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The influence of atmospheric and oceanographic conditions on the occurrence of Portuguese Man-o-War (*Physalia physalis*) along the Iberian coasts. The case of summer 2019 and potential future implications

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The pleustonic, open-ocean dweller *Physalia physalis* can reach European Atlantic coasts when the combination of wind and currents drags the colonies from their typical habitats in the open ocean towards these shores. Usually, this passive advection happens during the winter months, when low-pressure atmospheric systems typically move from west to east accompanied by strong westerly winds. This is particularly fortunate for humans, as most of the presence of these potentially dangerous organisms on beaches occurs during the low tourist season. However, in early summer 2019, a number of *P. physalis* colonies arrived on the beaches of the southern Iberian Peninsula, causing closures, economic damage, and social concern. Different stakeholders wondered why this unusual event occurred and if it was a sign of change in these organisms' distribution areas as a consequence of climatic shifts. With the aim of elucidating the potential causes of the atypical arrival of *P. physalis* colonies during summer months to these important touristic destinations, we utilize the most advanced, freely available, datasets of atmospheric and oceanographic conditions in the affected region. Our study reveals that summer 2019 presented particular atmospheric characteristics, with very low atmospheric pressure on both sides of the Iberian Peninsula and associated westerlies that drove a peculiar oceanographic setting with abnormal eastward currents and larger-than-average waves in the Gulf of Cádiz. All these elements combined drag the free-floating colonies onto the affected beaches and cause social alarm in the affected communities. Even if summer 2019 was unique on record, there are indications that wind and wave conditions along the western European coasts might become more favorable for the arrival of floating organisms from the open ocean in the decades to come, calling for improved monitoring and alert systems in the region.

KEYWORDS
Atlantic Ocean, Iberian coasts, ECMWF, Copernicus, *Physalia physalis*, ocean-atmosphere interactions

1 Introduction

The Portuguese man-o-war (*Physalia physalis*) is a pleustonic organism that dwells on the surface of the open ocean, particularly in temperate and tropical regions (Mapstone, 2014). *P. physalis* drifts carried by currents and also align its pneumatophores with the wind so they can glide passively following the general wind direction (Iosilevskii and Weihs, 2009). No active swimming has been described for these organisms so far (Munro et al., 2019). The individuals are, actually, colonies formed by different polyps (Totton and Mackie, 1960) that specialize in singular functions (Munro et al., 2019) and they can be potentially dangerous to humans because of their potent venom (Prieto et al., 2015). Yet, they typically live in open-sea regions away from the coasts, hence, with limited interactions with human beings.

However, in certain cases, they could be transported by the combination of currents and winds (Lee et al., 2021) towards the coasts, creating social alarm and economic harm (Prieto et al., 2021; Macias et al., 2021). Along the eastern coasts of the North Atlantic (Figure 1A), *P. physalis* has been observed on a number of occasions during recent decades (Wilson, 1974; Labadie et al., 2012; Prieto et al., 2015; Ferrer et al., 2015; Headlam et al., 2020) although it is difficult to determinate the origin of the individuals observed on the beaches (*e.g.*, Prieto et al., 2015; Headlam et al., 2020; Ferrer et al., 2024), as very few studies have gathered data on the colonies beyond the coasts.

Their presence along the Iberian coasts is more common during the winter/spring months and typically associated to the presence of strong westerly winds linked with low-pressure atmospheric systems (*e.g.*, storms) over the North Atlantic (*e.g.*, Prieto et al., 2015). This is fortunate, because beaches are typically not crowded in those months, so interaction with humans and the associated social and economic damage (Condon et al., 2013) is limited. However, at the beginning of summer 2019 there were *P. physalis* colonies arriving to different areas of the European Union (EU) west coasts, both to the continent and to the Atlantic archipelagos as Madeira, Azores and Canary Islands (GelAvista data base; http://gelavista.ipma.pt/).

One of the most notable events was the unusual arrival of *P. physalis* colonies to beaches in the Cádiz province, on the northern shores of the Gulf of Cádiz (GoC) from 25th June to 17th July 2019 (Figure 1B). The GoC is a particular region in the North Atlantic, characterized by a complex circulation pattern, including an anticyclonic surface ocean circulation (Pérez-Rubín et al., 1999; García et al., 2002; García-Lafuente et al., 2002b), which is particularly prevalent during the spring-summer season (Vargas et al., 2003; Sánchez and Relvas, 2003). This circulation pattern is influenced by the wind patterns over the western façade of the Iberian Peninsula, which transition from northerly (summer upwelling season) to westerly or south-westerly in winter (Fiúza et al., 1982; Relvas and Barton, 2002), attributable to the seasonal migration of the Azores high. This displacement triggers fluctuations in the circulation of the broader Subtropical Gyre, which, as per Machín et al. (2006), lead to conspicuous seasonal changes in the Gulf of Cádiz's surface circulation.

A significant portion of the surface transport volume within the coastal current is channeled towards the Strait of Gibraltar (see orange arrows in Figure 1B), contributing to the Atlantic Jet (AJ) entering the Mediterranean Sea (Criado-Aldeanueva, 2004). The remaining fraction veers southwards and subsequently south-westwards, eventually converging with the Canary Current (schematics shown in Figure 1B).

Long-term (1996 – 2022) current meter measurements (located at 36.49°N and 6.96°O accessible via https://portus.puertos.es/#/) corroborate a predominantly anticyclonic circulation throughout the year. However, these observations also indicate north-westward velocities during wintertime. At a more local scale, close to the northern shores of the GoC, coastal counter-currents flowing westward have been described (e.g., Garel, 2017; de Olivera et al., 2022) in certain periods of the year.

Furthermore, recent studies (Sirviente et al., 2023) have highlighted a direct connection between the intensity of the coastal flow in the northern GoC and the velocity of the AJ. The AJ shows both seasonal and sub-inertial variabilities linked to the atmospheric forcing over the western Mediterranean Sea (e.g., Candela et al., 1989; Garcia-Lafuente et al., 2002) and to the local impact of the zonal winds (e.g., Macias et al., 2016). This variability at different time-scales plays a crucial role in the transport of water masses and organisms, including *P. physalis*, into the Gulf of Cádiz – Alboran Sea region.

The anomaly in the summer of 2019, when *P. physalis* colonies arrived to the northern shores of the GoC, was characterized by a low number of sightings (36) compared to typical 'winter arrivals' (e.g., 74 in 2010, 247 in 2013 and 149 in 2018) (Macias et al., 2021). However, the social alarm was large as beaches were in full occupancy (Supplementary Table 1). Local authorities were even forced to close some of these very popular touristic areas with the associated economic losses. Local and regional stakeholders wanted to know why this event took place and what is the likelihood of reoccurrence. In essence, understanding of the factors contributing to the anomalous occurrence during the summer of 2019 is crucial to enable prompt and effective responses in potential future instances.

In this study, we analyzed the atmospheric and oceanographic conditions of the relevant time period (spring and early summer 2019) in order to propose a potential mechanism for the unusual arrival of those colonies to the GoC shores. Atmospheric reanalysis data from the latest ERA5 dataset provided by the European Centre for Medium Weather Forecast (ECMWF) and oceanographic conditions from Copernicus Marine Service were obtained and analyzed for the period of interest over the Region Of Interest (ROI, shown in Figure 1A).

Moreover, we analyze the past trend of wind intensity and direction in the ROI to try to identify potential future conditions in the context of global change to understand if events such as the one in summer 2019 are more likely to happen in the future. Leveraging freely available datasets and products, this study showcases the critical role of publicly funded research in providing actionable insights for coastal management, ultimately improving the safety and security of coastal activities and underscoring the importance of continued investment in such research efforts.

