 2015, 2018 and 2022 while 2013 was *Sargassum* free. Although most years experience a single major bloom during summer, 2015 and 2018 also witnessed winter blooms (Johns et al., 2020; Rutten et al., 2021; Skliris et al., 2022; Wang et al., 2019). Several factors contribute

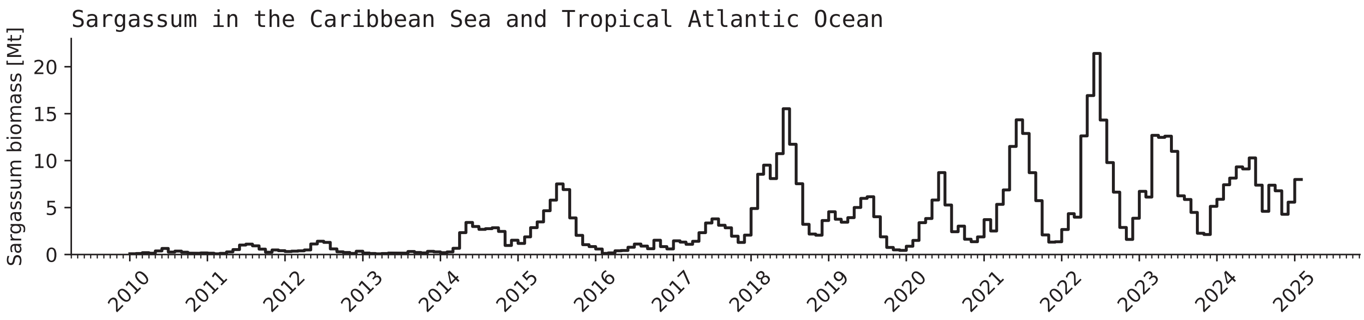


Fig. 6. Monthly evolution of *Sargassum* biomass across the tropical Atlantic and the Caribbean Sea (from 100°W to 0°E, from 0°S to 30°N). Biomass is estimated from the fractional coverage derived from MODIS images detection.
Adapted from Jouanno et al. (2023).

to the interannual variability of *Sargassum* distribution (Fig. 5). According to Marsh et al. (2023) and Skliris et al. (2022), the Atlantic Ocean modes of variability appear to play a major role, particularly the Atlantic Meridional Mode (AMM) on interannual to decadal timescales. Negative AMM phases, associated with strengthened easterly trade winds, drive the ITCZ southward, dragging *Sargassum* aggregations into nutrient-rich waters. Conversely, positive AMM phases lead to northward ITCZ migration, warmer SSTs, and less favorable conditions for blooms. Furthermore, Atlantic Niño can modulate the effects of AMM, as seen in 2018 with a positive phase. In addition, the reinforcement of the wind during the negative AMM phase strengthens the African coastal upwellings and NEC, leading to increased southwestward transport of nutrients towards *Sargassum* in central NA. Finally, the inter-basin teleconnections for the tropical Atlantic are strong (Ferster et al., 2023; Huang, 2004) and some combinations in the mode of variability such as coupled positive Atlantic Multidecadal Oscillation (AMO)/negative NAO under negative El Niño-Southern Oscillation (ENSO) could favor essential physical and biological processes affecting the *Sargassum* population (Sanchez-Rubio et al., 2018). Taking into account these modes is, thus, essential in a perspective of more accurate seasonal forecasts (Marsh et al., 2021; Podlejski et al., 2024; Skliris et al., 2022).

As indicated in the previous section, nutrient supply is another factor that modulates the growth of *Sargassum* population. Riverine outflows and oceanic processes (e.g. currents, MLD) can modulate the nutrient input. Several possible sources of nutrients are mentioned in the literature, including major and nutrient-rich rivers (Oviatt et al., 2019; Skliris et al., 2022; Wang et al., 2019) and anthropogenic activities (Lapointe et al., 2021; Skliris et al., 2022; Wang et al., 2019). However, the extent of their influence remains debated (Jouanno et al., 2021b; Wang and Hu, 2016) as Amazon and Orinoco outflows do not show a high interannual variability (Djakouré et al., 2017). Finally, external factors such as hurricane influence have not yet been fully evaluated as they can be a source of nutrients (Oviatt et al., 2019) as well as a cause of disaggregation or sinking (Sosa-Gutierrez et al., 2022 discussed by Putman and Hu, 2022; Sun et al., 2024).

Temperature also affects growth. Although Skliris et al. (2022) considered it to have a minor influence, Podlejski et al. (2024) referred to it as a dominant growth-limiting factor, and in particular the timing of the warming of the waters off northern Brazil. This warming seems to act as a tipping point between growth and decay due to *Sargassum* tolerance range to high temperatures, and its timing, possibly related to AMM and NAO, may have a significant effect on *Sargassum* annual quantities. Temperature can also impact nutrient availability, but its net effect is complex and can vary regionally depending on a balance between physical ocean variables and nutrient availability (Wang and Hu, 2016; Wang et al., 2019). Although salinity and irradiance can influence *Sargassum* growth, their effects on interannual variability are relatively minor according to Podlejski et al. (2024) and Skliris et al. (2022). Wang and Hu (2016) also suggested that increased precipitations may provide additional nutrients, while Skliris et al. (2022) and Wang et al. (2019) indicated that the concentration of remnant *Sargassum* populations can influence subsequent blooms.

All these factors, in addition to the energy and direction of winds and waves (García-Sánchez et al., 2020; Rodríguez-Martínez et al., 2022; Rutten et al., 2021; Uribe-Martínez et al., 2022), the intensity of oceanic currents (Putman et al., 2018) and the dynamics of eddies (Brooks et al., 2019), can influence the transport and distribution of *Sargassum*, ultimately affecting the extent and location of stranding events. In view of the multiplicity of the drivers affecting *Sargassum* dynamics, of their interactions and of the sometimes divergent results between studies, further research is necessary to gain a better understanding of these seasonal and interannual variability.

4. Detection of *Sargassum* using remote sensing techniques

Sargassum aggregation can be detected using remote sensing techniques. Several sensors are used, either on board polar-orbiting satellites (e.g. MERIS, MODIS, OLCI) or on board geostationary satellites (e.g. ABI) (see Suppl. Mat. A for sensors' names and characteristics). Two main approaches are followed: spectral reflectance indices and machine learning algorithms (Lazcano-Hernandez et al., 2023).

4.1. Spectral reflectance indices approach

The approach based on spectral reflectance indices relies on combinations of spectral reflectance at several wavelengths that emphasize the optical signature of *Sargassum* relative to surrounding waters. The optical properties of *Sargassum* are influenced by the nature of its pigments in the visible range and by the leaf internal structure in the near-infrared (NIR), resulting in a low reflectance in the visible range and a slight increase between 580 and 650 nm with a local minimum at 632 nm, due to absorption by fucoxanthin (400–600 nm) and chlorophyll-c (632 nm), and in a pronounced “red-edge” around 700 nm and a high reflectance beyond (Dierssen et al., 2015; Hu et al., 2015). In contrast, water molecules strongly absorb light in the visible and in the NIR and the ocean layer is optically opaque in the short-wave infrared (SWIR) (Fig. 7). The principle of the method of detection of *Sargassum* that is based on spectral reflectance indices (SRI) involves computing a spectral

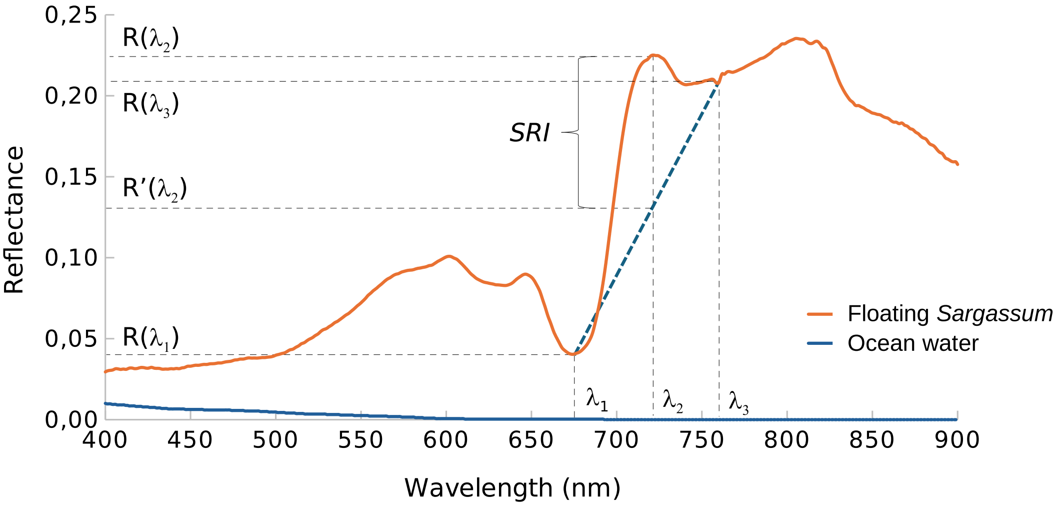


Fig. 7. Remote sensing reflectance of floating *Sargassum* and ocean water. SRI: Spectral Reflectance Index.

