

Unravelling environmental drivers and patterns of Portuguese man o' war (*Physalia physalis*) blooms in two ocean regions: North Atlantic and the Southeast Pacific

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ABSTRACT

Jellyfish blooms can significantly impact marine food webs, biochemical processes and human health, disrupting various economic sectors, including fisheries, aquaculture and tourism. Thus, understanding the regional drivers and patterns of jellyfish occurrence is key for developing effective management strategies. The Portuguese man o' war (*Physalia physalis*) is a hazardous, cosmopolitan siphonophore of particular concern, requiring a deeper ecological understanding to effectively guide mitigation efforts. Our study reveals that the occurrence of *P. physalis* in both the North Atlantic (Azores, Portugal) and the Southeast Pacific (Australian East Coast) is driven by region-specific wind patterns and increased primary productivity (>30 % model contribution), with warming conditions emerging as an additional occurrence driver on the Australian East Coast (~20 % model contribution). These insights resulted from machine learning models (Boosted Regression Trees) trained with high-resolution environmental data against field data describing the temporal variability of *P. physalis* occurrence (North Atlantic: 2008–2021; Southeast Pacific: 2016–2020). The models achieved excellent predictive performance (AUC North Atlantic: 1.00; AUC Southeast Pacific: 0.92) and allowed hindcasting occurrences over 30 years, uncovering contrasting trends between the two regions, with decadal fluctuations in the Azores and a significant increase in occurrence over time on the Australian East Coast. Overall, we provide a better understanding of the drivers and patterns of *P. physalis* occurrence, which can support the development of coastal management strategies. Importantly, the anticipated changes in productivity and temperature conditions in both regions may result in increased blooms in the years to come, further exerting impacts on the ecosystems, human health, and the economy.

1. Introduction

Jellyfish populations, including medusozoan cnidarians and ctenophores, can experience rapid and extensive blooms that significantly impact marine food webs and biochemical processes, with far-reaching consequences for fisheries and aquaculture (Boero et al., 2008; Hamner

and Dawson, 2009; Purcell, 2005). The presence of large numbers of jellyfish can disrupt the survival of fish stocks by preying on larval fish or competing for resources (Lynam et al., 2004; Tilves et al., 2016). Damaging fishing gear and reducing catches, these events can impact coastal communities and the tourism industry (Licandro et al., 2010; Conley and Sutherland, 2015; Bosch-Belmar et al., 2021) Furthermore,

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they pose a direct threat to human health through the venom contained in their nematocysts, which can cause life-threatening effects (Fautin, 2009; Geetha et al., 2019; Cegolon et al., 2013). These multifaceted challenges and impacts highlight the need for a comprehensive understanding of the drivers of jellyfish occurrences to inform the development of effective management strategies.

One species of concern is *Physalia physalis* (Linnaeus, 1758), commonly known as the Portuguese man o' war, a cosmopolitan hydrozoan species belonging to the order Siphonophorae (Bardi and Marques, 2007). This planktonic predator floats on the sea's surface, propelled by an air-filled pneumatophore that acts as a hydrostatic skeleton and sail (Totton and Mackie, 1960; Iosilevskii and Weihs, 2009; Prieto et al., 2015). As a siphonophore, *P. physalis* is a colonial organism composed of four types of specialized zooids with distinct functions (Munro et al., 2019). Its tentacles can extend up to 30 m and contain over 750,000 stinging cells. These dactylozooids, with defensive and predatory purposes, present a serious risk to human health, causing painful stings that may result in necrotic, neurotoxic, and cardiotoxic effects (Labadie et al., 2012; Wilcox et al., 2017). Despite being considered a public health concern in many regions worldwide (Bastos et al., 2017), knowledge about the ecology of *P. physalis* remains remarkably scarce, limiting the ability to predict its occurrence and develop adequate management strategies.

Current research for the Atlantic Ocean suggests that the occurrence of *P. physalis* and the observed regional variations are influenced by multiple environmental drivers interacting across various spatial and temporal scales, which can also shape the species' nutritional ecology (López et al., 2019; Lopes et al., 2016). Wind is considered a primary driver, as *P. physalis* passively drifts on the water's surface, its pneumatophore aligning with prevailing wind patterns can determine its spread (Totton and Mackie, 1960; Bourg et al., 2024). Sea surface temperature also has been indicated to play a crucial role, with warmer temperatures - often expressed as Marine Heat Wave events (Fragkopoulou et al., 2023) - linked to increased occurrences of the species (Fierro et al., 2021). Under specific conditions, warming seas may trigger its occurrence in new areas, primarily at higher latitudes, as reported for other jellyfish species (Purcell, 2005; Purcell et al., 2007; Gibbons and Richardson, 2008; Richardson et al., 2009). However, there is no consensus on whether this trend with temperature is universal (Condon et al., 2012), with some studies reporting an inverse relationship between *P. physalis* occurrence and rising temperatures due to environmental stress. Ocean productivity can further play a role, as *P. physalis* feeds on small fish and plankton, suggesting that nutrient-rich waters may support its proliferation (Lynam et al., 2004; Attrill et al., 2007). The diversity, interaction, and seasonality of these drivers (Prieto et al., 2015; Tiralongo et al., 2022; Purcell, 2005; Condon et al., 2013) underscore the need to establish and compare baseline data across different regions and timeframes (Hernández, 2020). Such integrated approach may provide valuable insights into the broader ecology of *P. physalis* and help developing effective management strategies to mitigate the risks associated with its occurrence.

