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Is simultaneous arrival of pelagic *Sargassum* and *Physalia physalis* a new threat to the Atlantic coasts?

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A R T I C L E I N F O

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A B S T R A C T

The massive influxes of pelagic *Sargassum* and *Physalia physalis* have become an increasingly recurrent phenomenon on the Atlantic coasts, affecting the economy and the structure of coastal ecosystems. For the first time, a study assesses the simultaneous arrival of these pelagic organisms. This study was conducted from June/2019 through June/2021 on the littoral of La Habana, one of the circulation points of the currents that form the North Atlantic Subtropical Gyre (NASG) run. Transects of 40 m were located parallel to the shoreline, the biomass of pelagic *Sargassum* was weighed, and the number of colonies of *P. physalis* was counted at the intertidal zone. The biomass of pelagic *Sargassum* was estimated as dry biomass. The simultaneous arrival of pelagic *Sargassum* and *P. physalis* was reported. Simultaneous arrivals of these pelagic species were recorded in the winter seasons, with the occurrence of cold fronts, low mean temperatures (22–27 °C), and strong northerly winds. Most months with the arrival of these pelagic species coincided with a negative average magnitude of the Arctic Oscillation Index, which favors the occurrence of cold fronts and northerly winds. The mean landing dry biomass of *Sargassum* during the peak months was low (0.73 ± 0.54 kg/m^2) compared to the Mexican Caribbean. 145 *P. physalis* colonies over 100 m of coast length per year were reported during the study period. The higher visual occurrence of *Sargassum natans* I and the higher percentage of left-handed *P. physalis* colonies (56.16 ± 3.37) may indicate that the NASG area, which encloses the Sargasso Sea, could be the primary source of arrivals to La Habana littoral. As reported, the distribution of sightings of pelagic *Sargassum* and *P. physalis* coincided in several regions in the Atlantic Ocean and represents an urgent call for coordinated monitoring and development of predictive forecasting of beach landings. This work suggests that there are Atlantic coastal sites such as La Habana littoral that could host the dangerous simultaneous arrivals of pelagic *Sargassum* and *P. physalis*. Finally, the use of remote sensing techniques with in situ observations is considered important for future work, since using remote sensing techniques alone seems to miss important events such as those documented in this study.

1. Introduction

Pelagic *Sargassum* is a brown alga (phylum: Heterokontophyta, class: Phaeophyceae, order: Fucales, family: Sargassaceae) that reproduces vegetatively in the open ocean, which consists of the species *Sargassum fluitans* (Børgesen) Børgesen and *Sargassum natans* (Linnaeus) Gaillon (Areces et al., 1993). These algae have small gas vesicles that allow them to float on the water column (Gower and King, 2019). On the other hand, *Physalia physalis* Linnaeus, 1758 (phylum: Cnidaria, class: Hydrozoa, order: Siphonophora, family: Physaliidae) is a floating polymorphic colony, where each polyp and medusa with specialized functions are integrated to work as a single individual (Mapstone, 2014). *P. physalis*, like pelagic *Sargassum*, move by the force of currents and wind (Ferrer and Pastor, 2017; Brooks et al., 2018). *P. physalis* can also have two distinct forms, so it is considered a species with dimorphism (left- and right-handed individuals) (Ferrer and González, 2020). The dimorphism is believed to be an adaptation of the species to avoid stranding the entire population onshore to die (Woodcock, 1944). "Left-handed" colonies sail to the right of the wind, while "right-handed" colonies sail to the left (Totton and Mackie, 1960). For this reason, it is an important feature for predicting the origin of the arrival of *P. physalis* in the Atlantic Ocean. The worldwide distribution of this dimorphic

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wind-driven organism is a very controversial and poorly known phenomenon at present.

Arrivals of pelagic *Sargassum* and *P. physalis* have historically been reported in the Atlantic Ocean. However, since 2014, arrivals of these pelagic organisms have increased on the coasts (Franks et al., 2011; Smetacek and Zingone, 2013; Prieto et al., 2015; Ferrer and Pastor, 2017, Headlam et al., 2020; Bourg et al., 2022). Schell et al. (2015) and Ferrer and Pastor (2017) place pelagic *Sargassum* and *P. physalis* respectively at a common site called the Sargasso Sea. The Sargasso Sea is an oceanographic region defined by the surrounding currents of the North Atlantic Subtropical Gyre (NASG), where historically the ancient Portuguese fleets could contemplate the large seaweed assemblages in their crossing (Hydrography, 1832). Ferrer and Pastor (2017) propose that the NASG, which encloses the Sargasso Sea, could be a point of origin of *P. physalis* arrivals in the Atlantic Ocean. The relation on the arrival of these pelagic species to the coast of the Atlantic Ocean, however, has not been studied. It is now known that the massive amounts of *Sargassum* that began affecting Atlantic coasts in 2011 were part of the Great Atlantic *Sargassum* Belt, which extends from the West Coast of Africa to the Gulf of Mexico (Wang et al., 2019). However, *Sargassum* influx from the Sargasso Sea continues, although in a lesser magnitude than the latter. This is because the Sargasso Sea is located in an oligotrophic zone (Morel et al., 2010), which limits disproportionate growth, while the site where the Great Sargasso Belt departs is a highly eutrophic zone (Wang et al., 2019), which favors greater growth.

Sargassum coverage in the Atlantic in 2019 reached a record 356 km^2 according to Wang et al. (2019), which has become an alarm for several Atlantic Ocean regions. The massive arrival of pelagic *Sargassum* has caused severe damage to nearshore ecosystems and harmed the economy of several countries, as many depend on beach tourism. Van Tussenbroek et al. (2017) reported a 61.6–99.5% decline in nearshore seagrass biomass at Mexican Caribbean sites such as Puerto Morelos, Mirador Nizuc, Xahuayxol, and Xcalak. This degradation is caused by the *Sargassum*-Brown-Tides resulting from the decomposition of massive accumulation of these algae. In addition, Yamasaki et al. (2014) report that pelagic *Sargassum* may also negatively impact the pelagic ecosystems and associated fisheries. On the other hand, the arrival of *P. physalis* in coastal areas causes a socio-economic impact, mainly on the sun and beach tourism. The sting of these organisms can cause damage to human health (Martínez et al., 2010) and even death (Prieto et al., 2015). According to the World Health Organization (WHO), *P. physalis* is a dangerous aquatic organism for human health and suggests not to bathe in places they usually arrive (WHO, 2003). *P. physalis* also represent a potential hazard to coastal ecosystem food webs because they are efficient consumers of zooplankton (Pitt et al., 2014).

The arrival of these pelagic organisms on the western and eastern Atlantic Ocean coasts has been related to temporary oceanographic/climatic changes, which modify the direction and speed of the winds (Prieto et al., 2015; Torres-Conde and Martínez-Daranas, 2020). In this way, the Arctic Oscillation Index (AOi) is used to measure variability in the northern hemisphere atmosphere and changes in the climatic conditions of the Atlantic Ocean by regulating the intensity of winds and precipitation (Budikova, 2012). The AOi is a major contributor to weather and climate variability in the middle and high latitudes according to Budikova (2012). The AOi fluctuates stochastically between its positive and negative phases on daily, monthly, seasonal, and annual time scales (CPC, 2021). During the positive phase of the AOi, a negative geopotential anomaly is created at the pole and the Polar Jet Stream is intensified, which circumnavigates the region confining the cold air masses. However, in the negative phase, the anomaly is reversed and the belt weakens and deforms, favoring the intrusion of cold air masses at lower latitudes (Thompson and Wallace, 2001; Thompson et al., 2003). This last phase is the one that plays the most important role in the variability of the winter season in the tropics, including Cuba, due to a greater and significant exchange of atmospheric processes (tropic-extratropics). The AOi is also used to measure the frequency and intensity of the cold fronts, which influence strong northerly winds and low temperatures over the western Atlantic Ocean (Cedeño, 2015). These winter conditions have been reported as a predictor of the arrivals of *P. physalis* and pelagic *Sargassum* for northern Cuba by Zúñiga Ríos (1996), Pazos et al. (1996), Moreira et al. (2006), Torres-Conde and Martínez-Daranas (2020), and Torres-Conde et al. (2021). Therefore, air temperature, wind direction, and the number of cold fronts are key variables in understanding the arrivals to northern Cuba. In addition, remote sensing in the open ocean has become a useful tool for monitoring *Sargassum* bloom events in the Atlantic in the open ocean (Wang et al., 2019; Trinanes et al., 2021; Wang and Hu, 2021). However, some platforms have limited spatial and temporal resolution and the variability in the state of organic decomposition and water content in *Sargassum* leads to a significant variation in spectral reflectance (López-Contreras et al., 2021). Therefore, it is important for the scientific community not to ignore the contribution of in-situ observations. Furthermore, there remains a knowledge gap in the dynamics of simultaneous arrivals of these pelagic species in the Atlantic Ocean. Minimizing the social-economic impact of pelagic *Sargassum* and *P. physalis* arrivals on the coasts by improving forecasting systems requires longer monitoring series at points on both sides of the Atlantic Ocean, understanding the specific oceanographic/environmental conditions that cause them.