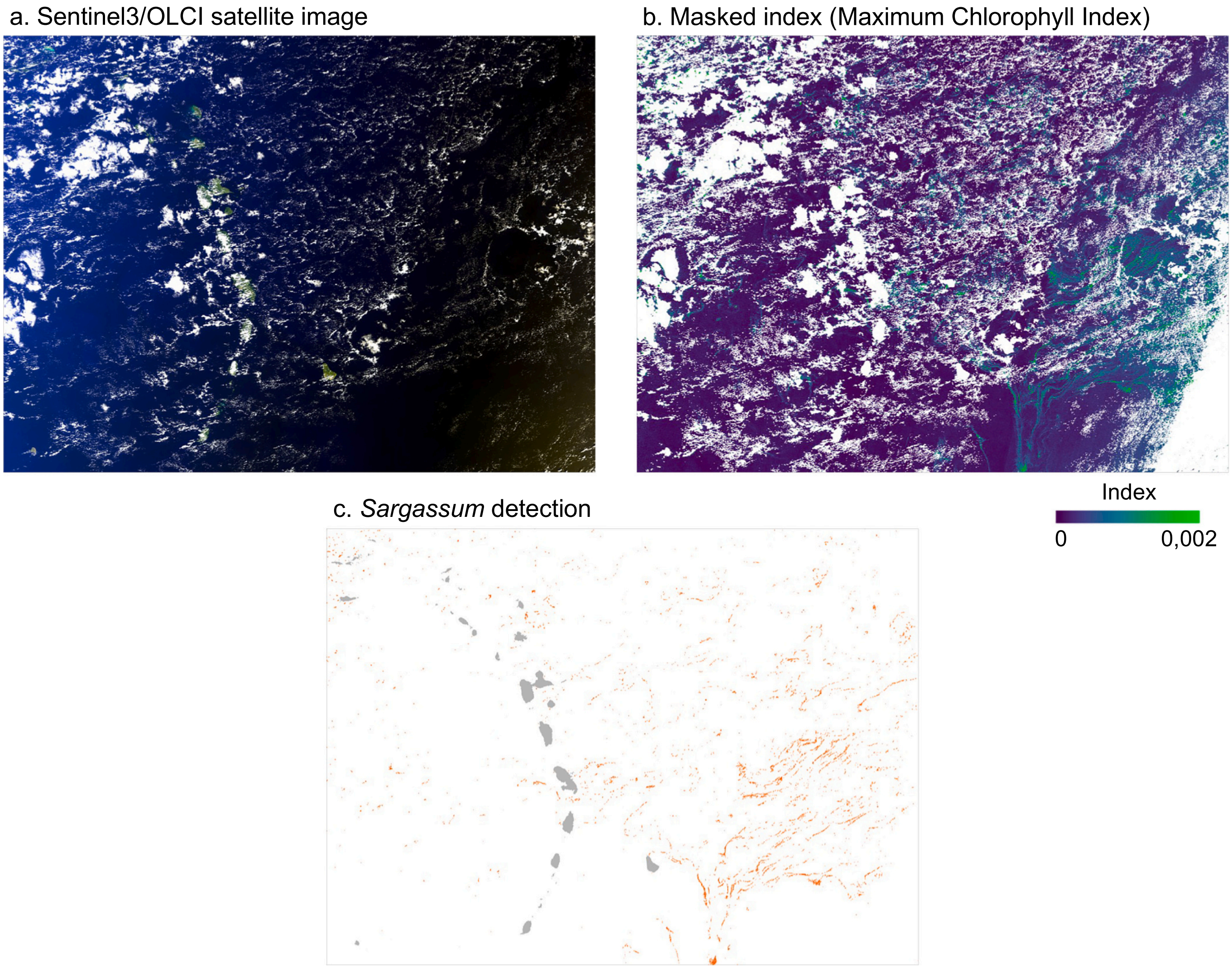


Fig. 8. Example of *Sargassum* detection by remote sensing in the Lesser Antilles. a: Sentinel3/OLCI satellite image from February 2, 2023; b: Masked index (Maximum Chlorophyll Index); c: *Sargassum* detection.

combination of reflectance for each pixel of a given image and comparing it to a predefined threshold value. Pixels for which the SRI is greater than the threshold value are supposed to indicate the presence of *Sargassum* (Fig. 8). The following sections detail the multistage process to implement the spectral reflectance index approach (Sections 4.1.1 to 4.1.6).

4.1.1. *Atmospheric correction*

The detection of *Sargassum* typically requires the water-leaving reflectance derived from satellite data (Level-2 products). Although some studies used Top-of-Atmosphere (TOA) radiance or reflectance (Gower and King, 2011; Gower et al., 2013, 2006; Minghelli et al., 2021; Ody et al., 2019), the atmospheric correction step is essential to remove the contribution of atmospheric effects (absorption/scattering by aerosols, air molecules, gases) from the TOA radiances. The standard open-ocean algorithms assume a zero water reflectance in the NIR (called the “black pixel” assumption) (Gordon and Wang, 1994; Mobley et al., 2016; Siegel et al., 2000), which is not relevant for *Sargassum* detection purposes because it leads to an overestimation of the aerosol contributions when *Sargassum* is present as a result of a non-zero reflectance in the NIR. This bias often leads to an underestimation of *Sargassum* abundance and signal removal (Hu, 2009; Hu et al., 2015; Schamberger et al., 2022b). To prevent such an effect, only the molecular (Rayleigh) scattering effects are subtracted from the TOA radiance (e.g. Descloitres et al., 2021; Minghelli et al., 2021; Ody et al., 2019; Podlejski et al., 2022; Shin et al., 2021; Wang and Hu, 2016, 2018, 2021) (more details in Suppl. Mat. B). However, note that Schamberger et al. (2022b) extended the POLYMER algorithm (Steinmetz et al., 2011) to account for both aerosols and sunglint effects by considering neighboring *Sargassum*-free pixels to determine the aerosol model and by assuming a spatially homogeneous aerosol distribution over a regional study area.

4.1.2. *Cloud, land and sunglint masking*

The clouds and their shadowing effect onto the sea surface, lands, and sunglint are characterized by high reflectance level, which could lead to false positive detections (i.e. wrong detection of *Sargassum* occurrence) when computing spectral reflectance indices. Masking these sources of false detections is thus crucial to discard them prior to computing the reflectance index. The process relies on a high-pass filter at a given wavelength set with an empirical threshold (e.g. Descloitres et al., 2021; Minghelli et al., 2021; Ody et al., 2019; Podlejski et al., 2022; Wang and Hu, 2016, 2018, 2021) (more details in Suppl. Mat. C). For cloud shadowing effects, the uniform threshold value approach is not sufficient because the cloud shadow reflectance is lower than the threshold. Techniques such as Local Total Rayleigh-corrected reflectance (LTR) (Descloitres et al., 2021; Minghelli et al., 2021; Wang and Hu, 2018) or dilating cloud masks to include adjacent shadowed pixels (Ody et al., 2019) mitigate this issue. More complex methods can be implemented to mask clouds, e.g. by comparing the difference of reflectance between a pixel and the background to a threshold (Sun et al., 2024; Wang and Hu, 2020). Note that other supplementary preprocessing steps can be performed, e.g. computing a coastal mask to prevent false detection of high NIR reflectance features such as coral reefs, phytoplankton blooms or shallow waters (Gower and King, 2008, 2011; Podlejski et al., 2022; Wang and Hu, 2016) or reducing image noise by using the Trainable Nonlinear Reaction Diffusion (TNRD) model (Wang and Hu, 2020).

