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Estimation of jellyfish abundance in the south-eastern Spanish coastline by using an explainable artificial intelligence model based on fuzzy logic

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Abstract

Jellyfish swarms have a direct negative impact on human enterprise, specially on places dependent on the sun and beach economy. The local economy and the health of bathers may be at risk from the emergence of these gelatinous organisms. Economic losses can be mitigated by monitoring the occurrence of jellyfish on the coast. Due to the lack of jellyfish data, environmental citizen science is presented as an alternative for data collection. In this study, fuzzy logic-based models have been used to modelize the knowledge from citizen comments collected by the Infomedusa app. The effect of local climatological factors such as wind speed and direction on the incidence of jellyfish on the coast was studied. The fuzzy logic-based models showed that winds perpendicular to the coast lead to a higher occurrence of jellyfish swarms in central and eastern Malaga, while winds parallel to the coast have a greater influence in the westernmost coasts. Wind speed has a different effect on jellyfish incidence depending on the study area and wind direction. Data extracted from the Infomedusa app can help to address the historical scarcity of scientific data on jellyfish. This app presents an opportunity for future studies to expand the knowledge about the occurrence of these organisms on the coasts and may contribute to the prediction of onshore arrival.

Keywords

Model-ecosystem, Coastal Waters, Explainable Artificial Intelligence, Fuzzy Rules-Based System, Fuzzy Clustering, Environmental Citizen Science

1. Introduction

Since the 1950s, the increase in jellyfish populations has been perceived as a potential problem (Purcell, 2012). This is because the upwelling of these gelatinous organisms directly and indirectly interferes with activities such as fishing (Graham et al., 2003; Knowler, 2005; Nagata et al., 2009; Dong et al., 2010; Boero 2013; Nastav et al., 2013), aquaculture (Doyle et al., 2008; Delannoy et al., 2011; Bosch-Belmar et al., 2017; Halsband et al., 2018) or industrial production processes located along the coast (Daryanabard and Dawson, 2008).

Sun and beach tourism is one of the most important economic sectors to the Spanish economy affected by jellyfish blooms (Bernier et al., 2014), particularly in some places such as the Costa del Sol (Romero-Padilla et al., 2020). This enclave in southern Spain has undergone territorial, social and economic transformations induced by tourist activity, which in turn has boosted other economic activities such as fishing, intensive agriculture, communications and port and commercial activity. In this way, it is estimated that tourism on the Costa del Sol had an economic impact of 14,442 million euros in 2019 due to the arrival of a total of 13 million visitors. Jellyfish can undoubtedly have an impact on tourism, not only because of the negative perception instilled by specimens stranded on the sand, but also as a consequence of their stings, which in many cases can cause intense pain when they come into contact with bathers (De Donno et al., 2014).

The economic losses caused by the appearance of jellyfish on beaches can be partially mitigated by monitoring their populations, statistical analysis of historical records (Ghermandi et al., 2015) and the development of predictive models that allow the establishment of control measures and the removal of specimens that reach the beaches

(Bellido et al., 2020). However, this faunal group has traditionally been considered an unimportant component of the marine ecosystem (Brotz et al., 2012) and has been systematically excluded from the methodological manuals of routine scientific zooplankton surveys and trawl surveys (Heinle, 1965; Pugh, 1989; Hay, 2006). This means that historical records on the abundance of jellyfish populations are nowadays scarce (Brotz et al., 2012).

In the absence of scientific data and historical records, crowdsourcing systems through Environmental Citizen Science (ECS) have emerged as an alternative methodology for data collection (García-Soto et al., 2021). This is possible due to the the popularisation of mobile devices, which allow the participation of a large number of citizens in research and complex scientific problems through sensors and apps integrated in the smartphones (Boero, 2013). These data are sent to a server where it is possible to perform data mining, analysis and information dissemination tasks (Zamora et al., 2016; Komninos, 2018), allowing scientists to overcome limitations of budget, equipment or spatial scale imposed in most research projects (Zamora et al., 2016).

A clear example of non-driven open distributed collaboration, is the monitoring of relative abundances of jellyfish through the *Infomedusa* app. Infomedusa (https://infomedusa.es/) was developed by the Diputación Provincial de Málaga (Malaga County Council) in collaboration with the Aula del Mar de Málaga, and has been used effectively to monitor the presence or absence of jellyfish along the Costa del Sol (south-eastern Spain). Based on the database generated by this app, it has been possible to demonstrate: (i) the effectiveness of ECS as a valid pathway for scientific production from the participation of citizens in science and research, (ii) the effect of climate oscillations on jellyfish swarms and their incidence on beaches (Bellido et al., 2020), and (iii) the effect of different local climate components on jellyfish abundance from classical statistical modelling techniques (e.g. Generalised Additive Models) (Gutiérrez-Estrada et al., 2021).