This work was carried out to analyze the dynamics of beaching of *P. physalis* and pelagic *Sargassum*, and to assess for the first time whether the arrival of these pelagic species coincide in an area where the currents of the NASG run. *Sargassum* morphotype and *P. physalis* dimorphism were used as predictors of arrival origin. The relationship between remote sensing imagery and pelagic Sargassum dry biomass landings during peak months on this coast was examined. A recent analysis and synthesis of available data archives advances our understanding of the distribution of pelagic *Sargassum* and *P. physalis* sightings around the Atlantic Ocean. This work also contributes with a high temporal resolution (monthly) to the monitoring of pelagic *Sargassum* and *P. physalis* landings in the western Atlantic Ocean and the climatological and oceanographic conditions that cause them.

2. Material and methods

2.1. Study area

Calle 16 beach is located in La Habana, 2.3 km from Playita Tritón (23°05′34′′N, 82°27′15′′W) (Fig. 1). The length of the beach is approximately 100 m. The area is composed of a rocky supralittoral, followed by a rocky sublittoral dominated by the urchin species *Echinometra lucunter* (Linnaeus, 1758), and then there is an abrasive rocky zone down to the terrace edge, where there is a continuous coral reef according to Zlatarski and Martínez-Estalella (1980) and Caballero and Guardia (2003). This area offers food and lodging services to visitors. It is completely urbanized and has tourist and recreational activities, mainly in the summer. On the other hand, the study area is affected by strong winds from the north during the winter season and from the east the rest of the year according to Lluis-Riera (1983).

2.2. Data collection

Sampling was conducted monthly, from June 2019 through June 2021 in the last days of each month (25–30). Two 40 m transects, separated by 5m were placed to cover 80% of the beach dimension. A random number table was used to select five points on each transect where sampling would take place. At each point, a 25 × 25 cm square frame was flipped perpendicularly until covering the width of the strip of drift at the intertidal zone (≈5 m). The biomass of pelagic *Sargassum* was weighed at every point. The wet biomass was dried in an oven at 60 °C for 6–10 h. Subsequently, the dry weight was obtained using a technical scale Baxtran (Model Super SS). It was visually observed which

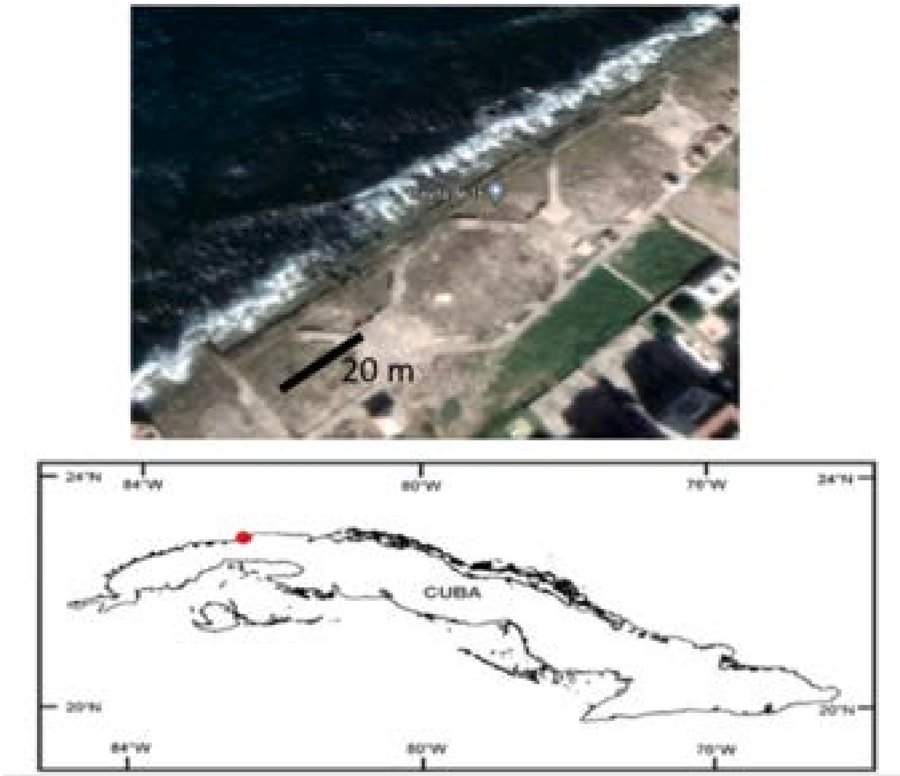

Fig. 1. Map of the study area (Calle 16 beach).

pelagic *Sargassum* morphotype was arriving the most. For the identification of morphotypes, the criteria of Schell et al. (2015) were followed. The remaining pelagic *Sargassum* was removed from the site every month to avoid interfering with the next month's evaluation. For *P. physalis* the number of colonies was counted in each entire transect, covering the intertidal zone (≈5 m) (Fig. 2). The dimorphic form of each colony was noted in situ. If the float of *P. physalis* was oriented to the left it was identified as left-handed *P. physalis*, while if the float was oriented to the right it was identified as right-handed *P. physalis*. The colonies found were removed from the site every month to avoid interfering with the next month's evaluation. Each transect covered an area of ≈ 200 m^2. The total area of study was ≈ 400 m^2. For seven days before each sampling, wind direction and temperature of the air data were obtained from the Windguru website (https://www.windguru.cz/). The number of cold fronts per month that appear in the Monthly Summaries of the Cuban Institute of Meteorology site (http://www.insmet.cu/) (INSMET) was noted. For seven days before each cold front, Arctic Oscillation Index (AOi) data were obtained from the database of the United States Climate Prediction Center (www.cpc.ncep.noaa.goc) (CPC, 2021). The data of pelagic *Sargassum* and *P. physalis* sightings in the Atlantic Ocean were taken from the Global Biodiversity Information Facility (GBIF.org, 2021a; GBIF.org, 2021b; GBIF.org, 2021c) (www.gbif.org). Remote satellite imagery of *Sargassum* coverage in the peak months on this coast were obtained from the Optical Oceanography Laboratory, Satellite-based *Sargassum* Watch System (SaWS, 2022) (https://optics.marine.usf.edu/edu/projects/saws.html)