4.1.3. Spectral reflectance index

SRI are combinations of reflectances at different wavelengths. Various SRI, tailored to different sensors and spectral bands, have been proposed (see Suppl. Mat. D for indices' names and Suppl. Mat. E for a list of SRI and SRI-based studies). However, a common strategy is based on the reflectance difference in the NIR and a linear baseline drawn between two surrounding bands, typically the red band and either one NIR or one SWIR band (Eq. (1)). This method quantifies the red-edge reflectance and minimizes the environmental noise (e.g. residual atmospheric effects, sunglint) making it relevant for large-scale studies (Hu, 2009; Qi and Hu, 2021). The three most common indices based on this method are the Floating Algae Index (FAI), the Alternative FAI (AFAI) and the Maximum Chlorophyll Index (MCI).

$$\mathrm{SRI} = \mathrm{R}_{\lambda 2} - \mathrm{R}_{\lambda' 2} \tag{1}$$

$$\text{with } \mathrm{R}_{\lambda' 2} = \mathrm{R}_{\lambda 1} + (\mathrm{R}_{\lambda 3} - \mathrm{R}_{\lambda 1})^{*}\frac{\lambda_2 - \lambda_1}{\lambda_3 - \lambda_{1.}}$$

with $\mathrm{R}_{\lambda 1}$, $\mathrm{R}_{\lambda 2}$, and $\mathrm{R}_{\lambda 3}$ the reflectance values at wavelength λ_1 (red), λ_2 (NIR) and λ_3 ($> \lambda_2$, NIR or SWIR)

Three main reflectance index approaches are used to detect *Sargassum*: computation either of an index, of several indices in a multistep process or of an index deviation. Gower and King (2008, 2011), Ody et al. (2019), and Shin et al. (2021) computed spectral reflectance indices (MCI, AFAI, DVI, SRG, SI). The presence/absence of *Sargassum* within a pixel was assessed by comparing the index value to a threshold.

Hu et al. (2015) opted for a three-step process to detect *Sargassum*. At each step, an index is computed (in order: NDVI, LD and RGR) and compared to a threshold. The occurrence of *Sargassum* is acknowledged if the three indices are above thresholds.

The most commonly used process is the computation of an index deviation, to highlight the spectral signal of *Sargassum* in a pixel whose dominant spectral signal is that of water due to the low fractional coverage (FC) of the algae (Qi and Hu, 2021). The method is outlined in Wang and Hu (2016) and Descloitres et al. (2021). The index deviation is the difference between the index value of a given pixel and the median index value of its surrounding *Sargassum*-free water pixels called background ($\mathrm{SRI}_{\mathrm{bg}}$). This value is not constant throughout the image due to large- and local-scale variations in water reflectance and is thus calculated for each region of the image. Wang and Hu (2016) proposed a 2-step calculation of $\mathrm{SRI}_{\mathrm{bg}}$ to effectively exclude *Sargassum*-contaminated pixels. Descloitres et al. (2021) proposed a variant of that method that accounts for local variations in SRI caused by variations in viewing geometry within a satellite scan. The index deviation with respect to the background is then derived as (Eq. (2)):

$$\delta\mathrm{SRI} = \mathrm{SRI} - \mathrm{SRI}_{\mathrm{bg}} \tag{2}$$

which is expected to depend solely on *Sargassum* abundance within a given pixel. While $\delta\mathrm{SRI} > 0$ theoretically means a *Sargassum* presence, Wang and Hu (2016) empirically determined an optimal threshold value to limit the number of false detections. The radiometric noise and the algorithm uncertainty do not allow the detection of *Sargassum* under that threshold value, i.e. for pixels with very low *Sargassum* fractional coverage.

The index deviation method can be implemented for different satellite sensors and/or reflectance indices, providing that threshold values are adjusted accordingly (e.g. MSI/AFAI in Descloitres et al., 2021, ABI/NDVI in Minghelli et al., 2021, MODIS/AFAI in Wang and Hu, 2016, VIIRS/AFAI in Wang and Hu, 2018, MSI/FAI in Wang and Hu, 2020). Descloitres et al. (2021) and Podlejski et al. (2022) added a final erosion-dilatation step to remove small isolated detections.

4.1.4. Estimation of Sargassum biomass

Quantifying *Sargassum* biomass from satellite data is based on the estimation of FC within pixels. Several methods are implemented to determine the FC (more details in Supp. Mat. F). The simplest one is to consider a proportional relationship between FC and the number of pixels identified as including *Sargassum* (Hu et al., 2016). However, as the FC of *Sargassum* differs from one pixel to another and is <1, such a computation tends to overestimate *Sargassum* cover. Alternative methods have thus been developed. Gower and King (2008, 2011) weighted the number of pixels by the difference between the index value and the background value, Wang and Hu (2016) estimated the FC from SRI values by linear unmixing, while Descloitres et al. (2021) considered a linear relationship between the FC and the SRI deviation.

Finally, Wang et al. (2018) and Wang and Hu (2020) proposed a relationship between SRI and *Sargassum* biomass directly by using a fit to in situ data, through a linear relationship for low index value and a two-degree polynomial otherwise.

4.1.5. Composite images

Composite imagery is often used to reduce noise, mitigate cloud effects, and enhance the signal-to-noise ratio (SNR). The techniques vary, including averaging reflectance over time using geostationary satellites (Minghelli et al., 2021), using maximum index values within a time series (Gower and King, 2008; Ody et al., 2019) or computing mean FC (Wang and Hu, 2016). These composites support monthly and seasonal analyses of *Sargassum* distribution and abundance (Wang and Hu, 2016).

4.1.6. Validation

The validation of *Sargassum* detection techniques is based on different types of data. Few studies use field data, mostly airborne photographs or data collected during cruises (Arellano-Verdejo et al., 2019; Hu et al., 2016; León-Pérez et al., 2023; Ody et al., 2019; Uribe-Martínez et al., 2022). Most studies rely on indirect comparisons, such as observation reports (e.g. Gower and King, 2011; Wang and Hu, 2016), visual inspections (Cuevas et al., 2018; Laval et al., 2023; Qi et al., 2020; Wang and Hu, 2021), or cross-validation with other sensors (e.g. Descloitres et al., 2021; Laval et al., 2023; Minghelli et al., 2021; Wang and Hu, 2016).

4.2. Detection by machine learning

Machine learning (ML) techniques offer a complementary approach to spectral indices. Unlike threshold-based methods, ML models integrate spectral and spatial features, thus reducing false positives near coastlines or clouds. While spectral index approaches deal with *Sargassum* detection at sea, ML algorithms have been focused on detection both in open ocean and onshore, on identification of decay stages or on false detection correction, using different types of images and algorithms (see Suppl. Mat. G for a list of machine learning-based studies). Satellite images are usually preliminary processed by removing atmospheric effects and applying a land and cloud mask (Arellano-Verdejo et al., 2019; Cuevas et al., 2018; Hu et al., 2023; Sun et al., 2024; Uribe-Martínez et al., 2022; Wang and Hu, 2021). The images are selected to ensure that the spectral variations of *Sargassum* features are captured for various environmental or geometric acquisition conditions, to ensure the generalizability of the ML model (Cuevas et al., 2018; Hu et al., 2023; Podlejski et al., 2022). A training dataset is usually manually delineated (Arellano-Verdejo et al., 2019; Arellano-Verdejo and Lazcano-Hernández, 2021; Cuevas et al., 2018; Hu et al., 2023; León-Pérez et al., 2023; Podlejski et al., 2022; Rutten et al., 2021; Valentini and Balouin, 2020; Vasquez et al., 2022). Input data include spectral reflectance at different wavelengths (Arellano-Verdejo et al., 2019; Laval et al., 2023; Zhang et al., 2022), spectral indices (Qi et al., 2022; Wang and Hu, 2021) or a combination of both (Cuevas et al., 2018; Hu et al., 2023; Sun et al., 2024; Uribe-Martínez et al., 2022). Different algorithms are used, including deep learning ones (e.g. UNet in Hu et al., 2023, VGGUnet in Wang and Hu, 2021). The validation step is based on ground truth data (Rutten et al., 2021), visual inspection (Cuevas et al., 2018; Hu et al., 2023; Laval et al., 2023; Wang and Hu, 2021), comparison with airborne images (Uribe-Martínez et al., 2022) or other satellite images classification (Hu et al., 2023; Uribe-Martínez et al., 2022). ML approaches show several advantages: they are fast, reliable, capable of analyzing a large amount of data, flexible so that they are adaptable to different satellite images; they do not rely on threshold definition and are able to take into account spectral information and spatial context (e.g. feature shapes, distance to the coasts, aggregations), thus limiting the false *Sargassum* detections in areas where the spectral reflectance index-threshold approach show limitations (e.g. zones near coasts or clouds) (Hu et al., 2023; Laval et al., 2023; Sun et al., 2024; Wang and Hu, 2021). However, the performance of the model depends on the training dataset which has to be representative of real-world conditions (Hu et al., 2023; Wang and Hu, 2021).

4.3. Limitations

4.3.1. Satellite sensor specifications

Satellite sensor specifications impact the performance of *Sargassum* detection. As reported by Laval et al. (2023), Ody et al. (2019) or Wang and Hu (2020), a finer spatial resolution allows the detection of smaller *Sargassum* aggregations, leading to more accurate mesoscale structure characterization. For example, MSI better identifies the structures of aggregations than OLCI, while the latter achieves better results than VIIRS. Effective detection requires the FC of *Sargassum* within a pixel to exceed a threshold, which depends on the radiometric noise of the sensor and on observation conditions, such as water turbidity and atmospheric conditions (Hu et al., 2015; Qi and Hu, 2021) (see Suppl. Mat. H). The detection thresholds are also dependent on spatial resolution and thus vary across the sensor's field of view (Wang and Hu, 2018). Hu et al. (2015) and Qi and Hu (2021) also proposed to distinguish between detection, which is informative on pixels that include floating materials, and discrimination, which is informative on the identification of the type of materials and species.