The present study aims to (1) unravel the main environmental drivers that contribute to the occurrence of *P. physalis* and (2) explore temporal trends in two contrasting ocean regions: in the temperate North Atlantic Ocean (Azores, Faial Island, Portugal) and the Southeast Pacific Ocean (Australian East Coast). For this purpose, machine learning models, specifically the Boosted Regression Trees algorithm, fitted high-resolution environmental data on temperature, productivity and wind predictors, against field observations describing the temporal variability of *P. physalis* occurrence to explain and hindcast occurrences over decadal timeframes. Insights from prior studies (e.g. Bourg et al., 2022; Ferrer et al., 2015; Prieto et al., 2015), provided the ecological foundations for our time-predictive modeling approach (a.k.a. time-specific species distribution models; Assis et al., 2017; Ingenloff and Peterson, 2021), which explores the main drivers and patterns of occurrence *P. physalis*. Our research advances the ecological

understanding of *P. physalis* and provides baselines for informed management actions (Condon et al., 2013; Ferrer et al., 2015), particularly relevant in the face of future climate change, as global warming may trigger increased *P. physalis* blooms (Canepa et al., 2020).

2. Methods

2.1. Ocean regions

Physalia physalis has a conspicuous and cosmopolitan distribution in tropical, subtropical, and occasionally in temperate regions of the world (Fenner, 2005), where it strands along shorelines (Castrìoti et al., 2017). In the present study two contrasting ocean regions were considered, specifically (1) the temperate North Atlantic, in the Azores (Faial Island, Portugal), approximately 38.5°N to 38.6°N and 28.5°W to 28.8°W, and (2) the temperate Southeast Pacific region, in the Australian East coast, approximately 33.91°S to 33.95°S and 151.24°E to 151.25°E.

2.2. Environmental data

Environmental data for the two study regions were acquired from the Copernicus Marine and Environment Monitoring Service (CMEMS). Data were sourced as monthly timeseries for the period 1993 to 2021 (to ensure consistency with occurrence data; refer to Supplementary Figs. 1–3) from two pre-processed reanalysis: the Global Ocean Physics Reanalysis and Forecast and the Global Ocean Biogeochemistry Analysis and Forecast. These datasets integrate and assimilate a wide range of satellite and in situ data to deliver comprehensive environmental information with low spatial and temporal uncertainty (Fragkopoulou et al., 2023; Assis et al., 2024).

The considered predictor variables of *P. physalis* occurrence were based on prior studies. Specifically, our time-predictive modeling considered:

- (1) Sea surface temperature (°C), which can positively influence the growth, reproduction, and distribution of *P. physalis* (Bourg et al., 2022);
- (2) Primary productivity (C/m²/day), referring to the total production of organic matter by phytoplankton, which can serve as a direct indicator of nutrient availability to support higher trophic levels, including the prey of *P. physalis* such as small fish and zooplankton. Higher primary productivity can promote jellyfish blooms by increasing food availability (Lucas et al., 2014);
- (3) Wind speed (m/s), which can be critical in determining the occurrence of drifting *P. physalis*. Stronger winds can increase the distance the species is passively transported across the ocean surface. Areas subject to higher wind speeds may have more frequent occurrences of *P. physalis* (Bourg et al., 2024).
- (4) Wind direction (degrees, relative to true north), which can influence *P. physalis* distribution. Winds blowing towards the coast can increase the likelihood of stranded *P. physalis* occurrences, while offshore winds may reduce the chances of individuals reaching beaches (Graham and Hamner, 2001; Iosilevskii and Weihs, 2009).

2.3. Occurrence data

Presence and absence records of *Physalia physalis* in the Azores were registered from 2008 to 2021 under the program MONIJELLY (Atlantic Naturalist Association dataset). Beach-based surveys recorded stranded individuals at least one survey event every 15 days, yet with some interruptions (please refer to Supplementary Fig. 1) covering 5 beaches (Praia da Fajã, Almoxarife, Conceição, Porto Pim, and Porto da Feteira; Fig. 1). Records in the Australian East Coast covered 3 beaches (Clovelly Beach, Coogee Bay and Maroubra; Fig. 1) and were obtained from the available dataset of (Bourg et al., 2022), which comprises comparable