2.3. Data analysis

The temporal variation (between months) of the dry biomass of

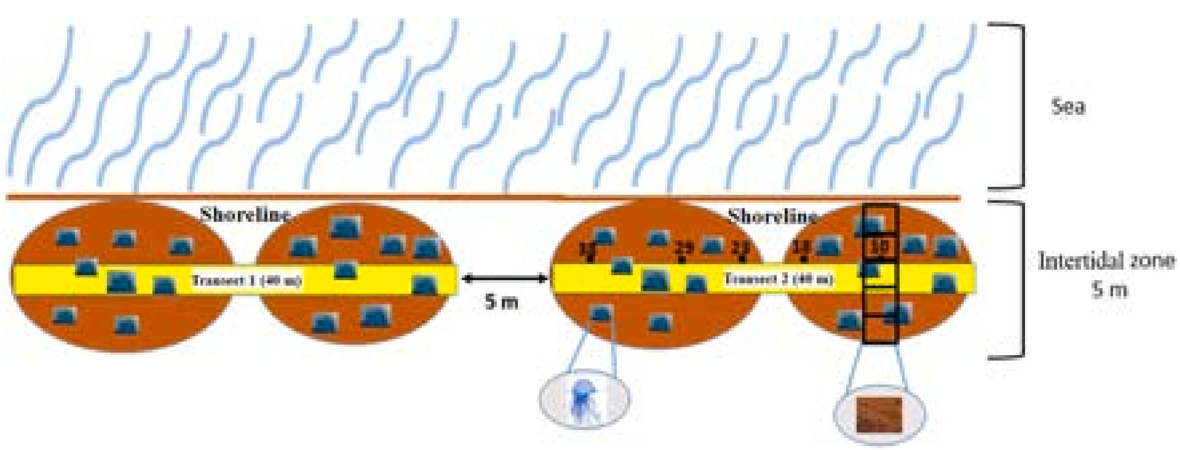

Fig. 2. Sampling methodology for the arrival of pelagic *Sargassum* and *P. physalis* colonies. Pelagic *Sargassum* was sampled at five random points along each transect. *P. physalis* colonies were counted throughout transect 1 and transect 2.

pelagic *Sargassum* and the number of colonies of *P. physalis* were analyzed. For this analysis, the data were standarized to g/m^2 for pelagic *Sargassum* dry biomass and to 200 m^2 for the number of *P. physalis* colonies. A Shapiro-Wilk test was subsequently performed. As the data did not fulfill the assumptions for parametric analysis ($W = 0.6893$, $p < 0.001$ for pelagic *Sargassum* and $W = 0.7525$, $p < 0.001$ for *P. physalis* colonies), a non-parametric test of multiple independent groups of Kruskal-Wallis by Rank was implemented. Pelagic *Sargassum* dry biomass (g/m^2) and the number of colonies of *P. physalis*/200 m^2 were used as variables, and months as factors. A Pairwise Wilcoxon Rank Sum Test with Bonferroni adjustment was conducted to analyze differences between group levels with a correlation of multiple testing. The mean and standard deviation of pelagic *Sargassum* dry biomass (kg/m^2) and *P. physalis* colonies/200 m^2 in the peak months were calculated. For comparison with other sites, the dry biomass was normalized to kg/100 m of coast length per year. Likewise, the number of *P. physalis* was normalized to colonies per 100 m per year. The percentage of each dimorphic form was calculated for the peak months. The mean and standard deviation of the percentage was calculated. To analyze the relationship between the arrival of pelagic *Sargassum* and *P. physalis* colonies, a Spearman's Rank Correlation analysis was performed. The same analysis was used to assess the relationship between the arrival of these pelagic species with the number of cold fronts and temperatures. For this purpose, the mean temperature per month was calculated and used. The sum of the number of cold fronts per month was used. In the case of pelagic *Sargassum* dry biomass, the values of the 5 points sampled per transect were summed. On the other hand, the prevailing wind direction and the mean and standard deviation of the temperature per month were determined. In each month with the presence of cold fronts, the mean and standard deviation of the Arctic Oscillation Index were calculated. Two maps of the sightings of pelagic *Sargassum* and *P. physalis* in the Atlantic Ocean were created. The geographic overlapping of these pelagic species on the maps made it possible to distinguish areas of coincidence in the Atlantic Ocean. Maps of the Greater Caribbean with the results provided by Satellite-based *Sargassum* Watch System (SaWS, 2022) (https://optics.marine.usf.edu/edu/projects/saws.html) for the peak months of pelagic *Sargassum* landing on this coast are presented. Remote sensing of floating algae is measured by the floating algal index (FAI). Floating algae often appears in images as slicks over the relatively homogeneous background in the FAI imagery. All statistical tests were performed using R's free software (R Core Team, 2021).

3. Results

3.1. Temporal variations of the arrivals of pelagic Sargassum and P. physalis colonies

Arrivals of pelagic *Sargassum* and *P. physalis* were recorded from November to April (winter season) in the sampling years. No pelagic *Sargassum* and *P. physalis* colonies were found in the rest of the months. Significant differences between months for both dry biomasses of pelagic *Sargassum* (g/m^2) ($N = 251$, chi-squared $= 220.2$, $df = 24$, $p < 0.001$) (Fig. 3) and number of *P. physalis* colonies per 200 m^2 ($N = 51$, chi-squared $= 48.47$, $df = 24$, $p < 0.001$) (Fig. 4) were reported. The mean landing dry biomass of *Sargassum* during the peak months was 0.73 ± 0.54 kg/m^2 (37 kg/100 m per year). December 2019, January 2020, December 2020, and January 2021 with 1.09 ± 0.41 kg/m^2, 1.32 ± 0.52 kg/m^2, 1.06 ± 0.47 kg/m^2, and 1.12 ± 0.42 kg/m^2, respectively, had significantly higher values than the other months. The arrival of the morphotypes *Sargassum natans* I Parr, *Sargassum natans* VIII Parr and *Sargassum fluitans* III Parr was observed. The predominant morphotype during the study period was *S. natans* I. Similarly, December 2019, January 2020, December 2020, and January 2021 with 17.5 ± 0.7 colonies/200 m^2, 18.5 ± 2.11 colonies/200 m^2, 17.5 ± 2.12 colonies/200 m^2, and 19 ± 1.41 colonies/200 m^2, respectively, had significant differences to other months for *P. physalis*. No pelagic *Sargassum* influxes were detected in the remote sensing imagery for the peak months on this coast (Fig. 5). A total of 289 colonies (in ~100 m of coast length) (~145 colonies per year) were reported during the study period. The mean and standard deviation of the number of colonies during the peak months was 13.5 ± 4.90/200 m^2. A higher percentage of left-handed colonies (56.16 ± 3.37) than right-handed colonies (43.81 ± 3.38) was reported during the study period. The correlation between the dry biomass of pelagic *Sargassum* and the number of *P. physalis* colonies was positively significant ($S = 685.2$, $p < 0.001$, $R = 0.96$).

3.2. Relationship between pelagic Sargassum and P. physalis with the number of cold fronts, mean temperatures, and Arctic Oscillation Index

The relationship between pelagic *Sargassum* dry biomass and mean temperature was negatively significant ($S = 3854$, $p < 0.001$, $R = -0.85$) (Fig. 6 A) and that with the number of cold fronts was positively significant ($S = 225.8$, $p < 0.001$, $R = 0.98$) (Fig. 6 B). Similarly, the relationship between the number of *P. physalis* colonies and mean temperature was negatively significant ($S = 38237$, $p < 0.001$, $R = -0.83$) (Fig. 7 A) and that with the number of cold fronts was positively significant ($S = 638.5$, $p < 0.001$, $R = 0.96$) (Fig. 7 B). The months with

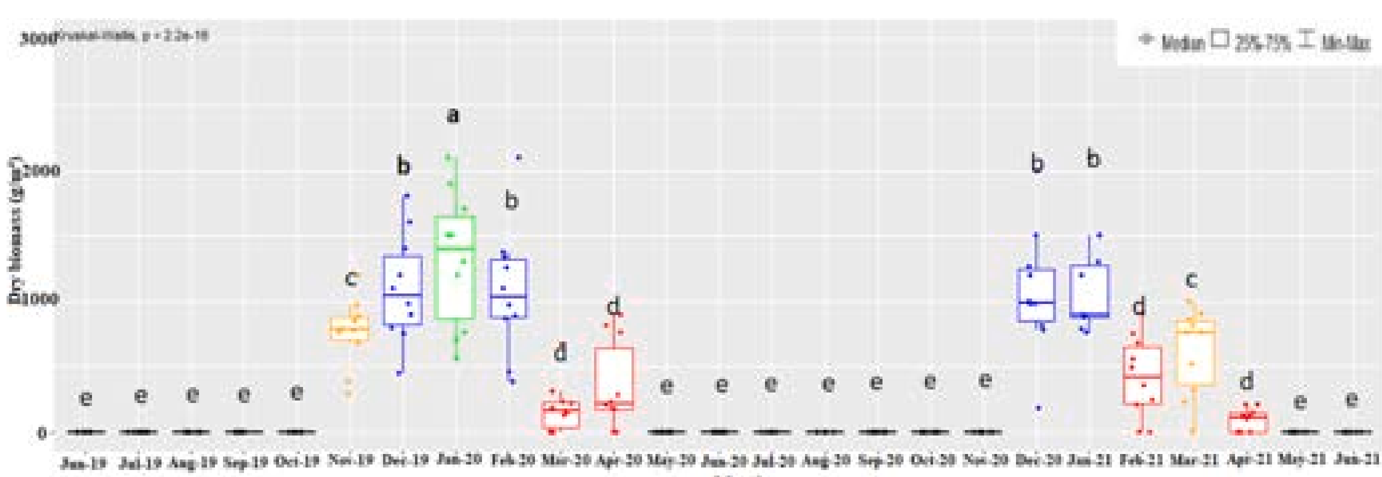

Fig. 3. Temporal variation of pelagic *Sargassum* dry biomass. Different letters and colors represent significant differences. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