The SNR of a given sensor is also crucial for detection: the higher the SNR, the better the detection (Hu, 2009; Hu et al., 2015; Wang and Hu, 2018). However, the spatial resolution remains the most sensitive parameter for improving the performance of *Sargassum* detection retrievals relative to SNR (Hu, 2009).

Similarly, the spectral resolution could alter the performance of discriminating *Sargassum* from other floating materials. Previous studies (Dierssen et al., 2015; Hu et al., 2015) revealed that while certain materials (e.g. oil, garbage) exhibit distinct spectral signatures, seagrass (e.g. *Syringodium*) or cyanobacteria (e.g. *Trichodesmium*) show a reflectance signature similar to *Sargassum*. Then, the discrimination between those species requires a high spectral resolution or specific bands to catch these differences since these species could lead to false detections (Podlejski et al., 2022; Qi et al., 2020; Wang and Hu, 2021).

The spatial and temporal coverage further constrain *Sargassum* detection. Sensors like ETM+ and MSI are primarily land-focused, which limit the amount of available data for open-ocean *Sargassum* monitoring (Hu, 2009; Ody et al., 2019), while sensors such as MODIS, with a broad swath, can cover large areas and mitigate sunglint (Gower et al., 2006). The temporal resolution is critical for tracking *Sargassum* dynamics and can help their detection as *Sargassum* aggregations persist over time compared to transitory phytoplankton blooms (Gower and King, 2011; Gower et al., 2013). However, the temporal resolution requirement for the observation of *Sargassum* for a given sensor is generally inversely correlated to the spatial resolution specification, e.g. geostationary satellites are able to provide a high temporal revisit (<1 h) but lack a high spatial resolution (often >1 km). In addition, the *Sargassum* detection is not feasible at hours for which the solar zenith angle is high because of the weak magnitude of the upward oceanic radiation, thus leading to strong sensor noise (Minghelli et al., 2021).

Finally, some of the artifacts observed for a given sensor could impact the performance of *Sargassum* detection. For example, MSI images are affected by stripes due to differences in the viewing geometry of the sensors, which are difficult to remove (Descloitres et al., 2021; Wang and Hu, 2020). They also suffer from discrepancies between the acquisition time of the different bands, which is problematic in case of fast-moving elements (Wang and Hu, 2020). Similarly, MODIS and VIIRS images are affected by stripes due to scan-to-scan discontinuities, calibration errors and varying radiometric responses of the detectors (Descloitres et al., 2021; Wang and Hu, 2018).

4.3.2. Environmental and observing conditions

The performance of *Sargassum* detection is dependent on environmental and observing conditions. Cloud cover, particularly frequent in the ITCZ, masks large portions of the ocean, reducing spatial coverage and observation frequency (e.g. Gower and King, 2008, 2011; Minghelli et al., 2021; Ody et al., 2019; Wang and Hu, 2016). Similar consequences are produced by haze or sunglint. Turbid atmospheric conditions, such as those caused by Saharan dust, alter the signal in the NIR and influence the performance of the *Sargassum* retrievals (Ody et al., 2019). The adjacency effects induced by the vicinity of lands or shallow waters in coastal water can contaminate the signal, preventing nearshore detection and leading to false detections (Gower and King, 2008, 2011; Gower et al., 2013). Thus, coastal masking is often applied, for instance in Hu et al. (2023) who recommend a minimum buffer of 30-km around lands to significantly improve *Sargassum* detection in MODIS images. However, such a buffer creates data gaps. *Sargassum* decay also alters water color and reduces the algae-water contrast hindering detection (Arellano-Verdejo and Lazcano-Hernandez, 2024).

4.3.3. Satellite image processing method

The image processing methods also influence the detection performance. Noise artifacts (e.g. stripes), which are common in MSI and MODIS images, can be mitigated through algorithms, but these may remove aligned aggregations (Wang and Hu, 2018). Atmospheric correction algorithms often neglect aerosol reflectance, which contributes to signal variability and makes difficult any threshold definition across large-scale scenes (Wang and Hu, 2016). Likewise, masking algorithms may exclude pixels with valid *Sargassum* signals while residual clouds may remain, leading to false positive detections (Hu, 2009; Podlejski et al., 2022; Wang and Hu, 2016, 2018).

The selection of a spectral reflectance index could also show some limitations. Although spectral reflectance indices such as NDVI and EVI are sensitive to environmental (thin clouds, aerosols) and observation (viewing geometry) conditions (Hu, 2009; Shin et al., 2021), FAI is sensitive to clouds and to the parallax effect and AFAI to sunglint (Hu, 2009; Ody et al., 2019; Wang and Hu, 2016). Relying on the reflectance index and a predefined uniform threshold pose challenges for generalization as they are dependent on environmental conditions (Wang and Hu, 2016).

The *Sargassum* biomass estimation is dependent on the method used. Not taking into account the FC of algae within a pixel leads to a biomass overestimation, especially for coarse spatial resolution (Hu et al., 2015; Wang and Hu, 2016; Wang et al., 2021). However, FC is a surface indicator that is only a proxy of biomass as it does not take into account volume (Section 4.3.4). In addition, the coefficients of the index-FC or index-biomass relationship can be determined in several ways (value extraction from images, radiative transfer, generalized linear model; in laboratory or in the field) producing different values, which also depend on the pure spectra used (Descloitres et al., 2021; Hu et al., 2015; Qi and Hu, 2021; Wang et al., 2018) and on the turbidity of water (Descloitres et al., 2021). Regardless of the method, the biomass tends to be underestimated since not all *Sargassum* patches are detected (Hu et al., 2015; Wang and Hu, 2016, 2021; Wang et al., 2018). Yet, this underestimation may be limited as detection oversights more likely concern the smallest ones (Wang and Hu, 2018, 2020). On the other hand, Laval et al. (2023) and Podlejski et al. (2022) highlighted many false detections using a spectral reflectance index approach. Podlejski et al. (2022) indicated a decrease of 50 % of *Sargassum* pixels after filtering, thus implying an overestimation of *Sargassum* biomass.

Composite images affect the performance of *Sargassum* detection as it can combine *Sargassum*-contaminated pixels and *Sargassum*-free pixels due to *Sargassum* drifting between several acquisitions (Minghelli et al., 2021). Instead of using the mean index value of all pixels, some studies use the maximum value (Section 4.1.5), leading to an overestimation of the index and then of the biomass (Wang and Hu, 2016). However, the mean value is sensitive to the number of data, as a too low number, e.g. due to the high cloud coverage in several images, could lead to a statistically biased mean (Wang and Hu, 2018).

Finally, the validation of *Sargassum* detection remains challenging due to a limited availability of ground truth data resulting from various challenges for data collection (e.g. access, size of the study area, *Sargassum* drift) (Wang and Hu, 2018, 2021). Other approaches show limitations, e.g. visual inspection is time consuming (Qi et al., 2020), cross-validation with other sensors is subject to uncertainties (Hu et al., 2016; Wang and Hu, 2021) particularly given the *Sargassum* dynamic between different acquisitions (Wang and Hu, 2018). In addition, the use of remote sensing images prevents all identification at the species level. Lastly, the estimation of biomass remains a challenging task because the collection of *Sargassum* uses different methods, is usually partial, and can include sand or other organisms (Rodríguez-Martínez et al., 2022).

4.3.4. *Sargassum aggregation condition*

An efficient detection of *Sargassum* is dependent on the degree of aggregation of the algae (Gower and King, 2008, 2011). However, Goodwin et al. (2022) reported that small fragments and clumps are more common in the open ocean than extensive windrows and mats, and thus important quantities of *Sargassum* may fall below the detection threshold. High wind conditions can further dissipate the aggregations, making them undetectable (Wang and Hu, 2016). Then, as the algae ages, *Sargassum* undergoes physio-chemical modifications including pigment degradation and epiphyte development, which alter the spectral signature (Chandler et al., 2023; Dierssen et al., 2015). Reflectance is also affected by buoyancy, which can decrease in the case of senescent algae. Submerged *Sargassum*, even at shallow depths, experiences significant signal attenuation (Gower and King, 2008, 2011; Hu et al., 2015; Marmorino et al., 2011) making *Sargassum* detection difficult beyond 2 m (Schamberger et al., 2022a). Finally, biomass quantification is limited by the 2D nature of the detection methods, which do not account for the structure and thickness of the aggregations. Compact aggregations contain more biomass (Dierssen et al., 2015; Wang et al., 2021), while up to 50 % of *Sargassum* biomass may be located below a depth of 2 m which is too deep for remote sensing detection methods (Ody et al., 2019; Schamberger et al., 2022a). Consequently, the current methods likely underestimate *Sargassum* biomass.