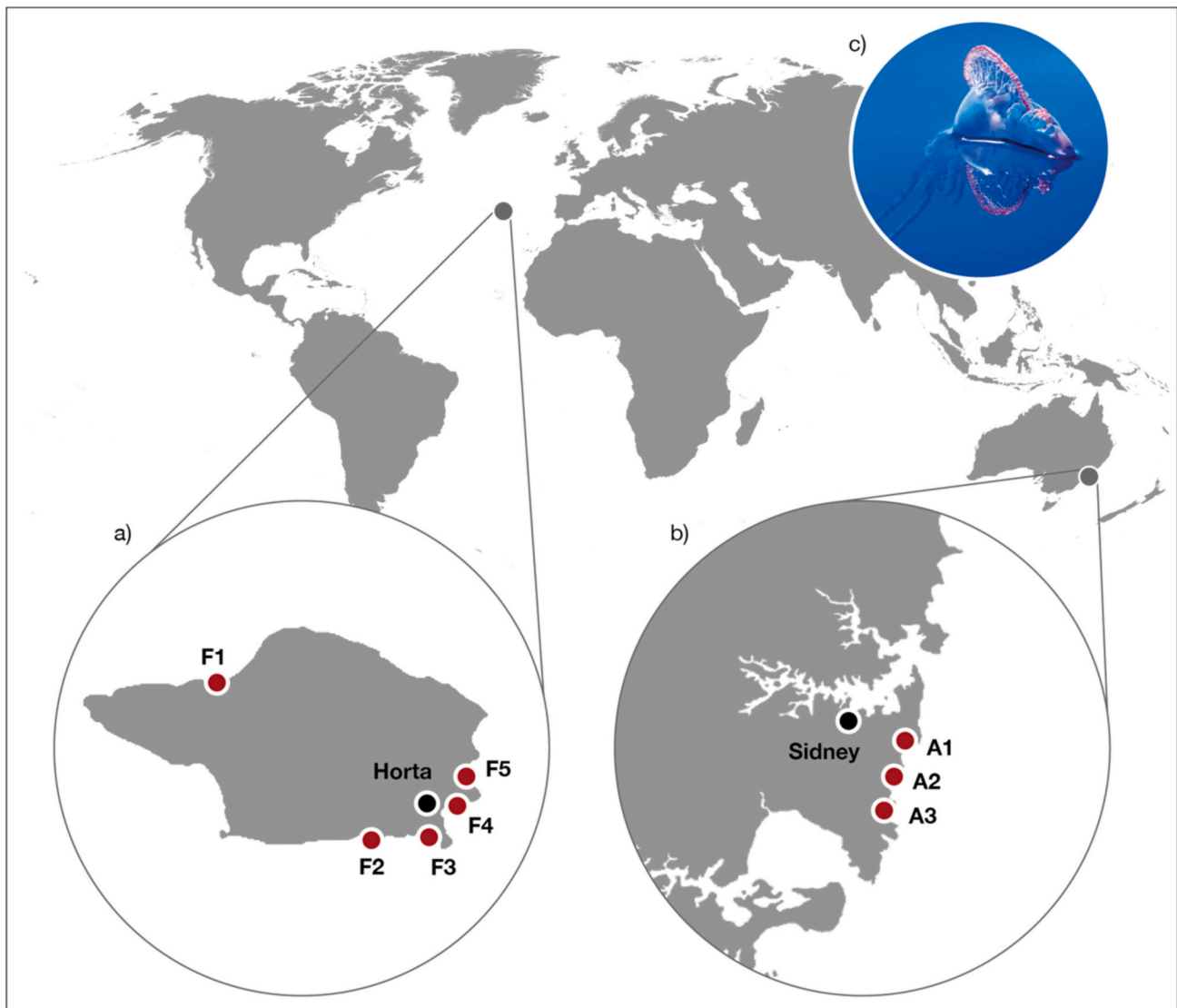


Fig. 1. Sampling locations for stranded individuals at a) Faial Island, Azores (F1: Praia da Fajã; F2: Porto da Feteira; F3: Porto Pim; F4: Conceição; F5: Almoxarife) and b) Australian East Coast (A1: Clovelly Beach; A2: Coogee Bay; A3: Maroubra); c) represents a floating Portuguese man o' war (*Physalia physalis*).

beach-based surveys of stranded individuals covering the period 2016 to 2020 (daily surveys, yet with some interruptions; please refer to data availability statement). To match the Azores dataset, presence records were considered for the flags “Likely”, “Some” and “Many”, while absence records for the flag “None”.

Both Azores and Australian records were aggregated per month to match the environmental data. This resulted in similar monthly records between regions, with the Azores and Australian East Coast having 142 and 138 records, respectively.

2.4. Modeling approach

We used the machine learning algorithm Boosted Regression Trees (BRT) to develop two independent models (i.e., Azores and Australian East Coast) fitting the occurrence of *Physalia physalis* against environmental data. The models provide the means to capture the distinct drivers influencing *P. physalis* occurrence in the two regions, while also enabling predictions under long-term environmental conditions beyond the timeframe used for model fitting. The BRT algorithm was chosen because it combines the advantages of both regression trees and boosting algorithms, handling interaction effects between predictor variables (environmental data) and response variables (occurrence records), and

can fit complex nonlinear relationship, while increasing parsimony and avoiding overfitting through proper hyperparametrization and forced monotonicity responses (Assis et al., 2017).