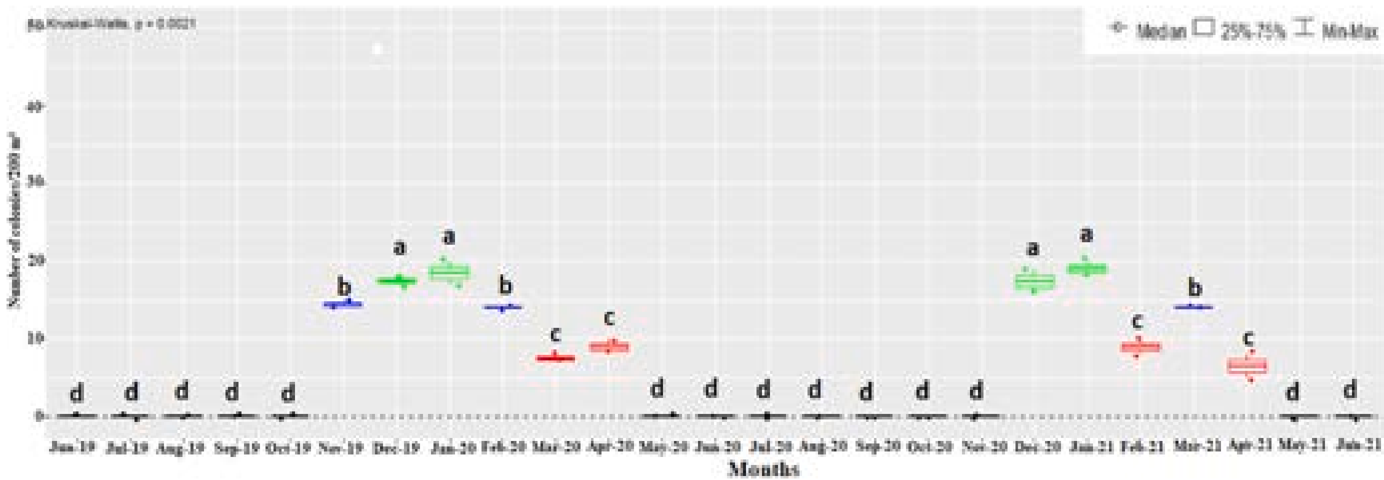

Fig. 4. Temporal variation of the number of *P. physalis* colonies. Different letters and colors represent significant differences. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

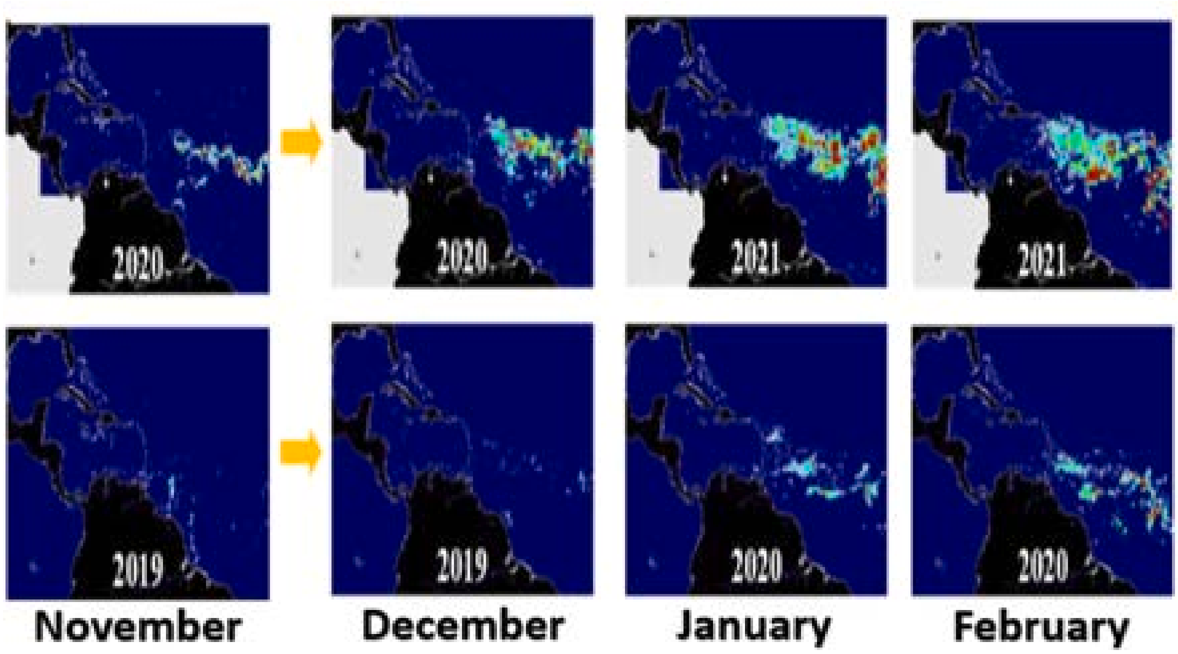

Fig. 5. *Sargassum* coverage in the Greater Caribbean in the peak months of landings on this coast (La Habana littoral) in the winter season 2019–2020 and 2020–2021.

the presence of these pelagic species were characterized by the presence of cold fronts, low mean temperatures, and wind directions mainly from the northern component. (Table 1). The occurrence of left-handed colonies was reported with winds mainly from the north-east, while the occurrence of right-handed colonies was reported with winds mainly from the north-west. The months with no arrivals coincided with the absence of cold fronts. The Arctic Oscillation Index was mostly negative in the months where arrivals and cold fronts were reported (Table 2). Only four (January 2020, February 2020, March 2020, and April 2021) of 11 months with arrivals showed a positive average index. Three (January 2020, February 2020, and March 2020) of these four months belonged to the 2019/2020 winter season. In addition, the wide and similar distribution of these pelagic species throughout the Atlantic Ocean can be observed in the maps of sightings (Fig. 8). Most sightings coincide at several points both in the western Atlantic Ocean and the eastern Atlantic Ocean. According to the data, the highest representation of sightings for pelagic *Sargassum* and *P. physalis* is in the western Atlantic Ocean.