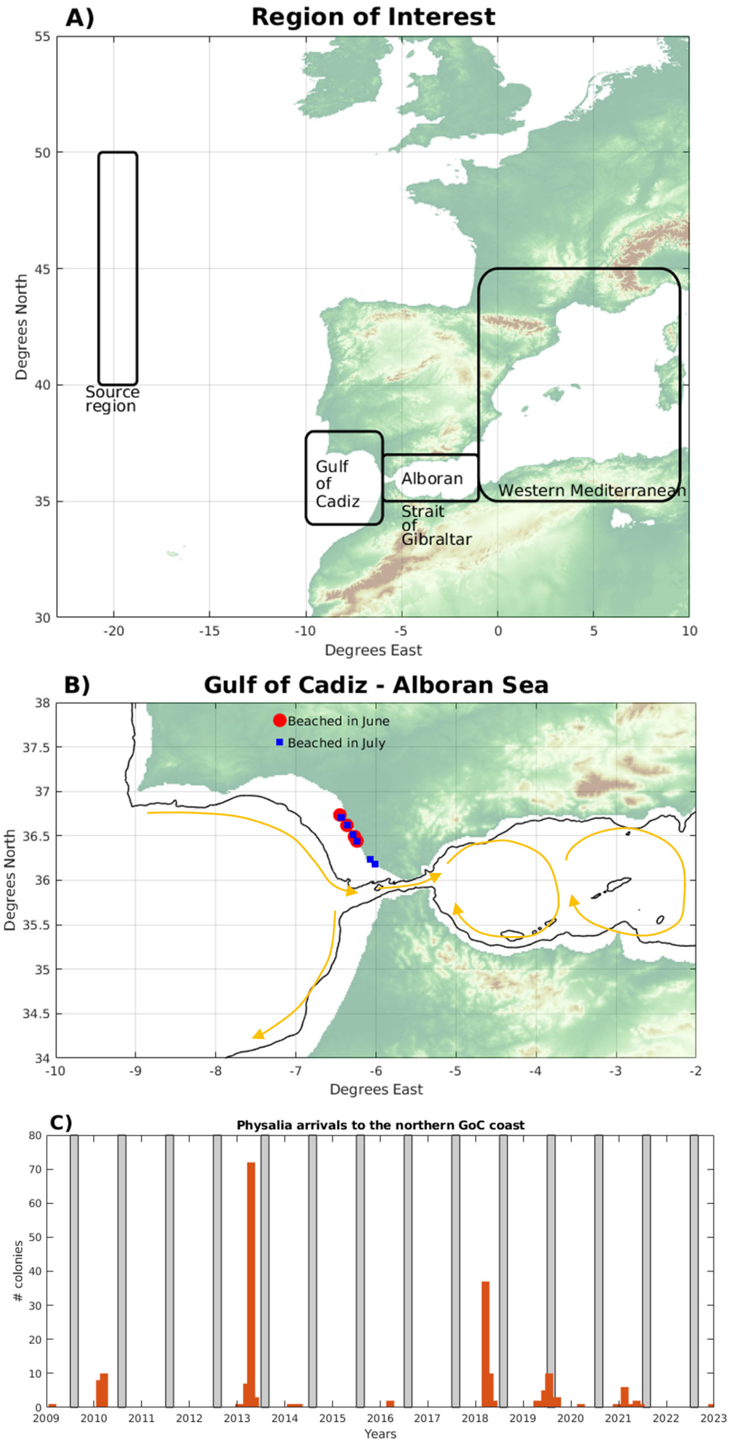

FIGURE 1
(A) Region of interest showing the main topographic features mentioned in the text. **(B)** Zoom-in of the Gulf of Cadiz region with positions of *P. physalis* beaching in June 2019 (red circles) and July 2019 (blue squares). The black line indicates the 200m depth and the orange arrows mark the general surface water circulation with the anticyclonic gyre in the GoC, the Atlantic Jet in the Strait of Gibraltar and the two main anticyclonic gyres in the Alboran Sea. **(C)** Registered arrivals of *P. physalis* colonies to the northern coasts of the GoC (including Portuguese and Spanish beaches) from 2009 to 2022. Grey bars mark the summer months (June, July, August) for each year. X-axis units is years.

2 Methods

In order to analyze the potential causes for the unusual presence of *P. physalis* on the northern coast of the GoC in summer 2019, both atmospheric conditions and surface-ocean state variables need to be considered.

2.1 Atmospheric conditions

Surface conditions in the ocean are largely dictated by its interaction with the atmosphere. Such interaction is determined by a number of factors, a very important one being the horizontal patterns of mean sea level pressure (*mslp*) as it determines barotropic currents in the ocean and is the main driver of the wind field (both zonal, *U10* and meridional, *V10* components). Hence, daily *mslp* and wind components were downloaded from cds.climate.copernicus.eu over the ROI (30°N-56°N and 19°W-10° E, Figure 1) from the ECMWF, ERA-5 reanalysis (Hersbach et al., 2020) at 1/12° spatial resolution and covering the period 01/1980 – 12/2020 (Supplementary Figure 1).

In addition, the monthly values of the North Atlantic Oscillation index (NAO) were obtained from the NOAA Climate Prediction Center website (*https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml*) from 01/1980 to 12/2020 (Supplementary Figure 1).

2.2 Oceanographic conditions

Surface ocean currents (*u* and *v* velocities) and significant wave height (*Hs*) are two key oceanographic variables that can influence *P. physalis* dispersion and that are currently available for our ROI (Figure 1) from COPERNICUS marine data store (https://resources.marine.copernicus.eu/) for the whole available period (01/1993 – 12/2020). Copernicus oceanographic models represents an open-access source of high-quality ocean reanalysis data including multi-layered data assimilation schemes and rigorous quality control protocols. Details of the used models are provided in Supplementary Figure 1, Supplementary Table 2 and here below.

Surface currents were obtained from the Copernicus Marine Environmental Monitoring Service (CMEMS) product IBI_MULTIYEAR_PHY_005_002 (https://doi.org/10.48670/moi-00029). The downloaded dataset consists of monthly values of surface *u* and *v* velocities over the ROI (Figure 1) for the period 01/1993 to 12/2020 (Supplementary Figure 1) at a spatial resolution of 1/12°. This product is based on the Nucleus for European Modelling of the Ocean (NEMO) v3.6 ocean general circulation model and assimilates altimeter data, *in situ* temperature and salinity vertical profiles and satellite sea surface temperature.

Wave height data come from the product IBI_MULTIYEAR_WAV_005_006 (*https://doi.org/10.48670/moi-00030*). We subsampled the whole dataset over the GoC region (35.5°N-38°N, 5°W-10°W) downloading monthly data for the period 01/1993 to 12/2020 (Supplementary Figure 1) at 1/20° spatial resolution. This model configuration is based on the Météo-France WAve Model (MFWAM) which assimilates significant wave height (SWH), altimeter data, and wave spectral data.

Also, in order to provide a general description of the overall conditions over the North Atlantic, surface current data (*u* and *v*) for the region 15°-65°N, 0°-80°W were downloaded from the GLOBAL-MULTIYEAR-PHY-001-030-MONTHLY (*https://doi.org/10.48670/moi-00021*). Data for spring months (April and May) were downloaded for the period 01/1993 to 12/2020 (Supplementary Figure 1) at 1/12° resolution. This dataset is produced by the same physical model (NEMO) driven at the surface by ERA-interim/ERA-5 (ECMWF) reanalysis but covering the whole earth. It assimilated observations using a reduced-order Kalman filter including along-track altimeter data (sea level anomaly), satellite sea surface temperature, sea ice concentration and *in situ* temperature and salinity vertical profiles.