Hyperparametrization tuning was achieved by the grid-search approach (Hutter et al., 2019). This method systematically tested all possible combinations within a specified range of key hyperparameters to identify the best-performing configuration. Specifically, a range of learning rates (0.1, 0.01, 0.001), tree complexities (2, 3, 4 and 5), bag fraction (0.1 to 0.9, step 0.1), number of trees (50 to 500, step 50) and minimum observations per node (2 to 10, step 2) were explored. Each model fitted predictors by forcing monotonic responses based on a priori ecologic assumptions, a key step in machine learning (Hofner et al., 2011). Specifically, positive responses were forced for temperature and primary productivity. No monotonic responses were forced for wind patterns. Sampling location (i.e., beach) was included in the models as a fixed effect to account for site-specific variability. Such fixed effects help to account for constant factors specific to each site, such as geomorphology, or the degree of exposure to prevailing winds, which could influence the likelihood of *P. physalis* occurrence. By treating location as a fixed effect, the model can isolate the influence of other predictor variables, such as temperature and wind speed, without conflating them with location-based differences.

Model performance was evaluated with the area under the curve (AUC), deviance explained, sensitivity (true presence rate) and specificity (true absence rate). The relative contribution of predictors to the performance of the model was also calculated (Elith and Leathwick, 2009). Response curves (a.k.a., partial dependency functions) were produced to assess ecological realism (Elith and Leathwick, 2009).

Both models were used to predict the probability of occurrence of *P. physalis* from 1993 to 2021. A decomposition of the predicted time series was performed to extract seasonality and temporal trends (Hyndman and Athanasopoulos, 2018).

3. Results

The models retrieved high performance for the two regions, explaining most of the variability found in the occurrence data (DE: >0.692; Table 1). All occurrence records of the Azores were accurately predicted (AUC: 1; Table 1). The performance of the model developed for the Australian East Coast was impacted by approx. 3.9 % and 11.8 % of incorrectly predicted presences and absences, respectively (Table 1).

The environmental predictors that contribute the most to explain the distribution of *P. physalis* in the Azores were wind direction (41.46 % contribution), followed by productivity (31.49 % contribution), wind speed (15.44 % contribution), and sampling site (7.15 % contribution, i.e., site-specific variability). Temperature had a neglectable effect on the model (<5 % contribution; Fig. 2). Wind direction was also the best predictor to explain the variability of *P. physalis* in the Australian East Coast (45.29 % contribution). This was followed by primary productivity (29.45 % model contribution) and temperature (20.56 % model contribution). Sampling site and wind speed had a neglectable effect on this model (<5 % contribution; Fig. 2). From this point onward only higher contributive predictor variables (>5 % contribution) are addressed and discussed.

The partial dependency plots showed that *P. physalis* in the Azores has higher probability of occurrence when the winds blow towards 38.61–75.32° and 87.97–191.77° (Northeast and East-northeast, East to South, respectively; corresponding to SW winds, as well as W and Northwest winds), when productivity is higher than 0.36 mgC/m³/day, and when the wind speed is higher than 1.03 m/s. Additionally, higher probability of occurrence can be found on the beaches Almojarife, followed by Feteira, Fajã, Conceição and Porto Pim (Fig. 3). In the Australian East Coast, *P. physalis* has higher probability of occurrence when the winds blow towards 0–26.30° (S-SW winds), 189.91–313.29° (N to NE winds) and 328.94–340.63° (S-SE), when primary productivity is higher than 0.35 mgC/m³/day, and when temperature is higher than 19.74 °C (Fig. 3).

Predicting to 30 years of environmental data revealed contrasting patterns between the two regions, particularly in the long-term (Fig. 4). Both regions showed marked seasonality, with a higher probability of occurrence associated with summer months (June through September in the Azores and December to March in the Australian East Coast; Fig. 4). In the long-term, the probability of occurrence in the Azores showed a sigmoidal trend, while a significant increase over time was predicted in the Australian East Coast. In detail, the probability of *Physalia physalis* in the Azores was higher between 1996 and 1999, 2002 and 2004 and between 2018 and 2021. Lower probability was predicted between 1994 and 1996, and in 2007, 2012 and 2013 (Fig. 4). For the Australian East

Table 1

Performance of the models developed for *Physalia physalis* in Faial Island (Azores, North Atlantic) and the Australian East coast (Southeast Pacific) inferred with deviance explained (DE), area under the curve (AUC), sensitivity and specificity.

Model	DE	AUC	Sensitivity	Specificity
Faial Island	0.928	1	1	1
Australian East Coast	0.692	0.922	0.961	0.882

Coast, the model predicted a low probability of occurrence between 1993 and 1995, followed by an increase, with maximum probability in the years 1998, 2001 and 2006 to 2007. In recent years, probability was never predicted lower than 0.6. The irregular fluctuations within the random component of both time series demonstrated a lack of any systematic structure (Fig. 4).

4. Discussion

This study inferred the potential environmental drivers shaping the distribution of a hazardous cosmopolitan jellyfish species. Machine learning models performed with high accuracy and showed that similar drivers can act differently in contrasting ocean regions, corroborating that ecological processes and patterns are regionally dependent (Hobbs, 2003; Thrush et al., 2005; Hernández, 2020). While wind direction and primary productivity were found important for *P. physalis* occurrence across the temperate North Atlantic Azores region and the Southeast Pacific Australian East coast, the effect of temperature was only evident in the Australian East Coast. Additionally, the models allowed to reconstruct long-term time series for the two regions. These showed contrasting trends, with the Azores found with a sigmoidal trend of occurrence, while the Australian East Coast was found with increased occurrence over time. This information is a major step forward in the understanding of *P. physalis* ecology, which can serve as a baseline to inform and guide future management actions in the face of future climate change.