4. Discussion

There are few studies available about pelagic *Sargassum* landing quantities and usually the sampling units are different. To establish a comparison with other studies, data were standardized to kilograms of dry biomass per 100 m of coast length per year. It was also used the mean mass-to-volume value (276 kg·m3) and the mean wet-to-dry weight conversion factor (8.49) provided by Salter et al. (2020). In this study (northwestern Cuba, 2019–2021), 37 kg of dry biomass per 100 m of coast length per year were found. Torres-Conde and Martínez-Daranas (2020) also reported low values of dry biomass (91.5 kg/100 m per year) for northwestern Cuba between 2018 and 2019. Moreira et al. (2006) reported an annual mean of macrophytes dry biomass (including *Sargassum*) of 1020 kg/100 m in northeastern Cuba (between 1993 and 1997). It seems that the northeastern Cuba is more

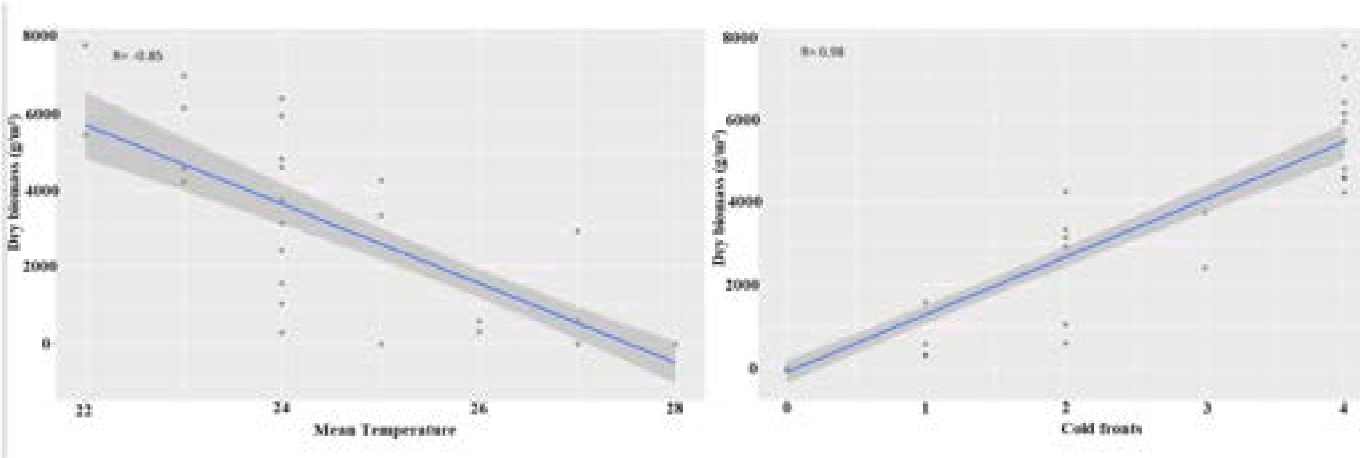

Fig. 6. Relation of the pelagic *Sargassum* dry biomass with the mean temperature (A) and cold fronts (B). R: Spearman Correlation Coefficient.

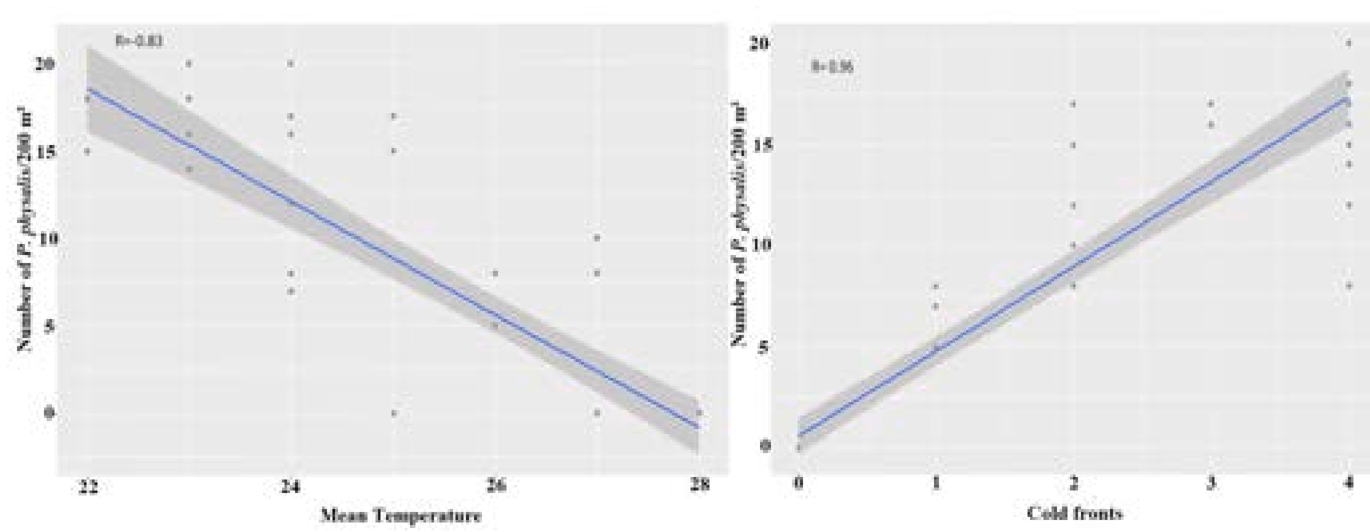

Fig. 7. Relation of the number of *P. physalis* colonies with the mean temperature (A) and cold fronts (B). R: Spearman Correlation Coefficient.

exposed to arrival of pelagic *Sargassum* than the northwestern Cuba. The low dry biomass reported in La Habana could be due to the fact that its geographical location protects its coasts from large arrivals of pelagic *Sargassum*. For southern Cuba, Moreira et al. (2006) reported an annual mean of macrophytes dry biomass (including *Sargassum*) of 2585 kg/100 m (between 1993 and 1997). The authors mentioned above state that southern Cuba is the most affected area in the country with respect to pelagic *Sargassum* arrivals. Moreira et al. (2006) consider that the lower arrival of macrophytes to the northern Cuba is due to the lower frequency of strong northerly winds that reach the Cuban coasts. On the contrary, the greater frequency of strong southerly winds in a greater number of months could favor high values of macrophytes biomass in regions of southern Cuba such as Punta del Este and Cayo del Sur according to Moreira et al. (2006). This is confirmed by this study, where 15 of the 25 months sampled showed prevailing southerly winds. Also, the months with prevailing northerly winds displayed arrival of pelagic *Sargassum* on the north coast. On the other hand, the mean dry biomass of pelagic *Sargassum* to the Mexican Caribbean coasts in 2018 (4500 kg/100 m) and 2019 (4200 kg/100 m) (Rodríguez-Martínez et al., 2022) have been higher than those historically reported in the north and south of Cuba. García-Sánchez et al. (2020) report similar high values of dry biomass (4400 kg/100 m) in Puerto Morelos, Mexico. Apparently, the Mexican Caribbean, being more geographically exposed, continues to be one of the sites most affected by the arrival of pelagic *Sargassum* from the North Equatorial Recirculation Region (NERR). Unlike the north coast of Cuba and similar to the south coast of Cuba, the Mexican Caribbean receives arrivals with prevailing winds from the east and southeast according to Rodríguez-Martínez et al. (2022). Brooks et al. (2018) propose a seasonal scenario of pelagic *Sargassum* in the Atlantic Ocean, where it begins its growth in the spring in the tropics. Subsequently, the biomass is dragged through the Caribbean towards the Gulf of Mexico during the summer. In this crossing, southern Cuba and Mexican Caribbean are affected by the large arrivals from the NERR. The authors mention connectivity between the Gulf of Mexico and the Sargasso Sea, which causes growth in the Sargasso Sea during the summer and early fall. At this point, temperature, light, and nutrients limit the growth of *Sargassum* that will later be exported in smaller quantities to the Caribbean during the winter. The northern region of Cuba seems to be affected at this point. Visually, a greater arrival of the morphotype Sargassum natans I was observed, which is more predominant in the Sargasso Sea (Schell et al., 2015). This could indicate that the Sargasso Sea continues to be one of the major sources of pelagic Sargassum arrivals for northern Cuba as has been reported since 1993 by Areces et al. (1993). Although likely, another important source of pelagic *Sargassum* is also the Gulf of Mexico. The occurrence of the morphotypes S. *natans* I, S. *natans* VIII, and S. *fluitans* III in northwestern Cuba had already been reported by Torres-Conde and Martínez-Daranas (2020). They also state that the arrival of pelagic *Sargassum* in northern Cuba are mostly

Table 1
Months of the sampling period (2019–2021), mean and standard deviation (SD) of pelagic *Sargassum* dry biomass (kg/m2), mean and standard deviation (SD) of *P. physalis* colonies/200m2, mean and standard deviation (SD) of the percentage of Left-handed colony, mean and standard deviation (SD) of the percentage of Right-handed colony, number of cold fronts, mean and standard deviation (SD) of the air temperature (°C), and direction of prevailing winds.