2.3 Observational dataset

A comprehensive dataset of *P. physalis* sightings was compiled from various sources, including published scientific articles, media reports, national and regional agencies, and personal communication (Prieto, 2021). This dataset encompasses 14 complete years (2009-2022) and covers the geographical area of the North East Atlantic Ocean and the Mediterranean Sea.

A subset of this dataset focuses on the exceptional summer 2019 event of swarms in the Gulf of Cadiz (GoC). During this period, the coastline was intensively monitored by technicians from the Andalusian regional government and lifeguards from the province of Cádiz, who systematically recorded and measured stranded colonies. Additionally, *P. physalis* sightings from 2019 were retrieved from three online databases: the Jellywatch Program (http://jellywatch.org), the PERSEUS Jellyfish Spotting website (http://www.perseus-net.eu/en/jellyfish_map/index.html), and the Medusapp dataset (https://www.medusapp.net/).

The stranding data from the summer 2019 event in the GoC is considered comprehensive, as the coastline was continuously monitored. This means that the absence of recorded stranding (*i.e.*, zero values) can be taken as a reliable indication of no colonies arriving on shore. The complete dataset is publicly available at the following link (Álvarez-Trasobares and Prieto, 2024 *upon acceptance of this manuscript*).

3 Results

For all years included in the observational dataset (2009 – 2022, detailed in section 2.3), *P. physalia* arrivals to the beaches always occur during the first half of the year with the only exception being the year 2019 when they were observed during the summer months (June, July and August grey bars in Figure 1C). This uniqueness prompted the following investigation of atmospheric and oceanographic conditions during this specific time-period.

To evaluate the particular conditions during summer 2019 we are using anomalies' analysis below. For this, we first calculate the climatological value of the study parameter (e.g., *mslp* or wind intensity) for the whole observational datasets (entire time-range) indicated in section 2. Then, we compute the anomaly for year 2019 by comparing the studied variable value in 2019 with their climatological one.

The following presentation of results will proceed from larger to smaller scales, starting with the examination of the general atmospheric conditions in the ROI for the study period (*i.e.*, June-July 2019).

3.1 Synoptic atmospheric conditions over the ROI

3.1.1 Mean sea level pressure

The anomaly of the *mslp* for the months of June and July 2019 with respect to their climatological mean (1980 – 2020) are shown in Figure 2. In both months, negative *mslp* anomalies are frequent in the studied area (ROI as shown in Figure 1A), both on the Atlantic and the Mediterranean sides of the Iberian Peninsula, with a mean *mslp* anomaly of -0.3 mb (min -3.5 mb) in June and -0.62 mb (min -2.4 mb) in July in the entire ROI. Maps of the mean *mslp* values for the months of June and July in the studied period (1979 – 2020) and their values for year 2019 are, additionally, shown in Supplementary Figure 2. During the summer of 2019, the high-pressure system (i.e., the Azores high) is displaced south-westward (Supplementary Figure 2C, D) of its usual location in the Eastern North Atlantic (Supplementary Figure 2A, B), explaining the anomalies shown in Figure 2.

Negative *mslp* anomalies on the Atlantic side of the ROI indicate the recurrent presence of stormy conditions that are typically associated with westerly winds in this region of the North Atlantic (e.g., Vargas et al., 2003). Additionally, negative *mslp* anomalies in the Mediterranean side of the ROI (mean anomaly -0.15 mb) (Figure 2) condition the water circulation around the Iberian Peninsula and, in particular, at the GoC.

The presence of low sea level pressure on the western Mediterranean Sea has been described to be linked with a higher intensity of the Atlantic Jet (AJ) entering through the Strait of Gibraltar (e.g., Candela et al., 1989; Crepon, 1965; García-Lafuente et al., 2002a) via the '*inverse barometer effect'*. The zonal velocity of the AJ has influence on the water circulation patterns on both sides of the Strait (Flexas et al., 2006; Renault et al., 2012) and has typically been linked to the sub-inertial variations of *mslp* on the western Mediterranean (i.e., 10–20 day periods). Therefore, a more detailed analysis of the *mslp* values in the Western Mediterranean basin could be of importance for our study.

Hourly *mslp* anomaly data for the months of June and July 2019 were extracted from the ERA-5 dataset and daily values were computed for the Western Mediterranean (see detail in Figure 1A). Daily anomalies with respect climatological values (1979 – 2020) were computed for both months and shown in Figure 3. This high-frequency data indicate that from 9th June to 20th July, the mean *mslp* over the Mediterranean was (repeatedly) lower than the standard sea level pressure (mean *mslp* anomaly of -1.2 mb), indicating a consistent and persistent low *mslp* anomaly that could, effectively, drive changes in the velocity of the AJ and the associated currents eastward (see Dastis et al., 2018 and section 3.2 below).

3.1.2 Wind speed and direction

The second atmospheric variable to analyze is the wind speed and direction derived from the ERA-5 reanalysis. Both wind characteristics are, indeed, determined by the atmospheric pressure distribution (section 3.1.1).

The mean wind velocity and direction for June-July in the analyzed period (1980 – 2020) and for the year 2019 are shown in Supplementary Figure 3. While the meridional (southward) wind intensity along the Portuguese coast is somewhat diminished (-0.15 m/s), its zonal (eastward) intensity in the northern region of the

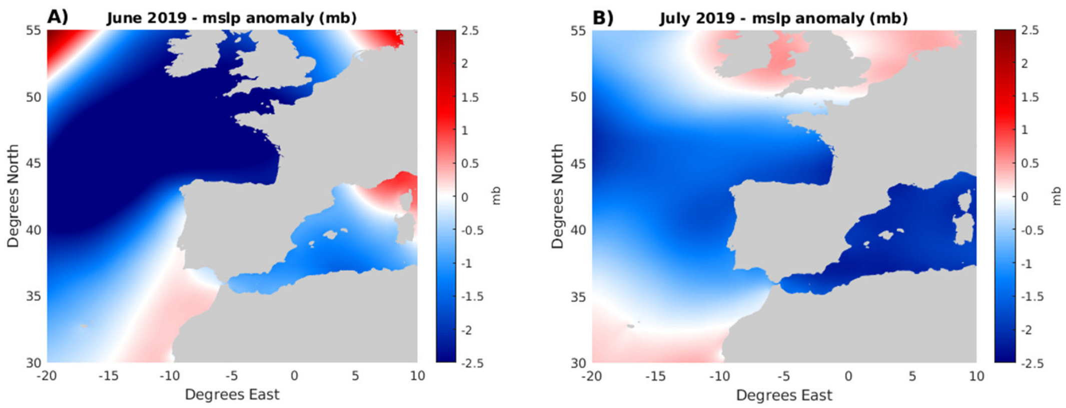

FIGURE 2
(A) Mean sea level pressure anomaly over the ROI for June 2019. **(B)** Mean sea level pressure anomaly over the ROI for July 2019. Anomalies are computed with respect to the long-term (1980 – 2020) mslp mean value for both months.