5. Transport and biological dynamics modeling

To understand and then predict the evolution and the strandings of *Sargassum*, the transport and biological dynamics have both to be taken into account, depending on the time scale of interest. They are both studied through modeling (Fig. 9).

5.1. *Transport modeling*

Sargassum is displaced on the ocean surface under the actions of the currents, but also of the waves (Stokes) and of a direct effect of the wind (windage). All these different contributions must be considered to properly model and forecast the trajectories of the *Sargassum* aggregations.

5.1.1. *Sources of current and wind data*

Different sources of current and wind data are used. Current data can be derived either from Oceanic General Circulation Models (OGCM), from merged observations, or from drifters (see Suppl. Mat. I). Drifters can be drogued, typically at a depth of 15 m, to reduce wind-induced slippage and drift caused by surface waves, thus more accurately representing subsurface currents (Johnson et al., 2020; Miron et al., 2020). Wind data can be derived from Atmospheric General Circulation Models (AGCM) or from merged observations (see Suppl. Mat. J).

5.1.2. *Influence of the wind*

Since *Sargassum* aggregations float in the surface layer, their trajectory is directly influenced by Stokes drift. As a portion of *Sargassum* may emerge above the water surface, it is also subject to wind forcing, known as windage. The combined effects of Stokes and windage are difficult to disentangle and generally treated as one single effect. This effect is significant, and many studies recommend integrating a windage correction into models, where *Sargassum* velocity is calculated as suggested in Johns et al. (2020) (Eq. (3)):

$$\mathrm{U_S} = \mathrm{U_C} + \alpha_\mathrm{W} {*} \mathrm{U_W} \tag{3}$$

with U_S, U_C and U_W the velocities of the surface, of the surface current, and of the wind at 10 m above the surface respectively, and α_W the windage.

The optimal value of α_W depends on the reference current velocity, ranging from 0 to 3 % (see Suppl. Mat. K), and has a major impact on simulated trajectories (Podlejski et al., 2024; Putman et al., 2018). This variability may reflect the influence of the aggregation structure (Johnson et al., 2020; Marsh et al., 2022; Podlejski et al., 2023), *Sargassum* buoyancy (Putman et al., 2018) and regional conditions such as depth of water and wind fetch (Johnson et al., 2020; Lara-Hernández et al., 2024; Podlejski et al., 2024; Putman et al., 2020). Podlejski et al. (2023) suggested a more complex modeling of *Sargassum* drift (Eq. (4)):

$$\mathrm{U_S} = \alpha_\mathrm{C} {*} \mathrm{U_C} + \alpha_\mathrm{W} {*} \alpha_\mathrm{A} {*} \mathrm{U_W} \tag{4}$$

with α_C a coefficient that modulates current velocity to take into account *Sargassum* resistance to flow and α_A a coefficient modulating wind speed to represent the deviation angle between *Sargassum* drift and wind directions.

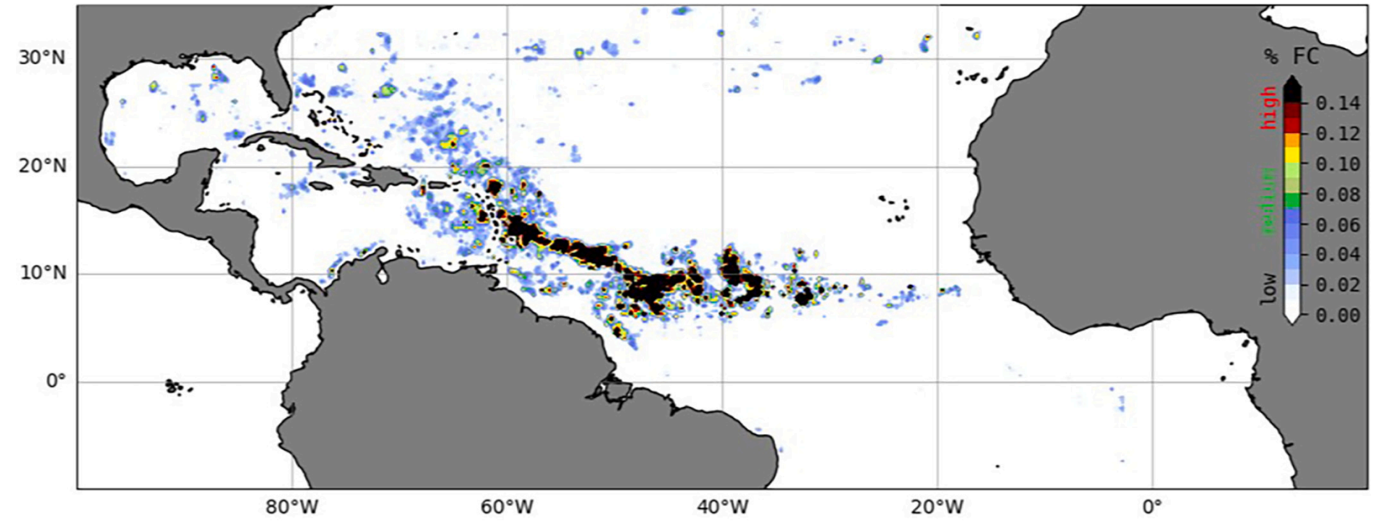
The value of these coefficients depends on the current data used, in particular their spatial resolution, and on *Sargassum* aggregation structures (Podlejski et al., 2024).

Alternatively, the influence of windage can be reduced by considering particles with a density close to that of seawater, forcing them to drift predominantly below the surface and thus being less impacted by wind (*Sargassum*-adapted MOTHY model from Daniel et al. (2021)).

5.1.3. *Design of experiments*

Current and wind data are used to advect a continuous *Sargassum* coverage (in the Eulerian approach, Jouanno et al., 2021a, 2025) or to advect particle (in the Lagrangian approach), with dedicated tools such as Ichthyop (Berline et al., 2020; Johns et al., 2020; Michotey et al., 2020; Podlejski et al., 2024; Putman et al., 2018, 2020), Parcels (Van

a. MODIS *Sargassum* cover – July 2024



b. *Sargassum* seasonal forecast – July 2024

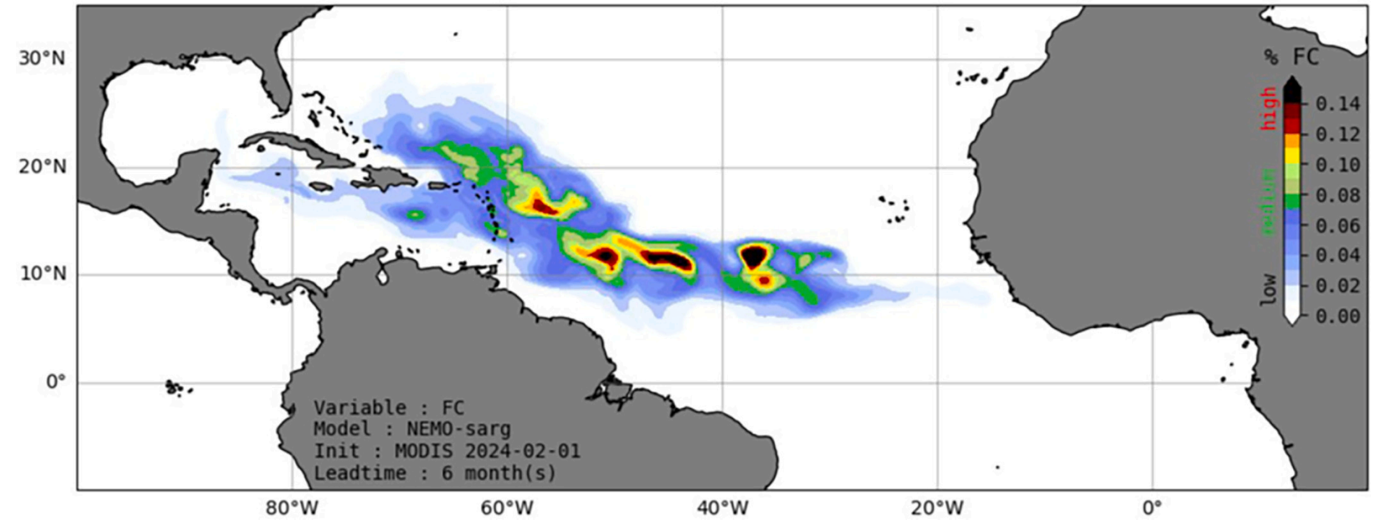


Fig. 9. Example of *Sargassum* coverage forecast for July 2024. a: *Sargassum* cover from MODIS detection for July 2024; b: *Sargassum* cover seasonal forecast for July 2024, from a 6-month simulation with NEMO-Sarg model, initialized with MODIS detection data from February 1, 2024.
Adapted from Jouanno et al. (2023).