The models performed with high accuracy, capturing 100 % of the variability in species occurrence for the Azores and 96 % for the Australian region. This high performance allowed to explore the potential drivers to explain the species' presence and stranding events. Land masses act as physical barriers within oceanic hydrological contexts, and, on a local scale, the occurrence of the *P. physalis* resulted mainly from wind influence. Particularly, wind direction emerged as the most important driver explaining the temporal variability of occurrence data. The species drifts downwind under strong prevailing winds (Bourg et al., 2024), underscoring the role of cross-shore wind patterns in beach stranding events (Iosilevskii and Weihs, 2009). In the Azores, the presence of *P. physalis* are explained by winds originating from the southwest, west, and north, aligned with the influence of the Gulf Stream and the Azores Current (Bashmachnikov et al., 2004; Caldeira and Reis, 2017). The northward-flowing Gulf Stream is expected to transport *P. physalis* from lower (warmer) latitudes, while the Azores Current, branching from the Gulf Stream and passing through the archipelago at varying latitudes, will further transport the colonies through the archipelago. This eastward transport has been reported for diverse planktonic life forms, including the large predator of *P. physalis*, the early juvenile stages of loggerhead seaturtle *Caretta caretta* (Evseenko, 2008; Vandeperre et al., 2019). The interaction between the source origin ocean currents with the specific cross-shore wind patterns is here hypothesized as the main driver of the observed stranding events. In Australia, the wind patterns explaining the beach stranding was inferred from South-Southwest, North to North-Northeast and South-Southeast. These regimes align with the East Australian Current (EAC), a current system that transports tropical waters southward along the eastern coast of Australia, which can provide a pathway for *P. physalis* to move from lower (warm) to higher (cold) latitudes. The interaction between southerly flowing warm water and the inferred wind patterns can promote beach strandings along the coast. The models showed a positive relationship between productivity and *P. physalis* probability of occurrence. Along the environmental timeseries explored for the two regions, periods with higher productivity may have supported a rich trophic web and abundant prey enhancing the occurrence of *P. physalis* (Richardson and Gibbons, 2008; Graham et al., 2014), although other large scale factors as hydrological and climatological may have also come into play (Graham and Hamner, 2001).

Importantly, the models also highlighted regional differences in the

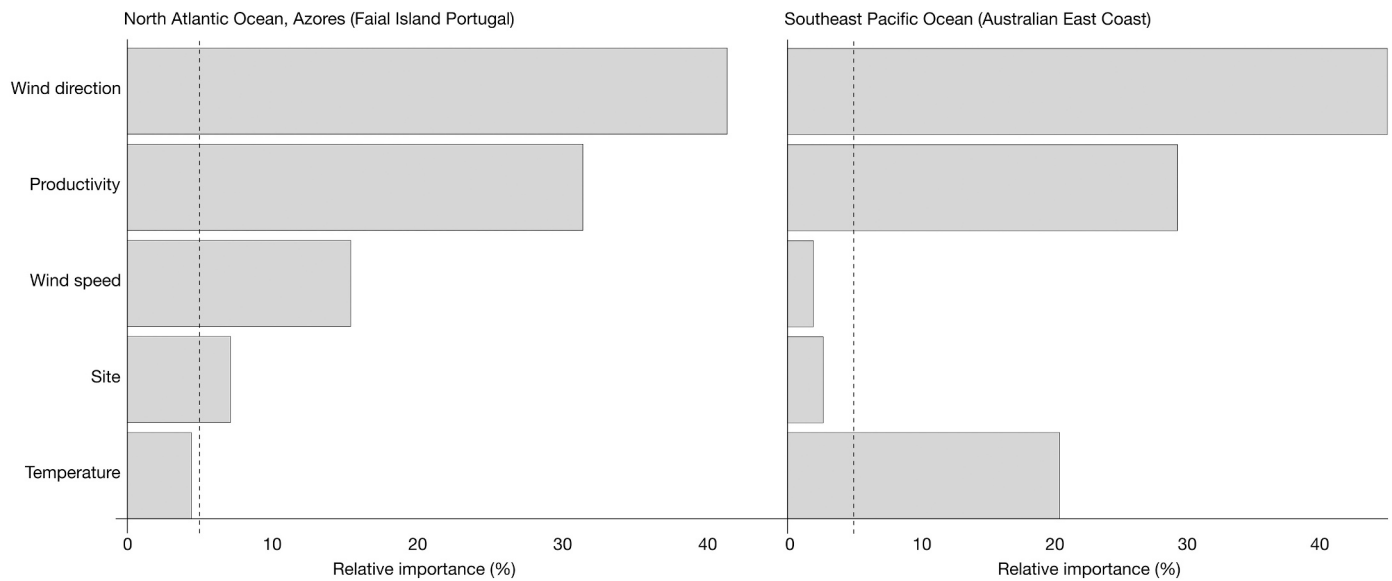


Fig. 2. Relative contribution of the predictor variables to the models developed for *P. physalis* in (left panel) the Faial Island (Azores, North Atlantic) and (right panel) the Australian East coast (Southeast Pacific). The dashed line depicts a 5 % relative contribution threshold.