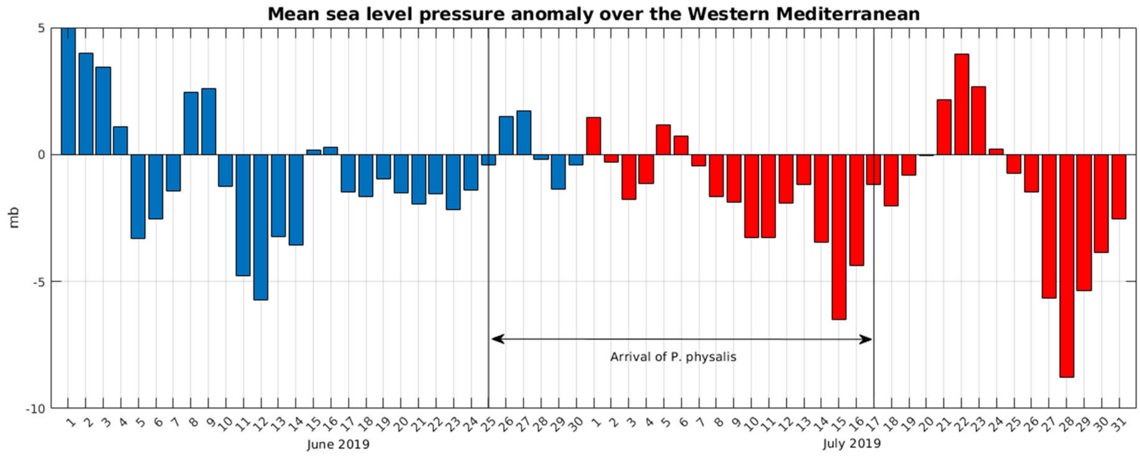

FIGURE 3
Daily mean sea level pressure anomaly over the Western Mediterranean Sea for the months of June (blue bars) and July (red bars) of 2019. The time interval during which *P. physalis* arrivals were detected on the coasts of Cádiz is indicated by the vertical black lines. Anomalies are computed with respect to the long-term (1980 – 2020) values of *mslp* over the Western Mediterranean for both June and July.

GoC is greatly enhanced in both months of summer 2019 (Figure 4).

An analysis of the wind velocity anomaly on the western boundary of the ROI (at 19°W) reveals a positive anomaly in both June and July 2019 (+0.5/1 m/s, respectively). Notably, the wind direction shifts eastwards during summer 2019 in this area as depicted in Figures 4A, D.

More locally, in the GoC – Strait of Gibraltar region the wind anomalies for both months are also directed eastwards, in a direction almost perpendicular to the beaches of the Cádiz province (Figures 4B, E). Winds are more intense in the GoC (+1.5/2 m/s, reddish background colors in Figures 4C, D) but weaker in the Strait region (-0.5/-1 m/s, bluish colors). This latter pattern is related to the fact that typical winds over the Strait during summer are easterlies (Dorman et al., 1995) and in the two studied months, the anomalies indicate more frequent westerlies, which are typically less strong than the easterlies in the Strait (see Supplementary Figure 4).

3.2 Surface ocean currents

In a very similar analysis to the one performed for winds, climatological (1993 – 2020) June-July surface current intensity and for the specific year 2019 are presented in Supplementary Figure 5. For 2019, the southward current along the Portuguese coast and the eastward coastal current in the GoC are enhanced in summer.

More details can be analyzed in the surface currents anomalies maps presented in Figure 5. Starting with the overall map of the ROI (Figures 5A, D), no clear patterns could be identified in the open Atlantic Ocean. However, a particular dynamic could be easily spotted, the high intensity of the AJ and the associated Western Alboran Gyre in the Strait of Gibraltar – Alboran Sea region. As commented in section 3.1.1, the strong increase of the eastward velocity of the AJ (+0.15/0.2 m/s) is most likely connected to the low *mslp* over the Western Mediterranean Sea via the '*inverse barometer effect*' (Dastis et al., 2018; Bolado-Penagos et al., 2021).

For both months, also the eastward flowing current along the northern coast of the GoC (García-Lafuente et al., 2006) is reinforced (+0.05/0.1 m/s, Figures 5B, E). A closer look at this northern region of the GoC reveals that also over the continental shelf the direction of the anomaly is towards the east, i.e. coastward (Figures 5C, F). It is worth mentioning that this current anomaly is concurrent in direction with the wind anomalies described above (Figures 4C, F).

There is also a significant statistical relationship between the zonal (eastward) velocities of the AJ (surface values at the eastern exit of the Strait of Gibraltar) and of the surface current in the northern GoC (<100m depth) (Figure 6A). For both months (June and July) the correlation between both velocities is moderate (r^2>0.6) but significant (p<0.01) and indicates an acceleration of the eastward currents in the northern coast of the GoC when the AJ velocity increases.

Furthermore, both months of summer 2019 show the higher mean *u* velocity on the northern coasts of the GoC during the 1993–2020 period (Figures 6A, B). These values of the coastal current are, indeed, clearly identified as outliers in the statistical analysis (Figure 6C). The zonal velocity of the AJ is not an outlier in June (Figure 6D) although it is outside the 75% percentile range, while zonal AJ velocity for July is, indeed, identified as an outlier in the analysis (Figure 6D).

3.3 Surface waves

Finally, and on a more local scale, the actual arrival of floating *P. physalis* colonies to the Cádiz beaches could also be impacted and determined by the waves' action (*e.g.*, through Stokes drift). Figure 7 shows the anomalies maps of significant wave height (*Hs* in m) for June and July 2019 in the GoC. In both months, *Hs* was higher (10–