Sebille et al., 2021), custom codes (in IDL, Alleyne et al., 2023b) or MOTHY (Daniel et al., 2021).

For the Lagrangian approach, synthetic particles are typically released in these models at *Sargassum* locations with forward or backward tracking for various time durations, ranging from a few days (Johnson et al., 2020; Lara-Hernández et al., 2024; Putman et al., 2020; Van Sebille et al., 2021) to months (Marsh et al., 2021) or even years (Alleyne et al., 2023b; Berline et al., 2020; Brooks et al., 2018; Franks et al., 2016; Johns et al., 2020; Podlejski et al., 2024; Putman et al., 2018). The particles are either randomly distributed (Brooks et al., 2018; Putman et al., 2018) or equally distributed between *Sargassum*-included pixels highlighted by remote sensing. To account for *Sargassum* abundance, each particle is assigned a weight, function of *Sargassum* density in the pixel (Berline et al., 2020; Jouanno et al., 2021a; Marsh et al., 2021; Podlejski et al., 2024; Putman et al., 2018). Forward tracking helps identify transport and stranding regions from predefined source areas, while backward tracking is used to determine the source regions for *Sargassum* transport and stranding at specific locations. These simulations provide insights into the connectivity of oceans between regions and help tracking *Sargassum* pathways and predicting quantities of *Sargassum* that may beach. Machado et al. (2024) also used drift simulations to explain changes in *Sargassum* chemical composition.

Other approaches to model *Sargassum* drift include statistical models (Wang and Hu, 2017), simulated trajectories with the Maxey-Riley equation (Beron-Vera et al., 2019; Miron et al., 2020), Transition Path Theory to data-derived Markov Chain model (Beron-Vera et al., 2022), reoccurring trajectory models (Xu et al., 2022) or tracking *Sargassum* movements through hourly detection from geostationary satellites (Minghelli et al., 2021).

5.2. Biogeochemical modeling

Although transport is the main driver of *Sargassum*'s spatial distribution at short time scales (typically days to weeks) and during specific seasons (e.g. winter when low temperatures limit growth and September when highly stratified water columns reduce vertical mixing and nutrients supply), biological dynamics need to be considered in attempts to model seasonal or interannual *Sargassum* fluctuations (Berline et al., 2020; Brooks et al., 2018; Jouanno et al., 2021a, 2023, 2025). As detailed in Section 2.2, these dynamics are highly related to environmental conditions. Jouanno et al. (2021a) developed an Eulerian *Sargassum* model integrating transport and physiological aspects (growth, mortality, stranding, sinking) through variations in the C, N, and P content. Uptakes rates were modeled as a function of temperature, solar radiation and the N/C and P/C ratios within *Sargassum*, as well as N and P concentrations in seawater, while losses were attributed to mortality, stranding and sinking. The same model was adapted to a Lagrangian approach by Podlejski et al. (2024). Similarly, Brooks et al. (2018) developed a Lagrangian *Sargassum* model where growth was based on irradiance, temperature and nutrients conditions alongside mortality and sinking. Marsh et al. (2021) also included a biological component into their drift model, taking into account growth, mortality and sinking. These studies highlight the importance of considering biogeochemical parameters in modeling *Sargassum* evolution at seasonal and interannual scales, although no dominant factor emerges. Brooks et al. (2018) and Jouanno et al. (2021a) both agree on mortality and nutrient uptake as important biological drivers. Jouanno et al. (2021a) also reported high sensitivity of *Sargassum* distribution to growth rates and optimal irradiance, and to a lesser extent to windage, temperature and Stokes drift, while Brooks et al. (2018) underlined the effect of age-related light access limitations due to epiphyte growth and Podlejski et al. (2024) the effect of temperature on growth.

5.3. Validation

Transport and biogeochemical models are validated by comparisons with *Sargassum* index-based detection of satellite images (Berline et al., 2020; Brooks et al., 2018; Jouanno et al., 2021a, 2023, 2025; Lara-Hernández et al., 2024; Marsh et al., 2021; Putman et al., 2018). Drifters' trajectories can also serve as ground truth to evaluate and validate transport model forecasts (Brooks et al., 2018; Fidai et al., 2023; Johnson et al., 2020; Putman et al., 2020; Van Sebille et al., 2021). Some studies specifically released drifters into *Sargassum* aggregations to track them (Fidai et al., 2023; Putman et al., 2020; Van Tussenbroek et al., 2024). However, the choice of the drifter type is critical, as differences in trajectories can arise depending on whether a drifter is drogued or undrogued, or based on variations in size and shape (Miron et al., 2020; Putman et al., 2020; Van Sebille et al., 2021). Undrogued drifters have been shown to better represent the drift of *Sargassum* (Van Sebille et al., 2021). Most of the drifter-based model validations are qualitative. Liu and Weisberg (2011) proposed a skill score for trajectory model evaluation, which has been widely used for drifter-based quantitative validation.

5.4. Limitations

Detection encounters several limitations already presented previously (see Section 4.3), and so does modeling. These challenges impact the accuracy of trajectory forecasts and stranding locations (Johnson et al., 2020). Models show significant sensitivity to initial conditions (Jouanno et al., 2021a; Lara-Hernández et al., 2024; Miron et al., 2020; Podlejski et al., 2024; Van Sebille et al., 2021), especially over long distances or in regions with complex dynamics (Johnson et al., 2020; Miron et al., 2020). Forward and backward tracking often deliver different results (Johnson et al., 2020) and uncertainties increase with model complexity as errors can accumulate (Miron et al., 2020). Coupled models, while more comprehensive, introduce additional sources of uncertainty due to the large number of interacting parameters (Marsh et al., 2021). Oceanic circulation models perform well for large-scale currents, fronts and mesoscale eddies (Jouanno et al., 2021a; Putman et al., 2020). However, they lose in precision in some regions (e.g. Caribbean Sea, Gulf of Mexico, off North East Brazil and off West Africa) (Johnson et al., 2020; Jouanno et al., 2021a, 2025) or in locations with complex geomorphology (stagnation zone with undercurrents, river outflow, upwelling, transition zones between deep water and coasts) (Johnson et al., 2020; Marsh et al., 2022) and would benefit from higher resolution (Jouanno et al., 2021a, 2025). Surface transport accuracy is limited by the vertical resolution and the degree of ocean-atmosphere coupling, and could benefit from better integration of windage, Stokes drift and tides (Jouanno et al., 2021a,b; Miron et al., 2020; Putman et al., 2020; Van Sebille et al., 2021). A lack of knowledge concerning some oceanic processes, e.g. surface stratification, also affects the accuracy of models (Jouanno et al., 2025). Moreover, key processes like Rossby waves and geostrophic currents are challenging to simulate in equatorial regions (Johnson et al., 2020). Finally Marsh et al. (2022) raised questions about an eventual retroaction of *Sargassum* aggregations on wave fields by modifying the size of Stokes drift.

Biogeochemical models also add complexity and increase uncertainties since state of the art biogeochemical models used to force *Sargassum* growth and decay present difficulties in representing the upper ocean nutrient field and its sensitivity to climate variability (Jouanno et al., 2021a, 2023). Their accuracy is also constrained by the limited knowledge of some biological parameters, e.g. the difference in the physiological responses of the morphotypes or the causes of *Sargassum* mortality (Jouanno et al., 2025; Payne et al., 2024). Other elements such as iron are particularly difficult to model although the variability of their concentration in waters could significantly impact growth rate (Leemans et al., 2025). The exclusion of biological factors, such as growth, mortality, and grazing, further limits model precision, despite their known interactions with physical processes (Berline et al., 2020; Podlejski et al., 2024; Putman et al., 2018, 2020). The coupling of physical, biogeochemical and physiological models remains neglected, as no model accounts for direct nutrient inputs or competitive interactions with phytoplankton (Jouanno et al., 2021a).

Various approaches have been developed to study *Sargassum* dynamics, predominantly using Eulerian methods (Jouanno et al., 2021a, 2025) or Lagrangian frameworks (e.g. Berline et al., 2020; Brooks et al., 2018). However, recent studies (Beron-Vera et al., 2022; Bonner et al., 2024; Brooks et al., 2019; Miron et al., 2020) emphasize the importance of accounting for inertial effects when modeling *Sargassum*. These effects, which depend on the buoyancy and size of the modeled object, can influence simulated trajectories through mechanisms such as shear-induced lift, Coriolis and drag forces. The authors recommend modeling *Sargassum* as a network of elastically interacting inertial particles, representing either gas-filled bladders connected by flexible stems or *Sargassum* clumps interacting inside a raft. Despite these limitations, it is important to note that satellite-based detection, used for model validation, also has its own shortcomings. The inherent uncertainties and errors from satellite data are then propagated and may be amplified (Berline et al., 2020; Jouanno et al., 2021a, 2023; Lara-Hernández et al., 2024; Payne et al., 2024).