potential drivers of *P. physalis* occurrence. In the Azores, wind speed was identified as a key environmental factor influencing *P. physalis* occurrences, with a notably higher probability of sightings when wind speed exceeds 1 m/s. This finding suggests that the dispersal of *P. physalis* in the Azores is highly influenced by wind-driven transport mechanisms. This aligns with studies in other regions, which emphasize not only the prevailing wind direction but also the critical role of wind speed (Iosilevskii and Weihs, 2009; Ferrer et al., 2015; Prieto et al., 2015; Headlam et al., 2020; Ferrer and González, 2021; Macías et al., 2021; Bourg et al., 2022, 2024). In contrast, temperature emerged as an important driver influencing *P. physalis* occurrence along the East Coast of Australia, where higher sea temperatures significantly increase the probability of occurrence. This result aligns with other studies that highlight the positive correlation between elevated temperatures and the species' distribution for this region in Australia (Torres-Conde et al., 2021). Interestingly, while both regions exhibit similar temperature ranges (between 15 and 25 °C; please refer to Supplementary Figs. 2–3), temperature likely plays a more influential role in Australia East Coast due to other interacting factors, such as the East Australian Current, which transports warm water southward potentially with abundant *P. physalis*, their prey, or both. In the Azores, while *P. physalis* may experience warm temperatures within its thermal optimum, wind patterns may prevent the species from drifting into coastal areas, making temperature less relevant, as a standalone driver. The more limited coastline can also be a limiting factor. These regional differences underscore the importance of considering regional environmental dynamics when assessing the drivers of species occurrence.

Our models performed well despite limitations. The Azores model is based on data from one island, covering five sites, so findings may not generalize across the archipelago. Factors like island proximity, coastal morphology, and primary arrival direction of *P. physalis* likely influence outcomes, while steep volcanic coastlines pose additional detection challenges (Faerber and Baird, 2010; Costa et al., 2014). Similarly, the Australian East Coast model, drawn from three sites, showed some predicted presences despite absences, possibly due to local geology, hydrography, or specimen removal by tides, alongside stochastic marine events. In overall, the BRT machine learning technique excels at identifying hidden trends and complex interactions within sparse occurrence data, enabling the prediction of complete time series and a deeper understanding of the underlying ecological drivers, even when those relationships are not readily apparent through traditional statistical

methods.

The models predicted occurrence for 30 years of environmental data (1993 to 2021), and time series decomposition analyses allowed to infer seasonal and trend patterns. In both ocean regions, the species exhibits a peak of occurrence during the summer months, specifically from May to September in the Azores and from December to March in the Australian East Coast. Such seasonality pattern agrees with opportunistic datasets (e.g., gelavista.ipma.pt) and studies (Pikesley et al., 2014; Mghili et al., 2021). Crucially, the long-term predictions highlight contrasting trends between ocean regions. In the Azores, a sigmoidal pattern emerged, with low occurrence probability in the early years, an upturn from 1999 to 2004, and a notable rise in occurrence probability starting in 2014. These fluctuations align with studies suggesting multi-decadal cycles in jellyfish blooms (Richardson and Gibbons, 2008; Condon et al., 2013). Conversely, our analysis of the Australian East Coast revealed a significant increase in occurrence probability over time. Notably, these contrasting trends between the Azores and Australia align with emerging hypotheses that challenge the previous notion of a global rise in jellyfish blooms, suggesting instead that regional factors play a more critical role in driving local population dynamics.

This study advances our understanding of the drivers influencing *P. physalis* occurrence, and future climate change may pose challenges that must be acknowledged. Primary productivity, an important occurrence driver in both regions, forms the foundation of open-ocean marine food webs (Bopp et al., 2013), providing the energy source for higher trophic levels (Löscher et al., 2015). Numerous studies and models predict a global decline in productivity due to anthropogenic global warming (Steinacher et al., 2010; Bopp et al., 2013; Kwiatkowski et al., 2019). This decline is projected to be particularly severe in the North Atlantic (20° S to 65° N, encompassing the Azores) and the Western South Pacific (30° S to 30° N) (Steinacher et al., 2010; Kwiatkowski et al., 2019), potentially impacting *P. physalis* populations. On the other way, it is important to note that higher latitude regions are projected to experience an actual increase in productivity (Steinacher et al., 2010; Laufkötter et al., 2015), potentially offering suitable alternative habitats for *P. physalis* in the future. In the same way, in range edge regions, like in the Australian East Coast, warming may drive habitat expansions, with a temperature increment providing more suitable conditions for *P. physalis*. The coupling between increased productivity and temperature may challenge high latitude regions in the future owing to increased jellyfish occurrences (Steinacher et al., 2010; Laufkötter et al., 2015).