In non-driven applications such as Infomedusa, the information generated is not controlled by a structured scientific programme focused on obtained conclusions. Therefore, the collection of useful data and the obtaining conclusions requires a pre-processing of the information provided by the users and a subsequent meta-analysis characterised by the use of non-linearly correlated data associated with a high degree of uncertainty. Under these circumstances, techniques of explainable artificial intelligence such as fuzzy logic (FL) show better performance compared to the results obtained with others statistical procedures (Tang and Chi, 2005; Yi et al., 2016, Arrieta et al., 2020).

In particular, FL mathematically formalises the way humans interact with the environment and make decisions. Thus, models based on FL allow dealing with imprecise information in terms of fuzzy or fuzzy sets, making it possible to model any non-linear process and learn from the data through different learning algorithms (Martín del Brío and Sanz Molina 2006). In this way, FL models are a very good alternative for data processing in an environmental citizen science context. The bases of the proposed methodology (Aroba, 2003) have demonstrated its efficacy for modelling the qualitative behaviour of complex systems in diverse contexts, like: environmental (Fernández-Camacho et al., 2015), biochemical (Luis et al., 2018) or medical (Enríquez et al., 2018), where the obtained results were validated by experts in the corresponding fields, confirming the veracity and value of the generated qualitative information.

Therefore, this paper presents a methodology based on a FL approach for the characterization of the effect of local environmental conditions (wind direction and wind speed) on the incidence of jellyfish on the beaches of the Costa del Sol, located in the Andalusian coastline (southern Spain).

2. Material and methods

2.1. Study area

The study area is located in the province of Malaga (Andalusian region, south-eastern Spain). The Costa del Sol stretches from La Línea de la Concepción on the border with the province of Cádiz in the west to the cliffs of Maro-Cerro Gordo on the border with the province of Granada in the east, for approximately 185 km (Fig. 1). The Costa del Sol is made up of three distinct areas: (1) Western Costa del Sol, specialising in foreign tourism; (2) Eastern Costa del Sol, oriented towards inland and residential tourism; and (3) the capital area, with administrative, commercial and non-tourist residential functions (García and Ocaña, 1982).