Months	Dry biomass (kg/m2) (mean ± SD)	Colonies/200m2 (mean ± SD)	Left-handed colony (%) (mean ± SD)	Right-handed colony (%) (mean ± SD)	Cold Fronts	Temperature (°C) (mean ± SD)	Direction of prevailing winds
June 2019	0	0	0	0	0	28 ± 3.12	WSW
July 2019	0	0	0	0	0	28 ± 4.01	SSE
August 2019	0	0	0	0	0	28 ± 3.96	ESE
September 2019	0	0	0	0	0	27 ± 3.12	ESE
October 2019	0	0	0	0	0	27 ± 4.00	WSW
November 2019	0.75 ± 0.26	12.5 ± 6.36	60.66 ± 2.6	39.33 ± 2.59	2	25 ± 3.20	ENE
December 2019	1.09 ± 0.41	17.5 ± 0.7	51.63 ± 10.16	48.36 ± 10.16	4	24 ± 4.10	NNE
January 2020	1.32 ± 0.52	18.5 ± 2.11	59.41 ± 0.83	40.58 ± 0.82	4	22 ± 3.96	NE
February 2020	1.07 ± 0.49	16 ± 1.41	65.65 ± 1.34	34.31 ± 1.38	4	24 ± 3.68	ESE
March 2020	0.18 ± 0.20	7.5 ± 0.70	59.82 ± 3.79	40.17 ± 3.78	1	24 ± 3.33	ENE
April 2020	0.35 ± 0.33	9 ± 1.41	46.25 ± 3.18	53.75 ± 3.21	2	27 ± 3.01	NNW
May 2020	0	0	0	0	0	27 ± 4.32	ESE
June 2020	0	0	0	0	0	28 ± 4.55	WSW
July 2020	0	0	0	0	0	28 ± 4.61	SSE
August 2020	0	0	0	0	0	28 ± 3.77	ESE
September 2020	0	0	0	0	0	27 ± 3.99	SW
October 2020	0	0	0	0	0	27 ± 4.55	NNW
November 2020	0	0	0	0	0	25 ± 4.10	SSE
December 2020	1.06 ± 0.47	17.5 ± 2.12	54.44 ± 2.55	45.55 ± 2.55	4	23 ± 4.62	ENE
January 2021	1.12 ± 0.42	18.5 ± 2.11	55.8 ± 4.22	44.15 ± 4.25	4	23 ± 3.23	EN
February 2021	0.42 ± 3.17	10 ± 2.82	47.91 ± 3.69	52.08 ± 3.76	2	24 ± 3.90	NNW
March 2021	0.16 ± 0.35	15.5 ± 2.12	55.04 ± 2.96	44.95 ± 2.96	3	24 ± 4.44	ENE
April 2021	0.09 ± 0.08	6.5 ± 2.12	61.25 ± 1.76	38.75 ± 1.76	1	26 ± 4.00	SSE
May 2021	0	0	0	0	0	27 ± 3.94	ESE
June 2021	0	0	0	0	0	28 ± 3.11	ESE

Table 2
Mean and standard deviation (SD) of the Arctic Oscillation Index (AOi) in the months with the presence of cold fronts and arrival of pelagic *Sargassum* and *P. physalis* colonies.

Months with cold fronts and arrivals	AOi (mean ± SD)
November 2019	−1.45 ± 0.35
December 2019	−0.51 ± 0.96
January 2020	1.71 ± 1.05
February 2020	2.41 ± 2.11
March 2020	2.170 ± 0.66
April 2020	−0.01 ± 0.62
December 2020	−1.54 ± 1.00
January 2021	−2.60 ± 0.80
February 2021	−1.07 ± 1.66
March 2021	−0.04 ± 0.72
April 2021	1.84 ± 0.82

composed of the morphotype S. *natans* I.

Similarly, there are few studies available about *P. physalis* landing quantities. 145 *P. physalis* colonies/100 m per year were reported in this study. This value is higher than the 44 colonies/100 m reported between 2018 and 2019 by Torres-Conde et al. (2021) for the beaches of La Habana del Este. The results of this study are in accordance with Torres-Conde et al. (2021) which suggest that the arrival of *P. physalis* in the western Atlantic Ocean is more significant than in the eastern Atlantic Ocean and the Mediterranean Sea. For example, Prieto et al. (2015) reported less than 60 colonies per year between 2005 and 2012, except for an unusual arrival in 2010 (>>200 colonies). Badalamenti et al. (2021) report only 268 colonies of *P. physalis* in a time scale between 2011 and 2021, and 71 colonies between 1914 and 2009 for the Mediterranean Sea. Unfortunately, these studies for the eastern Atlantic Ocean do not specify the length of the coast sampled. On the other hand, the occurrence of a higher percentage of left-handed colonies could indicate that the major origin source is the North Atlantic Subtropical Gyre (NASG) zone, in which the Sargasso Sea is enclosed. Left-handed colonies sail to the right of the wind and right-handed colonies sail to the left of the wind (Totton and Mackie, 1960). Authors such as Ferrer and González (2020) argue that the dimorphic form is useful for predicting the origin of colonies from the open sea to the coast. The authors mentioned above found a greater number of right-handed colonies in the Bay of Biscay, which allowed them to conclude that the origin of the *P. physalis* colonies had been the NASG zone. The not inconsiderable percentage of right-handed colonies found in this study may also indicate that another source of origin towards La Habana littoral is the Gulf of Mexico, where *P. physalis* colonies can aggregate (Ferrer and Pastor., 2017). There are still few studies and a lack of knowledge on the arrival of *P. physalis* and its dimorphism in many regions of both the eastern and western Atlantic Oceans. In addition, more information needs to be provided such as the length or area of the coastline sampled.

The correlation between pelagic *Sargassum* and *P. physalis* colonies was high (Fig. 9). For these pelagic species, the arrivals occurred in the winter season between November and April, in the two sampling years (Fig. 10). The months with the highest arrival of these pelagic species were December and January. These months displayed the highest records of cold fronts (4) with winds reaching 36 km/h from the northern component, and mean temperatures between 22 and 24 °C. This agrees with what was reported for northwestern Cuba by Torres-Conde and Martínez-Daranas (2020) and Torres-Conde et al. (2021) for pelagic *Sargassum* and *P. physalis*, respectively. The authors mentioned above state that the highest records of pelagic *Sargassum* and *P. physalis* arrivals, respectively, occur between November–January with the presence of four or more cold fronts, with strong winds from the northern