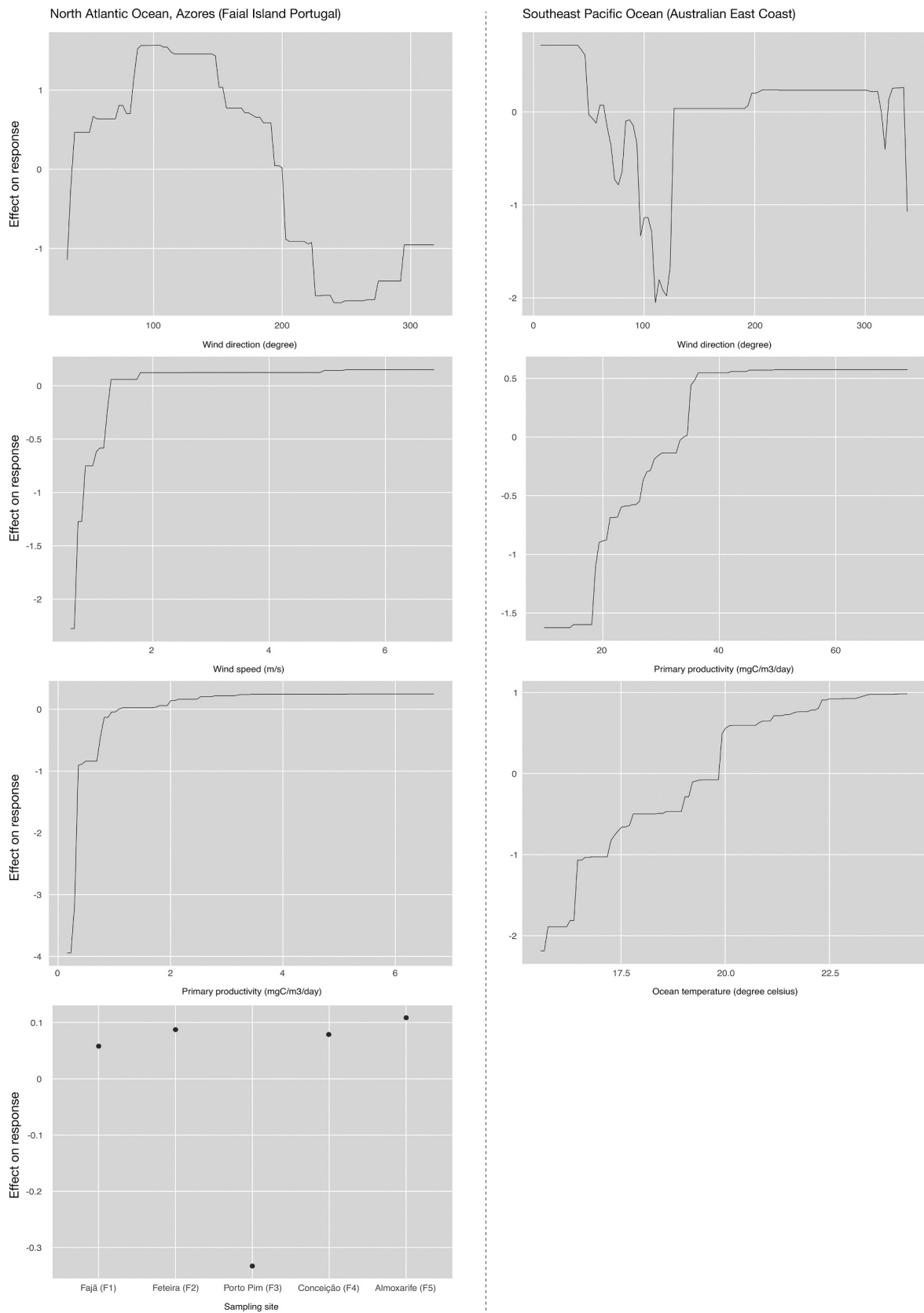


Fig. 3. Partial dependency plots depicting the effect of the most contributive predictor variables (>5 % contribution) on the probability of occurrence of *P. physalis* in the Faial Island (Azores, North Atlantic) and the Australian East coast (Southeast Pacific).