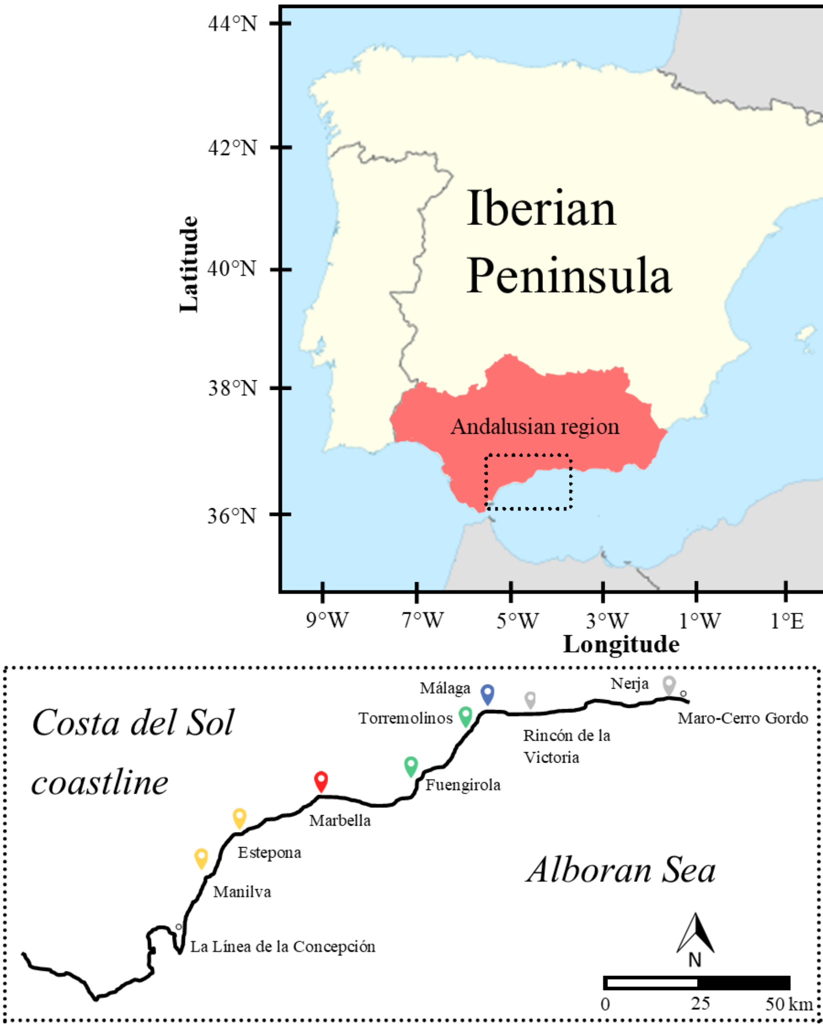


Figure 1. Study area. Location of the main beach sets cities. Colours on the mark point represent membership to the different beach sets: Set 1 (Blue), Málaga beaches; Set 2 (Gray), Nerja-Rincón de la Victoria beaches; Set 3 (Green), Torremolinos-Fuengirola beaches; Set 4 (Red), Marbella beaches; Set 5 (Yellow), Manilva-Estepona beaches. The border localities of the Costa del Sol to the west (La Línea de la Concepción) and to the east (Maro-Cerro Gordo) are also marked.

The Alboran Sea bathes the coastline of the study area and its surface circulation is characterised by the presence of two medium-sized anticyclonic gyres (Western and Eastern Anticyclonic Gyre) surrounded by the meandering flow of Atlantic surface water, the Atlantic Jet. Both anticyclonic gyres are separated by a cyclonic structure of more elusive existence called the Central Cyclonic Gyre (Peliz et al., 2013; Macías et al., 2016; García-Lafuente et al., 2021).

A total of 149 beaches belonging to 14 different localities have been analysed in this study, from Ancha de Casares beach in the west to Las Alberquillas beach in the east (Fig. 1).

2.2. Jellyfish relative abundance data

The relative abundance of jellyfish was obtained from the Infomedusa app, available in this google link: https://play.google.com/store/apps/details?id=es.infomedusa&hl=es. Infomedusa is a citizen science app available for iOS and Android smartphones and developed by the organisation Aula del Mar de Málaga (https://www.auladelmar.info/). Users have real-time knowledge of climatological and oceanographic variables through the app. The application has a functionality that allows users to chat in an individual forum for each beach about climate conditions and the presence or absence of jellyfish. A database is generated from the citizens' comments. In 2018 (between 25 January and 3 October), 40,276 comments were registered, of which 9,963 were validated and selected for the purpose of this study.

Since comments from citizens had a natural language structure, a transition network (TN) was designed for their processing. TNs has been widely used in different fields of knowledge (Woods, 1973; De Carolis et al., 1996; Gangopadhyay, 2001; Gutiérrez-Estrada et al., 2005). These systems are based on a data structure consisting of a set of nodes representing finite states which are connected through a series of arcs. This model consists on a transition between states according to the grammatical category of the word read (Woods, 1970). The state changes are determined by the grammatical category of the word read, with the input being the user's comment in the chat and the final output being the information corresponding to the number of jellyfish. The outputs of the system were set to a series of discrete values: ‘None’ (0); ‘Few’ (1), ‘Some’ (2), ‘Many/Much’ (3), and ‘Very many/very much’ (4). A detailed explanation of this process can be found in Gutiérrez-Estrada et al. (2021).

2.3. Environmental data

Due to the planktonic nature of this species, climate could allow huge accumulations of jellyfish along the coastline. Two of the main factors influencing jellyfish strandings are the direction and speed of the prevailing local winds that cause the migration of surface water towards the coast (Graham et al., 2001; Bellido et al., 2020; García-Lafuente et al., 2021; Gutiérrez-Estrada et al., 2021). Winds in the study area are characterised by seasonal behaviour. In winter-spring they have a north-westerly component and in summer the south-easterly component predominates (Mercado et al., 2012).

Wind data was obtained from the Spanish Meteorological Agency (http://www.aemet.es/en/portada). Five different set of beach localities and four different weather stations were used to deal with differences in coastlines morphology and orientation (Table 1).

Table 1. Description of the weather stations and localities covered.