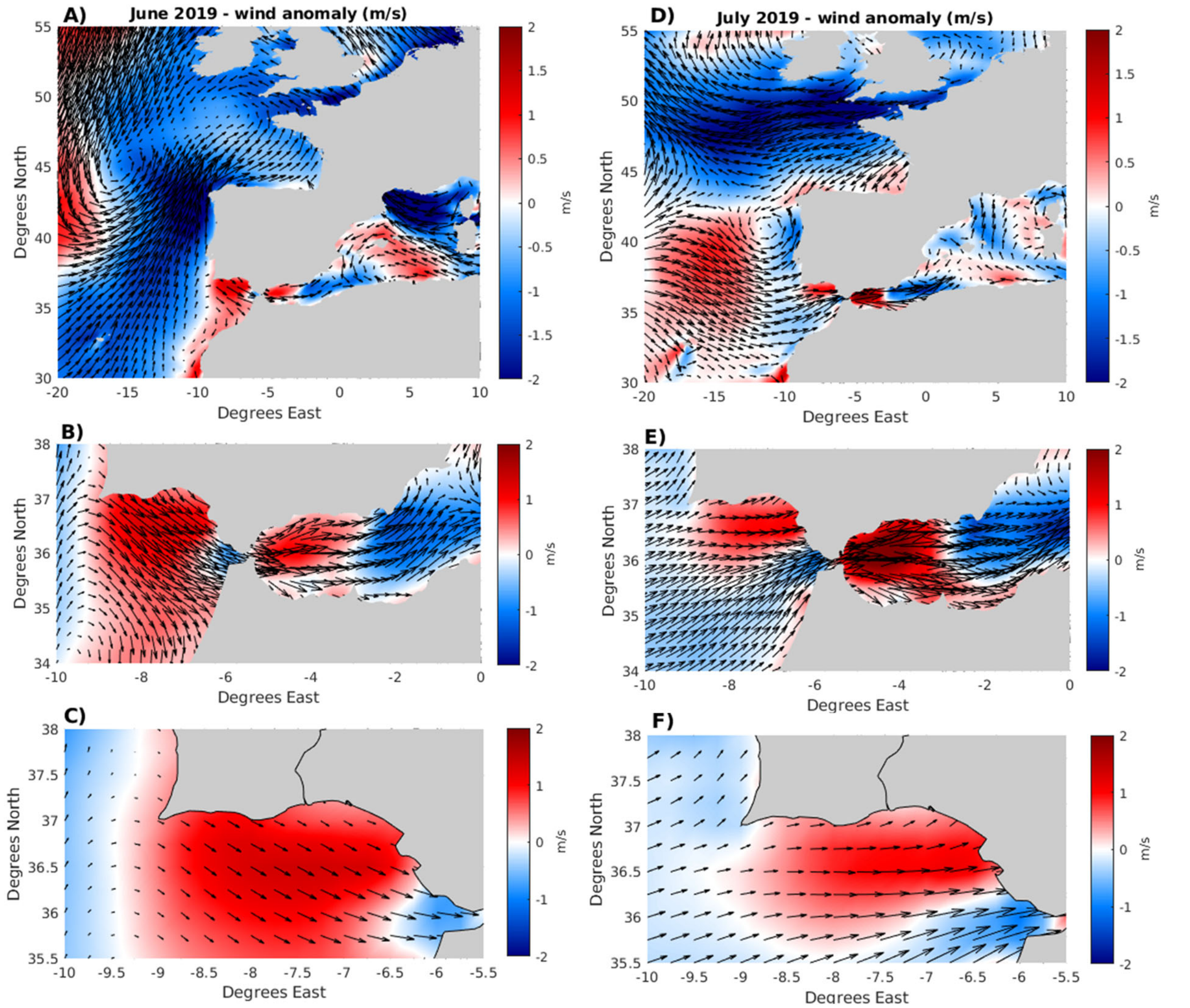

FIGURE 4
Mean wind anomalies for June (left column) and July (right column) 2019. Background color indicates the magnitude of the change and the arrows indicate the direction of the anomaly. Anomalies are computed with respect to the long-term (1980 – 2020) values of winds for both June and July. **(A, D)** show the whole ROI, **(B, E)** focus on the GoC – Strait of Gibraltar – Alboran Sea region while **(C, F)** zoom in on the GoC region.

20 cm) than their climatology along the coasts of the Cádiz province, precisely in the region where *P. physalis* beachings were recorded (green circles in Figure 7).

4 Discussion

4.1 Synoptic situation in summer 2019

The contemporaneous presence of potentially dangerous marine organisms and beachgoers is a source of health and economic problems that is not usual along the southern Iberian coasts. Therefore, when in summer 2019 the presence of *P. physalis* forced the closure of several beaches, local authorities and stakeholders were concerned. The social alarm triggered numerous questions about why and how this event could happen and raised much interest in understanding if similar cases could likely occur in the future.

Fortunately, and thanks to the continuous investments in public research, nowadays we have access to datasets with enough quality to scientifically elucidate the causes of this rare event. Indeed, the analysis of atmospheric and oceanographic conditions in the region shown above depicts a clear picture of the circumstances that lead to the unusual arrival of *P. Physalis* colonies to the GoC shores in June and July 2019.

We hypothesize that a major driving of the full incident seems to be the very peculiar (for the summer period) atmospheric pressure distribution in the ROI, with persistent low *mslp* in those two months of 2019 (Figure 2) associated to a south-west displacement of the Azores high from its usual summer position (Supplementary Figure 2). Actually, the summer 2019 atmospheric situation resembles that of the typical winter situation in the ROI, with low *mslp* anomalies on the Atlantic side of the ROI indicative of stormy conditions passing through the region. Such low pressure atmospheric systems typically move from west to east and are

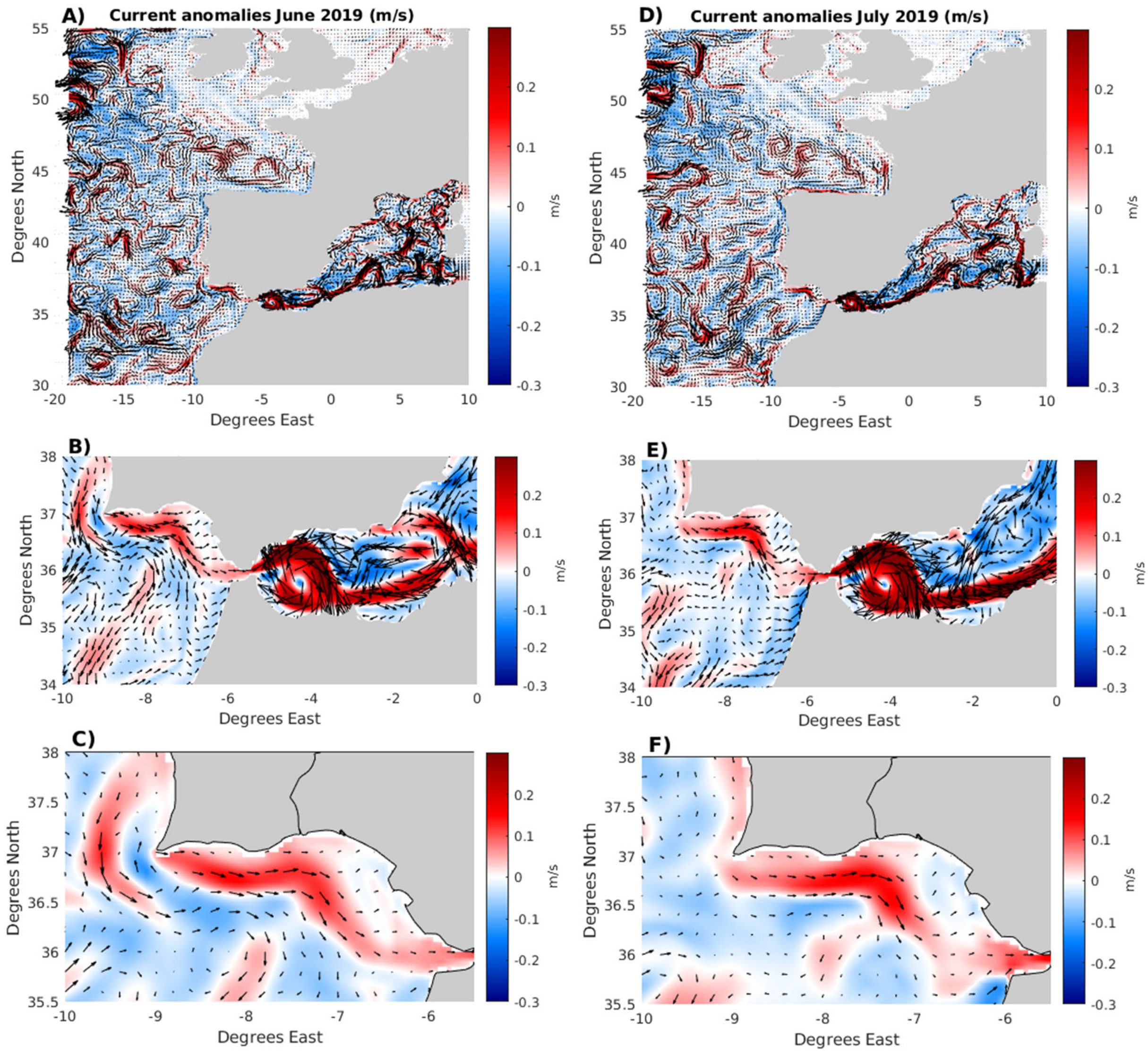

FIGURE 5
Mean surface current anomalies for June (left column) and July (right column) 2019. Background color indicates the magnitude of the change and the arrows indicate the direction of the anomaly. Anomalies are computed with respect to the long-term (1993 – 2020) values of surface currents for both June and July. **(A, D)** show the whole ROI, **(B), E)** focus on the GoC – Strait of Gibraltar – Alboran Sea region while **(C, F)** zoom in on the GoC region.

associated with more frequent and intense westerly winds at the surface connected to the Ferrel cell circulation. These westerlies were particularly conspicuous in the northern area of the GoC (Figure 4) where wind anomalies for the two studied months were clearly directed towards the coasts of Cádiz.