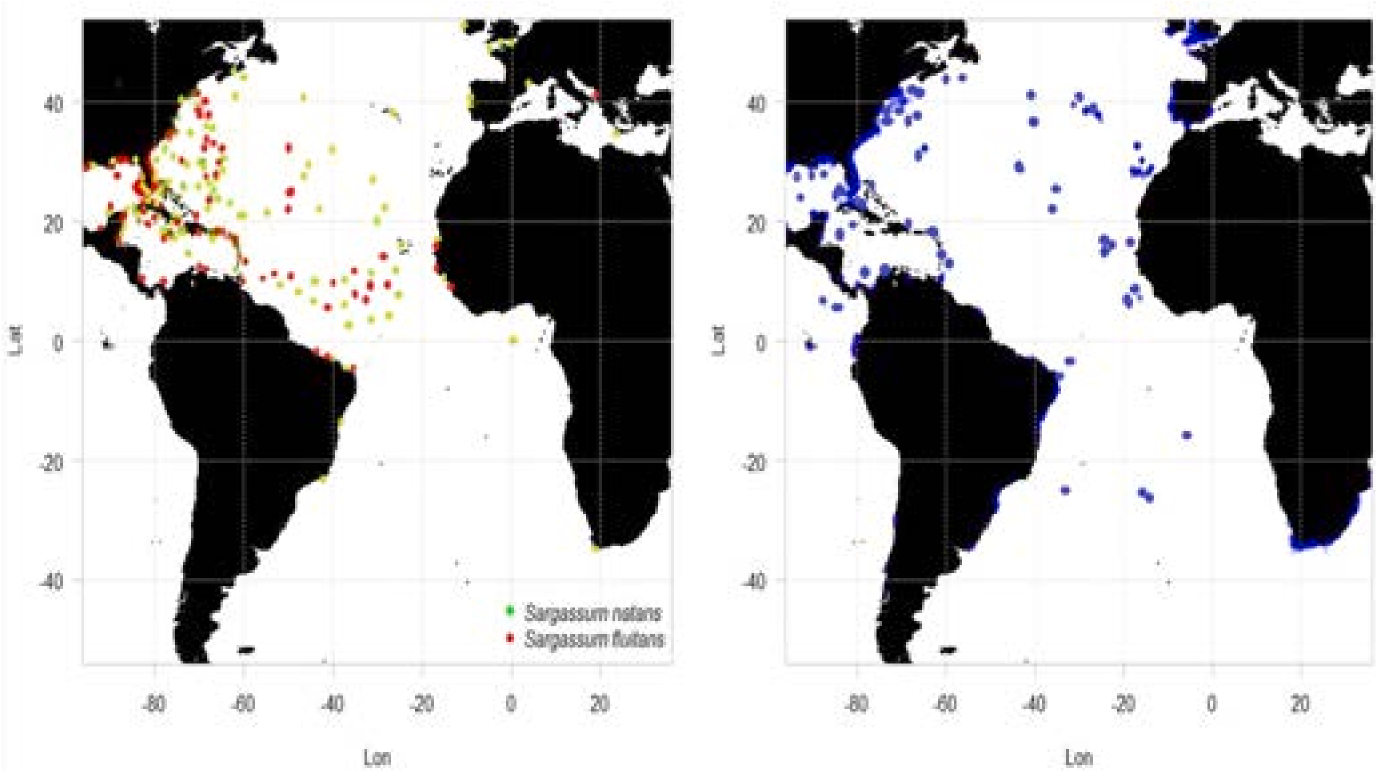

Fig. 8. Maps of sightings distribution of pelagic *Sargassum* (A) and *Physalia physalis* colonies (B) on the Atlantic Ocean. Red points (*Sargassum fluitans*), green points (*Sargassum natans*), and blue points (*P. physalis*). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

component, and with temperatures below 30 °C with minimums of 17 °C. This is contrary to what has been reported for the Mexican Caribbean, where the arrival of pelagic *Sargassum* occurs mostly between April and September (Rodríguez-Martínez et al., 2022). Other authors such as Zúñiga Ríos (1996), Pazos et al. (1996), and Moreira et al. (2006) indicate that the presence of cold fronts favors the arrival of pelagic *Sargassum* in northern Cuba. These pelagic species have been found in the Gulf of Mexico and the Sargasso Sea (Schell et al., 2015; Ferrer and Pastor, 2017). Cold fronts generate cold waves from the northern hemisphere (Cedeño, 2015) that in turn may have driven the arrival of these pelagic species from a common site to La Habana littoral.

Remote sensing products failed to predict the *Sargassum* beach landing observed (in-situ) two winters in a row. López-Contreras et al. (2021) and Rodríguez-Martínez et al. (2022) comment that some platforms have limited spatial and temporal resolution and the variability in the state of organic decomposition and water content in *Sargassum* leads to a significant variation in spectral reflectance. Although the non-detection of pelagic *Sargassum* near the study coast may also have been due to the low *Sargassum* biomass landing reported. Prediction of Sargassum beach landings, using remote sensing techniques alone, appears to miss important events such as those documented in this study. Further studies that combine remote sensing with robust in-situ observations is recommended to increase the accuracy and refinement of Sargassum forecast models.

The highest proportions of left-hand colonies were reported with winds mainly from the north and east component, where the Sargasso Sea is located. Fontaine (1954) noted that the predominant form of *P. physalis* on the coasts of Jamaica was left-handed with prevailing easterly winds. The months with the highest proportions of right-handed colonies were reported with winds mainly from the north and west component, where the Gulf of Mexico is located. Woodcock (1944) observed that the majority of colonies from the Gulf of Mexico were right-handed, and sailed to the left of the wind direction. Totton and Mackie (1956) proposed that the occurrence of right-handed or left-handed colonies depends on the direction of the winds. In the Canary Islands they found left-handed colonies when the winds came from the east or northeast and right-handed colonies when the winds came from the west. In this study, during the peak months, the highest arrivals occurred mainly with winds from the north and east component. This is in agreement with Lluis-Riera (1983), who states that the study area is influenced by strong winds from the north during the winter season and from the east the rest of the year. The greater visual presence of the morphotype *S. natans* I and the greater proportion of left-handed colonies could indicate that the main point of origin is the Sargasso Sea, and secondarily the Gulf of Mexico. This is consistent with advection being an important mechanism in the distribution and movement of pelagic *Sargassum* (Brooks et al., 2018) and *P. physalis* (Iosilevskii and Weihs, 2009; Headlam et al., 2020) in the Atlantic Ocean. Bourg et al. (2021) also state that occurrence of *P. physalis* beaching events is consistent with the frequency and direction of favorable wind conditions in Sidney, Australia. On the other hand, advanced particle tracking Lagrangian models are being applied to simulate the dispersion, origin, and beaching of *P. physalis* colonies (Headlam et al., 2020; Macías et al., 2021). However, it is also recommended that these models be enhanced with in-situ observations such the dimorphism displayed by the *P. physalis* colonies landings.

Seven of the 11 months with arrivals had a negative behavior of the Arctic Oscillation Index (AOi). Wallace (2000) states that a negative magnitude of this index favors the high frequency of cold fronts and strong cold winds from the northern hemisphere towards the mid-latitudes. This is consistent with what was found in the results, in which most of the months with arrivals coincided with a negative mean magnitude of the AOi, the presence of cold fronts, and cold winds from the north component. The relationship between a negative magnitude of the AOi and the arrivals of pelagic *Sargassum* and *P. physalis* in northwestern Cuba is also consistent with the findings of Torres-Conde and

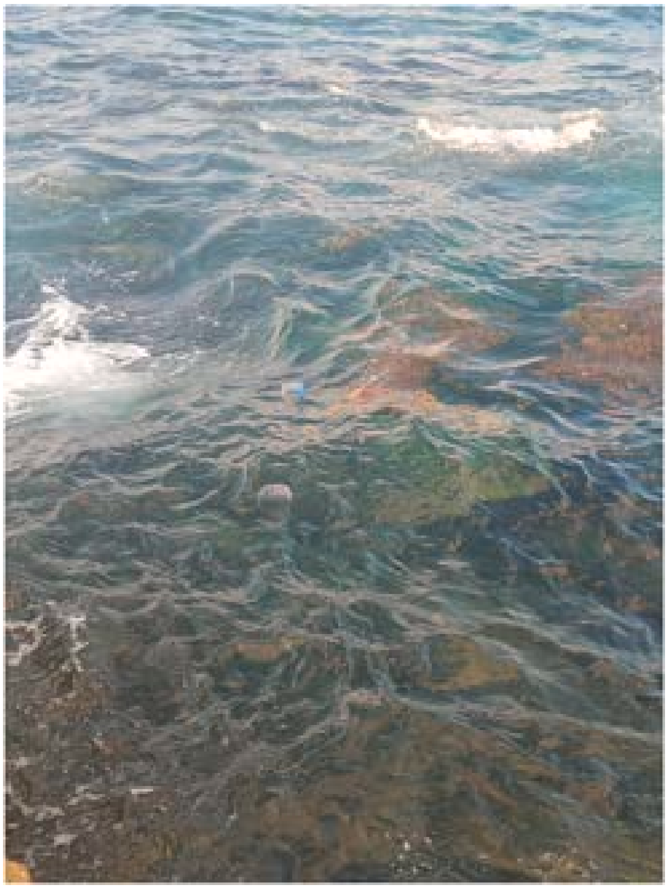

Fig. 9. The arrival of *P. physalis* colonies and pelagic *Sargassum* on Calle 16 beach, La Habana (February 18th, 2021).