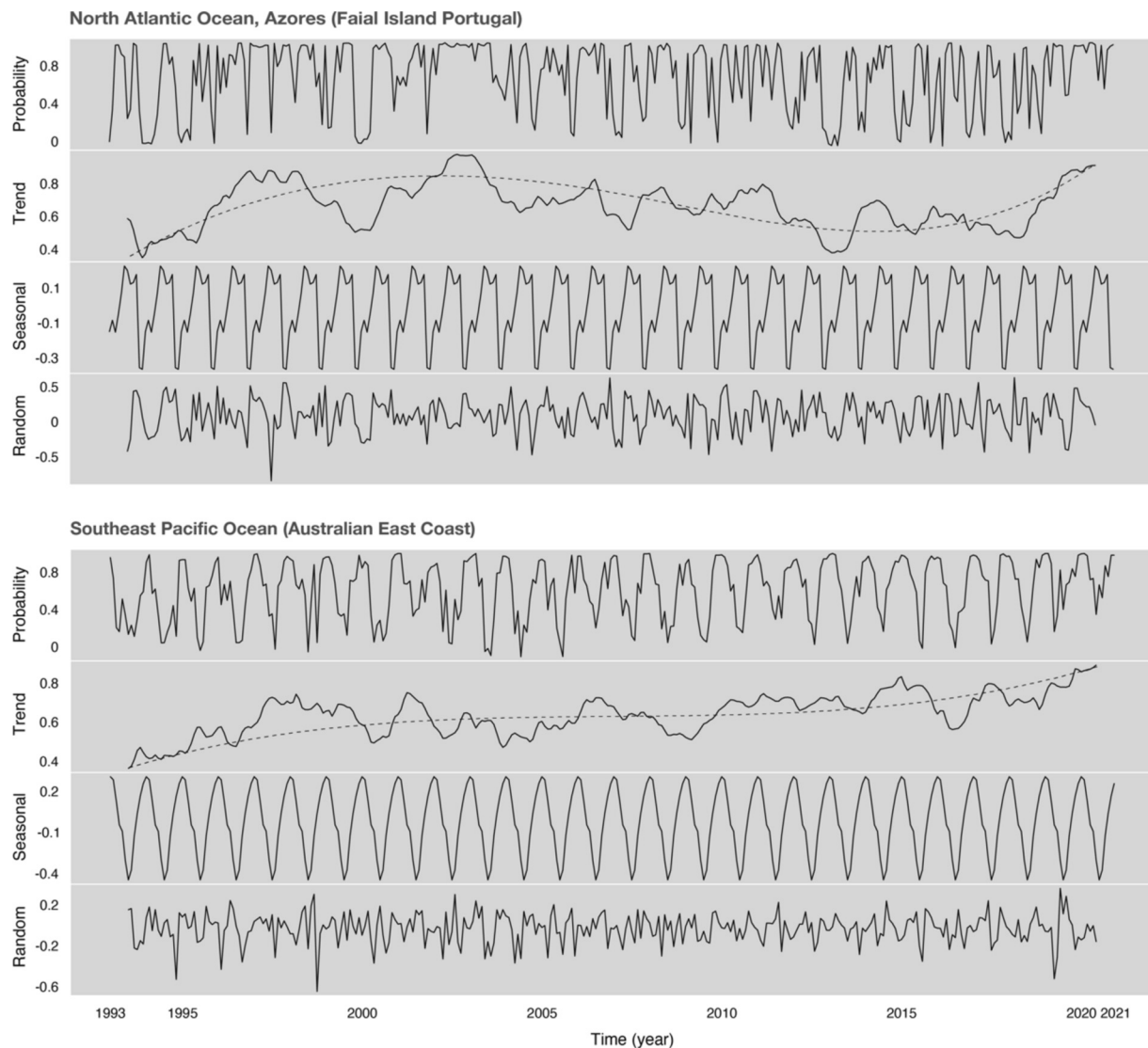


Fig. 4. Probability of occurrence of *P. physalis* predicted from 1993 to 2021 in the Faial Island (Azores, North Atlantic) and the Australian East coast (Southeast Pacific). Decomposition of additive time series of probability of occurrence given by the trend, seasonality and random component (fluctuations in the predicted data that cannot be attributed to the trend or seasonal patterns). Dashed line depicts the smoothed pattern of the long-term trend.

From a conservation standpoint, *P. physalis* emerges as a candidate species to track the effects of climate change, because it is cosmopolitan and resilient species (Canepa et al., 2020) and can be easily monitored. Consequently, active human intervention might become imperative for effective species management at some locations, encompassing not only *P. physalis* but also various other jellyfish species. Thus, the pursuit of further research into the underlying ecological responses remains essential.

5. Conclusion

This study identified the main environmental drivers shaping *P. physalis* occurrence in two distinct regions: wind patterns and primary productivity in the Azores, and wind direction, temperature, and productivity on the Australian East Coast. Using machine learning, hindcasting *P. physalis* occurrence over several decades revealed contrasting trends. While the Azores experienced multi-decadal oscillations, the Australian East Coast exhibited an increasing occurrence trend. These results emphasize the importance of regional studies, as global generalizations about jellyfish blooms can be misleading. The findings have critical implications for developing real-time monitoring and targeted

management strategies. As climate change alters marine ecosystems, it is essential to monitor its effects on jellyfish populations, given the potential socio-economic impact on tourism, fisheries, and public health. Proactive strategies, such as early warning systems based on predictive models - like the two utilized in this study- can play a crucial role in minimizing the adverse impacts of bloom events. Regional variations and climate-driven shifts in *P. physalis* distribution should be central considerations in both short-term and long-term policy-making.

CRedit authorship contribution statement

Lara Colaço Martins: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **José Nuno Gomes-Pereira:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Gisela Dionísio:** Writing – review & editing, Methodology, Data curation. **Jorge Assis:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jorge Assis reports financial support was provided by Foundation for Science and Technology - FCT. If there are other authors, they 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.2024.117278>.

Data availability

The data and code used to develop the models are permanently available at: <https://figshare.com/s/7cd6bd2de18a399494f6> (permanent DOI will be provided after manuscript acceptance).

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