However, this is not the only effect *mslp* had on the oceanographic conditions of the GoC – Alboran Sea region. The persistent low *mslp* over the Western Mediterranean Sea (Figure 3) may be responsible for the strong acceleration of the AJ entering the Mediterranean through the Strait of Gibraltar (Figure 5). This is a barotrophic phenomenon already known and described in the literature (e.g., Candela et al., 1989; Garcia-Lafuente et al., 2002a; Macias et al., 2016; Bolado-Penagos et al., 2021). What is less known, however, is the impact it has on the currents along the northern shores of the GoC.

As shown by the scatter plot on Figure 6A, there is a moderate but significant correlation between the zonal velocity of the AJ and the zonal intensity of the current on the northern shores of the GoC. This relationship has also been described by a very recent study (Sirviente et al., 2023) carried out using high frequency radar (HFR) measurements. The authors combined HFR analyses with high resolution modelling experiments in order to identify the Empirical Orthogonal Functions (EOFs) of the currents in the GoC to discretely study the subinertial signal (hence the orthogonal modes) and their forcing agents. They found significant correlations between the *mslp* in Liguria and the wind components in the GoC and Strait of Gibraltar.

This relationship between the currents in the northern coast of the GoC and the AJ velocity could be understood if the general circulation pattern in the GoC is considered. There, the water flows

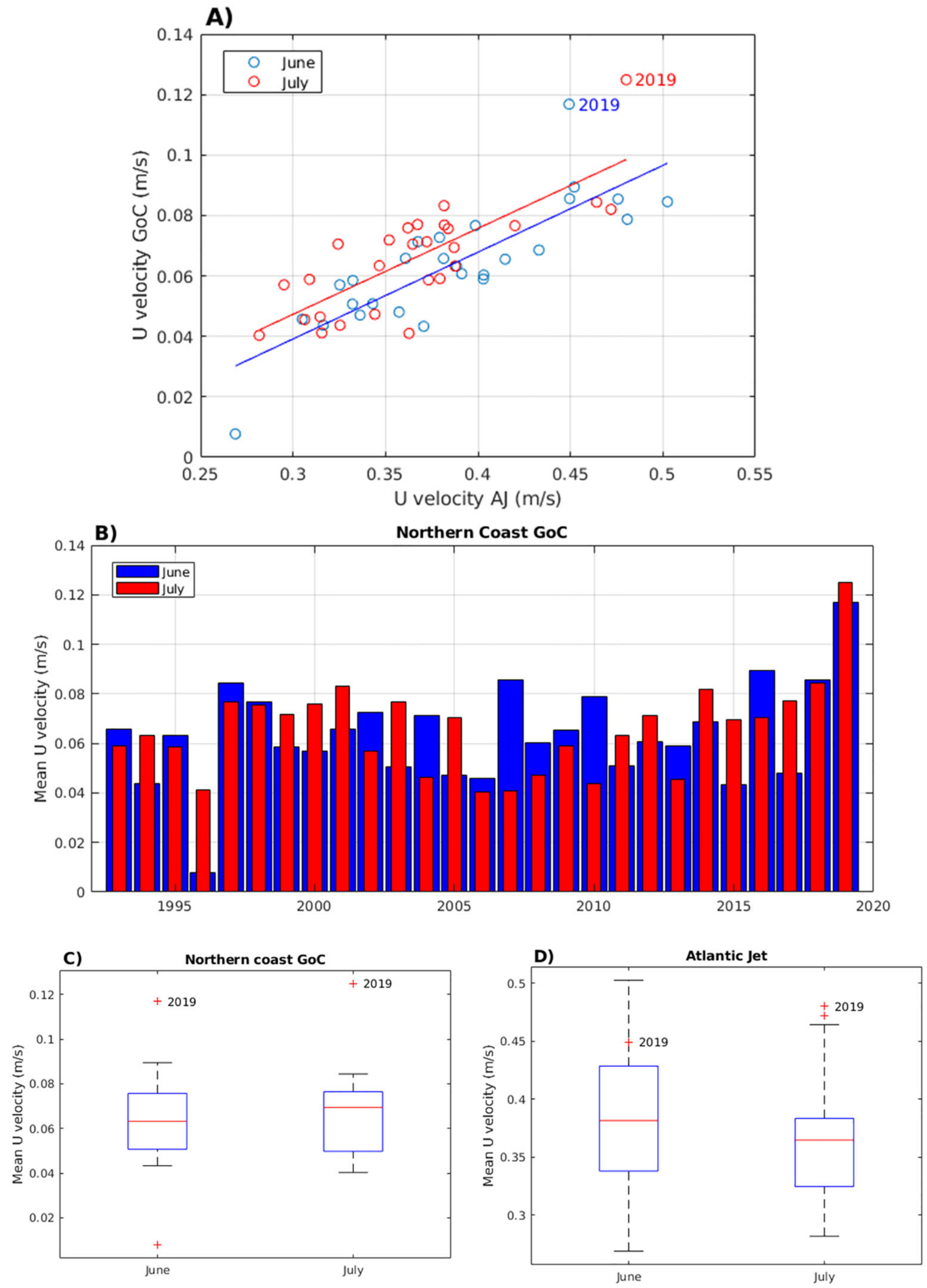

FIGURE 6
(A) Scatter plot of AJ zonal velocity (m/s) vs. mean zonal velocity (m/s) averaged over the northern coasts of the GoC (<200m depth) for the months of June (red dots) and July (blue dots) between 1993 and 2019. **(B)** Time series of mean zonal velocity (m/s) averaged over the northern coast (<100m depth) of the GoC for the months of June (red bars) and July (blue bars) from 1993 to 2019. Scatter box of the mean zonal velocity (m/s) averaged over the northern coast of the GoC **(C)** and of the AJ **(D)** for the months of June and July between 1993 and 2019.

around the Cape San Vincent in southern Portugal and mainly follows the isobaths as an eastward flowing current towards the entrance of the Strait itself (García Lafuente and Ruiz, 2007, see also sketch in Figure 1B). If the water flowing into the Mediterranean is accelerated within the Strait of Gibraltar by the barotrophic effect of the low *mslp* described above, this will imply a general increase of the eastward water movement in the GoC, particularly on its northern shores, where the water already moves eastwards (*e.g.*, Sirviente et al., 2023).

It is also worth considering that wind anomalies were directed eastward in this northern region of the GoC (Figure 4), aiding the acceleration of the water along the coastal fringe. The concurrence