Martínes-Daranas (2020) and Torres-Conde et al. (2021), respectively. On the other hand, three of the four months with arrivals that displayed a positive mean magnitude of the AOi were located in the 2019–2020 winter season. In this season the AOi showed the highest positive magnitudes in history according to Zhang et al. (2021). From January to March 2020, two strong positive AOi periods occurred according to Kim et al. (2020) and Lawrence et al. (2020), which is consistent with the results of this study. This is because the northern hemisphere stratospheric polar vortex was extremely strong, cold, and persistent (Zhang et al., 2021). This situation also led to record ozone depletion in the Arctic and unusually warm weather in the mid-latitudes (Zhang et al., 2021). This is consistent with one of the warmest years (2019) ever recorded in Cuba in almost seven decades, with a mean temperature of 26.6 °C (Fonseca-Rivera et al., 2020). This positive behavior of the AOi also resulted in the arrival of only 17 cold fronts in Cuba, which is below the annual average for Cuba (N = 19.5 from 1980 to 2018). Despite this, the arrival of these pelagic *Sargassum* and *P. physalis* did not cease. Some negative magnitudes of the AOi within January 2020, February 2020, and March 2020 may have caused the formation of short-duration cold fronts that in turn favored arrivals.

As a consequence of climate change, the AOi is showing abnormal behavior, causing an absence of winter in the northern hemisphere and the mid-latitudes. The positive trends of the AOi in recent years show us not only the effects of climate change but also the consequences in the mid-latitudes in terms of a decrease in cold fronts, anomalous temperatures, and changes in the distribution of marine species in the Atlantic Ocean (Hurrel, 1995; Fromentin and Planque, 1996). The oceanographic dynamics can usually be unpredictable and even more so with the strong implications of climate change. Continued monitoring of the arrival of these pelagic species is needed because the increasingly noticeable climate change may drastically change our understanding of their distribution and dynamics in the coming years.

In the maps, it can be seen how the sightings of pelagic *Sargassum* and *P. physalis* coincide in several sites of the Atlantic Ocean. Schell et al. (2015) place the accumulation of pelagic *Sargassum* in three fundamental sites: The Sargasso Sea, the Gulf of Mexico, and the area between Brazil and western Africa. According to the map, *P. physalis* is also found in these three areas, where it also shares distribution with pelagic *Sargassum* in the Carolinian, The Florida Keys, the Bahamas, Bermuda, Western Caribbean, Greater Antilles, Eastern Antilles, Southwest Caribbean, and Southern Caribbean. These species also share distribution in the eastern Atlantic Ocean but a much lower proportion than in the western Atlantic Ocean. Although pelagic *Sargassum* and *P. physalis* colonies coincide in many sites around the Atlantic Ocean, this does not mean that they always arrive simultaneously. For example, the simultaneous arrival of these pelagic organisms was not visually observed in Puerto Morelos (Mexican Caribbean) as it usually happens in some sites in northwest Cuba. Therefore, it would be essential to strengthen the monitoring of more localities around the Atlantic Ocean to check whether or not these pelagic species arrive simultaneously and in what proportions.

5. Conclusions

The simultaneous arrival of pelagic *Sargassum* and *P. physalis* in northwestern Cuba was confirmed. The arrivals of these pelagic species coincided in occurrence with similar meteorological and oceanographic conditions. The occurrence of cold fronts, which bring with them low temperatures and strong northerly winds, seems to drive arrivals from common sites such as the Sargasso Sea and the Gulf of Mexico to northwestern Cuba. The higher visual occurrence of *S. natans* I and the higher proportion of left-handed colonies may indicate that the NASG area, which encloses the Sargasso Sea, could be the main source of arrivals to La Habana littoral. The arrival of pelagic *Sargassum* was not alarming in northwestern Cuba as they are in the Mexican Caribbean, however, the simultaneous arrival of pelagic *Sargassum* and *P. physalis* colonies can be a problem for the sun and beach tourism and the coastal ecosystem. On the other hand, these pelagic species coincided in many areas in the Atlantic Ocean. However, although there are simultaneous arrival events in northwestern Cuba does not mean that they occur elsewhere, but it is a latent possibility that may become a new threat to the Atlantic coasts. Therefore, it is critical to strengthen monitoring on both sides of the Atlantic Ocean to increase knowledge about this important aspect. The implications of climate change on planetary oceanographic conditions are becoming increasingly unpredictable and changes in weather patterns more evident. The changes evidenced in the winter season of 2019–2020 regarding the influence of the Arctic Oscillation Index may have consequences on the distribution of pelagic *Sargassum* and *P. physalis* in the coming years and unusual events around the Atlantic Ocean. Finally, the use of remote sensing techniques with in situ observations is considered important for future work, since using remote sensing techniques alone seems to miss important events such as those documented in this study.

CRediT authorship contribution statement

Eduardo Gabriel Torres-Conde: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

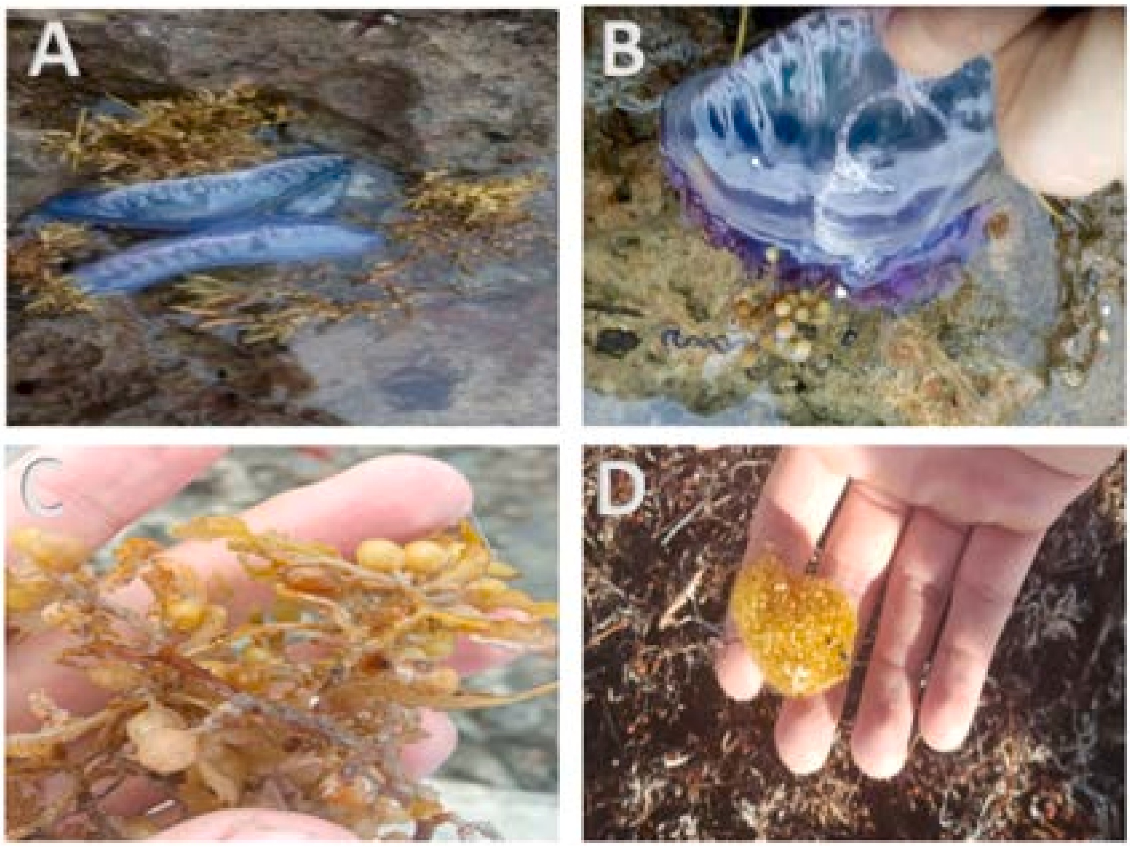

Fig. 10. Images of the association of *P. physalis* and pelagic *Sargassum* at intertidal zone on Calle 16 beach, La Habana (February 18th, 2021). Images A and B display the association of these pelagic species. Image A also shows two Left-handed *P. physalis*. Image C shows the morphotype *Sargassum fluitans* III. Image D shows great quantities of *Sargassum natans* I.

Data availability

Data will be made available on request.

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