6. Field measurements of *Sargassum* aggregations

While *Sargassum* remote sensing and drift modeling have advanced significantly in the last years, their validation requires in situ measurements that remain scarce. *Sargassum*-related field campaigns mainly focus on ecological aspects to inventory biodiversity or measure biochemical contents within aggregations rather than direct support for remote sensing and modeling (e.g. Casazza and Ross, 2008; Martin et al., 2021; Monroy-Velázquez et al., 2019; Van Tussenbroek et al., 2024; Wells and Rooker, 2004, reviewed in Alleyne, 2022; Changeux et al., 2023; Corbin and Oxenford, 2023; Dassié et al., 2022; Lapointe et al., 2014; Machado et al., 2022). To address this gap, a variety of offshore and onshore methods have been employed (more details in Suppl. Mat. L).

Offshore approaches are developed to identify, locate and quantify *Sargassum* aggregations. They include boat-based surveys (e.g. Changeux, 2017; Goodwin et al., 2022; Ody et al., 2019; Thibaut, 2017), airborne imaging (e.g. Dierssen et al., 2015; Hu et al., 2015, 2016; Szekielda et al., 2010), and drifter deployments on *Sargassum* mats (Fidai et al., 2023; Putman et al., 2020; Van Tussenbroek et al., 2024).

Data acquired from boats or aircrafts are of different types: geolocated photographs (Hu et al., 2015, 2016), hyperspectral acquisitions (Dierssen et al., 2015; Hu et al., 2015, 2016; Szekielda et al., 2010), geographical coordinates of aggregations (Changeux, 2017; Goodwin et al., 2022; Hu et al., 2015; Ody et al., 2019; Powers et al., 2013; Thibaut, 2017), aggregations size, weight or volume measurements (Brooks et al., 2019; Hu et al., 2016; Ody et al., 2019; Wang et al., 2018). While most of these studies aim at *Sargassum*, some are opportunistic, i.e. use acquisitions performed with other purposes to retrieve information concerning *Sargassum* (e.g. oil spill tracking in Hu et al., 2015, 2016; Powers et al., 2013; ichthyoplankton samplings in Sanchez-Rubio et al., 2018).

Onshore methods involve beach surveys (Maréchal et al., 2017), drone or airborne remote sensing (Arellano-Verdejo and Lazcano-Hernandez, 2024; Arellano-Verdejo et al., 2022; Fidai et al., 2024; Hernández et al., 2022; León-Pérez et al., 2023), citizen science initiatives (Arellano-Verdejo and Lazcano-Hernández, 2021; Arellano-Verdejo et al., 2022; Iporac et al., 2022; Putman et al., 2023; Triñanes et al., 2021) and videos or webcams deployed in land-based stations (Bouvier, 2024; Moisan et al., 2021; Putman et al., 2023; Rutten et al., 2021; Triñanes et al., 2021; Uribe-Martínez et al., 2022; Valentini and Balouin, 2020). Biomass can also be estimated by field measurements (e.g. thickness of stranded mats in Bartlett and Elmer, 2021) or by reports of *Sargassum* removal by hotels or municipalities (Rodríguez-Martínez et al., 2022; Sissini et al., 2017; Uribe-Martínez et al., 2022). Weight or volume measurements are also performed to assess morphotypes composition of beached *Sargassum* (Alleyne et al., 2023b; García-Sánchez et al., 2020; Mendez-Tejeda and Rosado Jiménez, 2019; Torres-Conde et al., 2023; Vázquez-Delfín et al., 2021).

7. Recommendations

The detection and prediction of *Sargassum* strandings occurring in the tropical Atlantic Ocean require a well-coordinated approach that integrates high-quality observations, model-based predictions and outputs tailored to the end-users. Despite recent advancements in monitoring systems and the development of indicators designed for decision support, many key gaps and issues need to be addressed in the future to significantly enhance the accuracy of *Sargassum* detection and forecasting, improve response planning of local authorities and increase the resilience of coastal communities.

7.1. Importance of in situ measurements and field data collection

The current monitoring systems heavily rely on satellite imagery and biogeochemical/physical models but they lack sufficient in situ observations to significantly improve the performance of remote sensing algorithms (e.g. validation of satellite-derived products) and dynamic model predictions. Standardized methodologies, long-term monitoring programs and expanded networks of in situ sensors are needed to enhance data quality, ultimately improving our understanding of *Sargassum* dynamics and variability. Ground truth data are required to calibrate satellite based indicators and to assess and improve detection and models, in both open ocean and nearshore areas where satellite sensors and models limitations are high due to shallow waters, proximity to land and complex geomorphologies. Onshore cameras would be useful to improve knowledge about strandings in terms of quantity or impacts, or on algae returning to the sea in specific configurations (Bouvier, 2024; Moisan et al., 2021). Although they may drift away from the rafts, the deployment of drifters inside *Sargassum* aggregations would also be a valuable source of information for detection and for physical and biogeochemical modeling thanks to their ability to continuously collect data regardless of cloud cover and to record physical parameters such as currents, winds or SST which impact *Sargassum* displacement and evolution (Fidai et al., 2023). An enhanced in situ data collection could integrate community-based reporting, where local knowledge and frequent updates from affected communities will contribute to a more comprehensive data set. Finally, citizen science should be fostered, both offshore (detection validation) and onshore (e.g. stranding report, morphotypes identification).

7.2. Benefit from the variety and the complementarity of observation satellite sensors

The remote sensing of *Sargassum* is currently based mainly on multispectral images in the visible and the NIR of a given sensor onboard a polar-orbiting satellite. Different complementary data could be exploited to highly increase the performance of satellite retrievals such as:

- Synthetic Aperture Radar (SAR) images: detection from SAR images relies on surface roughness and backscattering. Although it may be less relevant than the use of visible and NIR spectral data in *Sargassum* detection (Fidai et al., 2023; Qi et al., 2022), some encouraging results were reported by Biermann et al. (2024) and Navarro et al. (2024). SAR images could provide valuable complementary pieces of information to data acquired in the visible and NIR range, for example by overcoming weather conditions, and particularly the presence of clouds which are frequent in the ITCZ.
- Geostationary satellites: although detections from sensors on board geostationary satellites are limited by a low SNR and a low spatial resolution (Minghelli et al., 2021; Qi and Hu, 2021; Wang and Hu, 2016), their high temporal resolution as provided by a geostationary orbit is of great interest for investigating sub-daily *Sargassum* dynamics, particularly their drift speed and direction. They also enable the detection of large mats between cloudy periods, and their tracking across several days, thus improving the quality of alert bulletins (Minghelli et al., 2021). The Flexible Combined Imager (FCI) onboard Meteosat Third Generation (MTG) geostationary satellite (Kwiatkowska et al., 2016) which is positioned at a longitude of 0° will enable the study of *Sargassum* from their proliferation zones to their stranding zones.
- Hyperspectral images: thanks to a considerable increase in the number of bands and their lower width, hyperspectral images could improve *Sargassum* detection by enabling better identification of the various floating matter or by gaining understanding in *Sargassum* biological changes over time, e.g. depigmentation. In particular, the new National Aeronautics and Space Administration (NASA) hyperspectral sensors Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) and Geo-stationary Littoral Imaging Radiometer (GLIMR) will provide useful spectral information at different spatial and temporal resolutions that will be highly valuable for the *Sargassum* research field (Dierssen et al., 2023).
- Multi-sensor approach: each sensor has its own characteristics, favoring some properties over others (e.g. spatial vs temporal resolution), and provides a certain amount of information that can complement information from other sensors. As an ideal sensor dedicated to *Sargassum* remote sensing does not exist, an alternative approach is to develop multi-sensor synergy products by combining detections from sensors at different spatial, spectral and temporal resolutions, onboard polar-orbiting and geostationary satellites. More available observations would benefit these products, enabling the study of *Sargassum* dynamics in a changing marine environment, from coastal to open ocean and from local to global scales (Dierssen et al., 2023; Sun et al., 2024).