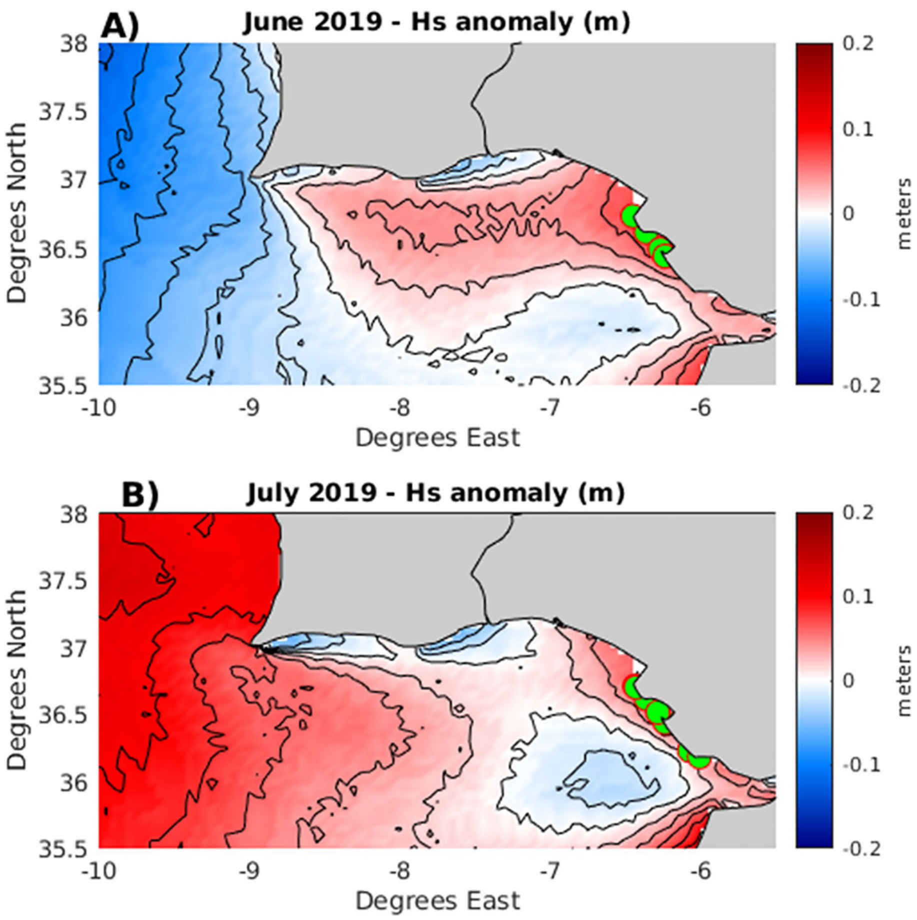

FIGURE 7
Significant wave height (Hs in m) anomalies for June 2019 **(A)** and July 2019 **(B)**. Green circles along the coast indicate the position of *P. physalis* arrivals for each analyzed month.

of both elements (hydrological and atmospheric) surely contributed to the fact that eastward velocities in the northern GoC for the months of June and July 2019 were identified as outliers in the statistical 27 year record analysis (Figure 6C).

Concomitant with the increased westerly winds and eastward surface current during summer 2019, higher than normal waves (+10/20 cm Hs) are simulated for the northern coasts of the GoC (Figure 7). It is, therefore, understandable that *P. physalis* colonies floating in the surface waters of the region were dragged to the coasts of the northern GoC (marked as green circles in Figure 7) where their arrival created alarm among beachgoers and forced beach closures.

One question remains open, however: why *P. physalis* colonies were close to the European continental margin and if the particular atmospheric and oceanographic conditions of the North Atlantic during summer 2019 had any influence on that circumstance. To evaluate this hypothesis, surface current data for the spring months (April and May) where downloaded from the global product available at CMEMS as described in section 2.2.

The mean currents for the spring period (April-May) in the North Atlantic are presented in Figure 8A. The strong Gulf Current flowing northwards along the American coasts, the eastward North Atlantic Drift and the Azores Currents are clearly identifiable. On the eastern boundary of our ROI (Figures 8C, D) the presence of eastward currents and typical westerly winds could be seen in the area between 40° and 50° north (Headlam et al., 2020).

During the months of April and May 2019, the general circulation patterns described above are reinforced in the overall North Atlantic (Figure 8B) with stronger eastward currents and westerly winds in the eastern boundary of our ROI (between 40-50° north) (Figures 8E, D). Furthermore, a report from an opportunistic vessel (fishing boat) signaled the presence of *P. physalis* on the position of the white cross in Figure 8B at the beginning of June (Prieto, *pers. comm.*).

We do not have confirming data, but it is likely that the region marked with the white cross in Figure 8B also contained *P. physalis* colonies during the spring months, as it corresponds to the typical open-ocean environment these organisms like to occupy (Mapstone, 2014). From there, and given the stronger east-flowing currents and the enhanced westerly winds (associated to the more regular presence of storms as indicated by the *mslp* anomalies), the colonies were likely transported towards the vicinity of the western European coasts, where they followed the main currents and winds towards the GoC and the Cádiz beaches as described by Prieto et al. (2015) for a winter event in 2010.

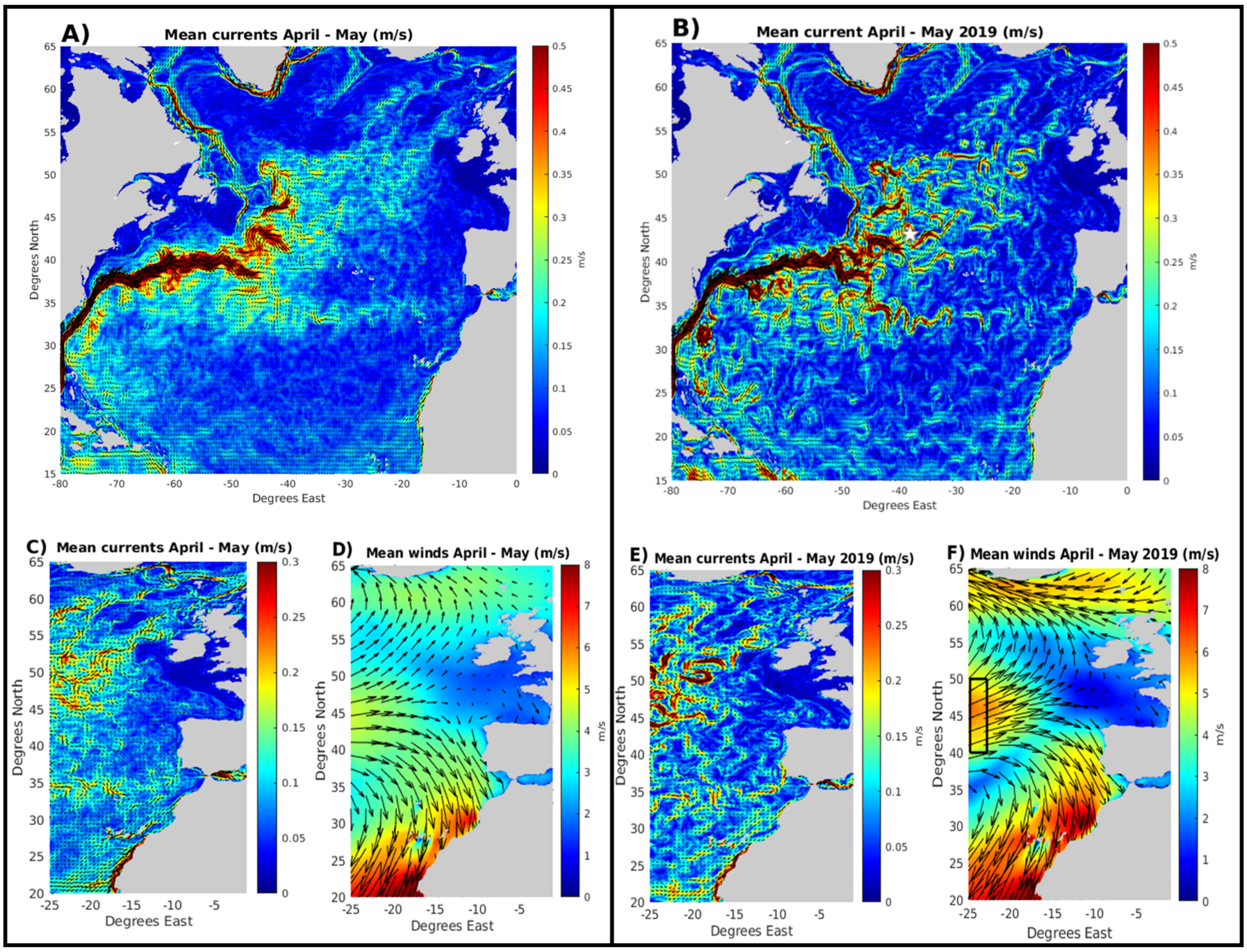

FIGURE 8
Contextual situation of the North Atlantic Ocean (currents) during the climatological spring (April – May) (mean in 1989-2020) **(A)** and during spring 2019 **(B)**. The white cross in panel **(B)** indicates the position of the opportunistic P. physalis sighting on 06/06/2019. **(C, D)** show the climatological spring (April – May) currents and winds over the ROI while **(E, F)** shows currents and wind for spring 2019. The black rectangle in panel F shows the 'source' area referred to in the text.