7.3. Relevant alternative approaches for Sargassum detection

Although efficient in detecting *Sargassum*, methods based on spectral reflectance indices have limitations that can be overcome by alternative innovative approaches:

- Artificial Intelligence (AI): Advances in AI offer promising avenues to improve *Sargassum* monitoring by recognizing complex patterns across large datasets from both remote sensing and in situ sources. Machine learning algorithms could be applied to historical and real-time data to identify recurring influx patterns, optimize the calibration of models, and potentially predict new stranding events with a higher performance. The use of AI could facilitate a continuous feedback loop between observed *Sargassum* dynamics and model-based predictions, enhancing the adaptive capacity of monitoring systems.
- Radiative transfer modeling: the detection performance is less efficient when *Sargassum* is immersed. The use of radiative transfer modeling based inversion approach may be relevant to retrieve *Sargassum* aggregations beyond 2 m depth and to provide subsequent higher biomass estimation (Schamberger et al., 2022a).

7.4. Biomass estimation

Satellite observations of *Sargassum* are limited to information regarding their coverage and current technology is unable to provide three-dimensional information. This gap prevents the computation of biomass variables essential for structuring effective adaptation and mitigation plans. However, a synergy between satellite observations and in situ measurements, such as those obtained by gliders or unmanned underwater vehicles, could fill this gap. By combining these approaches, it would be possible to obtain a more comprehensive and precise understanding of the vertical distribution of *Sargassum*, thereby enhancing the prediction of the quantities of *Sargassum* likely to strand.

7.5. Long-term data continuity

As with in situ data for which it is important to have standardized long-term monitoring protocols, the acquisition of satellite images from the same sensor and their processing by the same method over a long time period is fundamental to *Sargassum* monitoring. Such a time stability enables the analysis of *Sargassum* dynamics over the long term while limiting operational biases. Currently, the longest series of images available is that from the MODIS sensor for which the first available data were acquired before the beginning of the massive strandings (from 1999). Similarly, a multi-year database of physical and biogeochemical factors would also be valuable to improve the understanding of the drivers of growth and decay processes.

7.6. Improvement of the synergy between detection and forecast models

Effective *Sargassum* management depends on accurate and timely predictions, yet the integration between detection systems and model simulations remains insufficient. A higher synergy between remote sensing data, in situ observations and *Sargassum* dynamics modeling would provide a more robust foundation for forecasting.

At short time scales (days to weeks), model simulations need real-time observational input for initialization and predictions validation, particularly in complex coastal areas where wind and current patterns vary at finer scales. Joint studies that apply in situ tracking data (e.g. from drifters) to validate drift models can support an iterative model calibration process, thus improving forecast accuracy and reliability. The development of hyperspectral sensors could also be valuable for biogeochemical model refinement as they will provide information on the modification of spectral signatures that could be induced by biological and chemical transformations. Using *Sargassum* drift velocity derived from successive satellite snapshots can help to forecast drift, and/or correct the OGCM velocity field.

At seasonal time scales (weeks to months), although some models already allow a skillful prediction a few months in advance (e.g. Jouanno et al., 2023), the margin of progress remains important and concerns almost all compartments of the modeling system: initialization during winter and continuous assimilation of *Sargassum* observations, forcing (nutrients), biological modeling including optimization of unconstrained model parameters and parametrization of dynamic subgrid processes (stranding, aggregation). It is essential to take into account the results of ongoing studies on the transport, growth and mortality characteristics of *Sargassum* and their sensitivity to the environment.

7.7. Development of informative, standardized indicators for stakeholders

Outputs from detection and drift simulations may not be easily exploitable by stakeholders and by the general public. Moreover, local adaptation plans need comprehensive information to overcome the consequences of the strandings and to develop specific response strategies. To meet this need and to make information on the risk of stranding accessible to as many people as possible, several institutions have developed indicators. These indicators, mainly relying on 3- or 4-level categorical classifications, assign a stranding risk to a given geographical area, over a period ranging from 4 days to 3 months (e.g. *Sargassum* Inundation Risk (SIR) reports by the NOAA and the University of South Florida (USF) (https://cwcgom.aoml.noaa.gov/SIR/), *Sargassum* stranding forecast bulletins by Météo-France (https://meteofrance.gp/fr/sargasses), *Sargassum* Sub-regional Outlook Bulletin by the University of the West Indies (https://Sargassum-outlook.web.app/), *Sargassum* Tracker by the Caribbean Coastal Ocean Observing System (CARICOOS) (https://www.caricoos.org/Sargassum)). Some more quantitative indicators are also elaborated (e.g. comparison of *Sargassum* abundance to historical values in the bulletins of the Satellite-based *Sargassum* Watch System (SaWS) by USF (https://optics.marine.usf.edu/projects/saws.html), *Sargassum* concentration in CARICOOS bulletins). However, these indicators are sensitive to the accuracy of the input data (e.g. detection accuracy), rely on different methodologies whose assumptions and calculations are not explicitly detailed, making their reproducibility and their intercomparison difficult, and their multiplicity can also blur the message for end users. They also have a coarse resolution and don't consider local characteristics such as the possibility of stranded algae returning to the sea. In addition, there is no consensus on how to define a *Sargassum* stranding in terms of frequency or duration of events, nor a standardized framework to measure or evaluate their magnitude or intensity (Degia et al., 2022). All these limitations complicate the systematic development of these indicators and make them difficult to interpret and adopt. As reported in De La Barreda-Bautista et al. (2023), the expectations of the stakeholders relate to several aspects: on- and offshore presence or absence of *Sargassum* at different time intervals and locations, state of decomposition, location, time and quantity of strandings. Developing indicators at different time scales (in the next few days, weeks or months), at different spatial scales (global over the Atlantic, regional or local at a beach scale) and locations (in open sea or near shore), on different topics (*Sargassum* presence, probability of stranding, estimation of the quantity likely to strand, residual presence on a beach) could help decision-makers in managing the arrival of algae. Based on a standardized methodology, the indicators could then be adapted locally according to factors such as coastal morphology, management practices, environmental constraints or regional specificities. They could also be accompanied by a confidence index to indicate the degree of trust to be placed in them. Despite these challenges, ensuring clear public communication remains a priority to ensure that stakeholders and local populations are adequately informed. Observational tools, forecasting systems, and early warning bulletins must be designed for accessibility and practical use, providing stakeholders with reliable and actionable information. Developing these tools in conjunction with interdisciplinary collaboration and technological innovation should remain a long-term priority for monitoring and coastal management.

7.8. Development of regional collaboration and data sharing

Addressing the *Sargassum* issue requires a coordinated response at the regional scale, where shared data and joint initiatives can amplify the effectiveness of individual monitoring efforts (e.g. *Sargassum* Information Hub (https://Sargassumhub.org/), Sarg'coop (https://sargcoop.org)). A regional data-sharing framework that pools observational data, model outputs, and response strategies will enhance collective understanding and response capabilities. Additionally, fostering collaboration among scientific institutions, government agencies, and local stakeholders can streamline data collection and dissemination, supporting a unified, basin-wide approach to *Sargassum* management.

8. Conclusion

A new equilibrium state has emerged in the tropical Atlantic Ocean since 2011 with the introduction of two holopelagic *Sargassum* species, following an exceptional climate variability event. While these floating algae provide a biodiversity niche offshore, their massive strandings lead to severe environmental and health impacts, with cascading economic and social consequences.

This seasonal phenomenon exhibits interannual variability primarily driven by winds, surface currents and biogeochemical factors, modulated by the low-frequency North Atlantic variability.

Given the growing severity of *Sargassum* influxes, robust forecasting systems are critical for supporting adaptation and mitigation efforts in the affected regions. *Sargassum* are first detected using several satellite images, leveraging the distinct optical properties of the algae compared to the surrounding water. Detection typically relies on spectral index calculations, often associated with machine learning techniques. These detections serve as inputs for models that incorporate both physical parameters and biogeochemical parameters to simulate the drift and the biological dynamics, particularly algal growth and mortality. Significant progress has been made since the first strandings to enhance detection methods and model accuracy. However, challenges remain, as prediction accuracy is limited by sensor capabilities, observation conditions, availability of validation data, and our current understanding of atmospheric and oceanic processes, and of *Sargassum* ecology.

Future progress will require addressing these limitations through technological advancements and exploration of new data sources and methods. As the *Sargassum* issue is a multidisciplinary subject, strengthening the integration of detection and modeling methods and developing collaboration among scientists and decision-makers, at both local and regional scales, will be crucial.

CRediT authorship contribution statement

Marianne Debue: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation. **Thibault Guinaldo:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Julien Jouanno:** Writing – review & editing, Visualization. **Malik Chami:** Writing – review & editing, Methodology. **Sarah Barbier:** Writing – review & editing. **Léo Berline:** Writing – review & editing. **Cristèle Chevalier:** Writing – review & editing. **Pierre Daniel:** Writing – review & editing. **Warren Daniel:** Writing – review & editing. **Jacques Descloitres:** Writing – review & editing. **Jean-Raphaël Gros-Desormeaux:** Writing – review & editing. **Christophe Lett:** Writing – review & editing. **Audrey Minghelli:** Writing – review & editing, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.117923.

Data availability

Data will be made available on request.

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