The area highlighted in Figure 8F (and Figure 1A) has been identified as a potential source region for *P. physalis* colonies ending up on Basque shores (Ferrer and Pastor, 2017) or arriving to Irish beaches (Headlam et al., 2020). Other reports point to the North Atlantic Drift as the main carrier for sea turtle juveniles (e.g., Hays and Marsh, 1997) arriving from the eastern coast of the United States (Monzón-Argüello et al., 2012), while others indicate that the Gulf Stream and North Atlantic Drift could carry tropical seeds from the Sargasso Sea to the European coasts (Quigley and Gainey, 2018). All of the aforementioned reports support our hypothesis that *P. physalis* colonies found on the Cádiz shores in June/July 2019 came from the tropical central Atlantic carried by the stronger than average surface currents and westerly winds prevalent during the previous spring (April/May).

A notable aspect of the 2019 beaching events concerns the absence of *P. physalis* colonies in the Mediterranean waters of the Alboran Sea. Notably, previous research (Macias et al., 2021) has demonstrated that when large-scale aggregations of *Physalia* are detected in the Gulf of Cadiz (such in winters of 2010, 2013 or 2018), a significant proportion can be transported through the Strait of Gibraltar into the Mediterranean Sea. The lack of stranded colonies in the Alboran Sea during the summer 2019 event may be attributed to the relatively low number of individuals involved in this particular incident.

4.2 Climate context and potential future scenarios

When the summer event of 2019 occurred, there was a debate regarding whether this was a result of global change causing *P. physalis* to inhabit areas closer to the EU coasts and whether such events could become more frequent in the future. Our study indicates that there are currently no signs of *P. physalis* altering its habitat distribution and that the particular event in summer 2019 was the result of particular atmospheric and oceanographic conditions in the North Atlantic. However, there are indications that due to global change, similar situations may occur more frequently in the future.

Analysis of historical reanalysis (ERA5) wind fields in the area of interest indicates that over the last 43 years (1980 – 2022), wind intensity in the *'source area'* (identified in Figure 8F) has, indeed, increased (Table 1). In addition, the zonal (*u10*) component of the wind field shows a trend that is one order of magnitude larger than the trend calculated for overall wind velocity (Table 1). It is also noteworthy that the trend analysis conducted only for the summer months (JJA), indicates increasing trends that are 50% (for total intensity) to 166% (for zonal intensity) larger than those observed for the annual values (Table 1).

Although the computed trends are not particularly large and there is substantial inter-annual variability, with only the summer *u10* trend being significant at 95% confidence, this analysis suggests that stronger westerlies in the source area are becoming more prevalent, particularly during the summer months. This could create more favorable conditions for the arrival of *P. physalis* colonies to the EU coasts during summer.

In addition to the likely increase in zonal wind speed, there have been reports of an increased risk of coastal flooding (Vousdoukas et al., 2018) as a consequence of increased storminess in the ROI. Moreover, there has been an increase of tropical cyclone exposure in the region during the last few decades (Jing et al., 2024). The increase in these types of atmospheric phenomena could provide another mechanism for the enhanced arrival of *P. physalis* colonies to European coasts and beaches.

Forecasting future wind intensity and direction is extremely challenging due to inherent limitations and shortcomings of global circulation models (Lowe and Gregory, 2005; Marcos et al., 2011). However, for our ROI, there are certain patterns and atmospheric links that can be used to provide insights into plausible future conditions. One such condition is the correlation between wind intensity and the NAO index in the region (see Supplementary figure 6). Our results align with previous studies (e.g., Marcos et al., 2011; Mentaschi et al., 2017) and essentially indicate that with more positive NAO values, there is an increase in wind (and westerlies in particular) velocities in the source area for *P. physalis* (identified in Figure 8F). Indeed, our studied year 2019 is in the middle of a sustained positive NAO phase covering the period 2015 – 2021.

TABLE 1 Decadal trend (in m/s per decade) of the total wind intensity and of the zonal wind component averaged over the 'source area' identified in Figure 8 using annual values (central column) or summer values (center column).

Variable	Trend in annual values (m/s per decade)	Trend in summer values (JJA) (m/s per decade)
Total wind intensity	0.015	0.04
Zonal wind intensity (u10)	0.1	**0.15***

Bold values are significant at 95% confidence level (p<0.05).

There are indications that the NAO will tend to become more positive in the future (Mentaschi et al., 2017; Shimura et al., 2013; Woodwort et al., 2007), and that warmer surface Atlantic waters will accelerate this trend (Rodwell et al., 1999). More positive NAO values in the future could be associated with increased westerly intensity according to the past trends (Supplementary Figure 6).

Despite the uncertainty in the future projections mentioned above, there are already some suggestions that wind intensity (McInnes et al., 2011), and the associated significant wave heights (Hemer et al., 2013) will likely increase in the coming decades in the western European coasts. In fact, McInnes et al. (2011) even indicate that 90% of the investigated models show a substantial increase in wind intensity in our ROI, particularly during the summer months.

If the projected changes of the NAO and associated wind and wave fields into the future materialize, the conditions encountered in summer 2019 could become more frequent. Consequently, the probability and risks of human interaction with drifting *P. physalis* colonies in the summer months will also increase. This dictates the need for better monitoring and warning systems to be put in place in order to minimize economic impacts and health threats for the coastal communities of Western Europe.

5 Conclusions

In conclusion, our study highlights the potential occurrence of infrequent yet significant arrivals of potentially dangerous *P. physalis* colonies to Iberian coasts during the summer season.

Our findings reveal that the atmospheric and surface ocean characteristics during the spring and early summer of 2019 were conducive to the presence of floating *P. physalis* colonies near EU coasts. Specifically, a south-westward displaced atmospheric high-pressure system favored the presence of enhanced westerlies and increased oceanic surface currents towards the coasts. These atmospheric and oceanographic conditions carried open-water *P. physalis* colonies towards the northern GoC coasts, where they were ultimately reported.

The analysis of past trends in wind intensity indicates an increasing intensity of westerlies during the summer months. This trend seems to be linked to the NAO variability that is expected to become more positive in the coming decades. As a result, there appears to be an increased probability of similar conditions occurring in the future.

Our work underscores the importance of continued monitoring and analysis of atmospheric and oceanographic conditions, enabling us to proactively address emerging ecological and societal challenges. It emphasizes the need for ongoing research and collaboration to safeguard public safety, protect coastal ecosystems, and ensure the sustainable coexistence of humans and marine organisms in the face of potential future events.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. The whole dataset of Physalia sightings can be found at https://digital.csic.es/handle/10261/388560. Further inquiries can be directed to the corresponding author.

Author contributions

DM: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. LG-S: Data curation, Formal analysis, Investigation, Writing – review & editing. LP: Data curation, Formal analysis, Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1597193/full#supplementary-material

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