Weather station	**Location**	**Altitude (m)**	**Set of beach localities***	**Localities covered (From East to West)**
Málaga	36^{o} 39'N, 4^{o} 28'W	5	1, 2	Nerja, Torrox, Algarrobo, Vélez-Málaga, Rincón de la Victoria, Málaga
Fuengirola	36^{o} 32'N, 4^{o} 37'W	8	3	Torremolinos, Benalmádena, Mijas, Fuengirola
Marbella	36^{o} 29'N, 4^{o} 44'W	2	4	Marbella
Manilva	36^{o} 22'N, 5^{o} 15'W	140	5	Estepona, Casares, Manilva

*See Gutiérrez-Estrada et al. (2021)

These stations record hourly data from temperature (average, maximum and minimum, in ^{o}C), wind (gust, mean and maximum speed, and direction, in km/h), atmospheric pressure (hPa), precipitations (mm) and humidity (%). For the purpose of this study, only mean speed and direction were recorded. Data for each variable were daily averaged.

2.4. Proposed Fuzzy Logic Approach

Currently, Artificial Intelligence is reaching high levels of applicability. Within Artificial Intelligence techniques, those that allow us to understand the knowledge they have learned from the data are of greatest interest particularly in those areas where the comprehension of the models is important. This understanding is of vital importance to be able to certify its operation according to our trustworthy standards. This highly topical field is currently known as eXplainable Artificial Intelligence (known as XAI)

(Barredo et al., 2020). Inside the XAI techniques is FL (Fernández et al., 2019), which is one of the most successful areas of Artificial Intelligence in applied problems due to its expressive richness using linguistic terms to enunciate real world concepts and definitions. In this work we propose the use of a fuzzy rules-based model obtained through clustering mechanisms, which is described below.

The proposed FL approach (Aroba, 2003) is based on the methodology described in Sugeno et al. (1993), to build fuzzy models based on the fuzzy C-Means algorithm (Bezdek, 1981; Höppner and Klawonn, 2003) to generate fuzzy rules with this format: IF $x \in A$ THEN $y \in B$, where $x = (x_1, x_2, \dots, x_n) \in \Re^n$ are input variables (antecedents), A are n fuzzy sets, $y \in \Re$ is the output variable (consequent) and B is a fuzzy set for this variable.

The first step, before data processing, is to determine the variables of the dataset whose behaviour needs to be studied, so that, these selected variables will be the consequents in the fuzzy rules that will be generated. Therefore, the rest of parameters of the dataset will play the role of antecedents in the fuzzy rules. Then, the proposed methodology analyses automatically the dataset, so that the consequent parameters are fuzzy clustered in an optimum number of fuzzy clusters are obtained (Fukuyama and Sugeno, 1989). Once the consequent parameters have been clustered, each fuzzy cluster is projected onto the antecedent space (Sugeno et al., 1993), obtaining the membership grade of the antecedents to each fuzzy cluster. Finally, with the obtained information in the previous steps, is generated a set of graphical fuzzy rules, like in the Figure 2, where the antecedent variables are *A* and *B*, and the consequent variable is *C*.

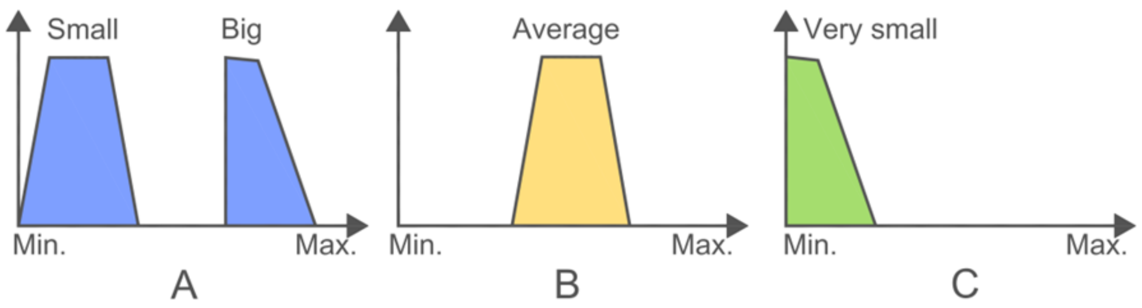


Figure 2. Example of graphical IF–Then fuzzy rule.

The fuzzy rule of the Figure 2 can be interpreted in natural language as:

IF *A* is small or big AND *B* is average, THEN *C* is very small.

The proposed fuzzy approach has been designed to be applied on multi-parametric quantitative datasets to generate automatically a Fuzzy Rules-Based System (FRBS) that provides a qualitative model of the processed data.

2.5. Comparison between the proposed FRBS models and GAMs

In order to compare the results obtained with FRBS models and Generalised Additive Models (GAMs), different values of interest or hot-points were inferred from the fuzzy rules generated for the antecedents (explanatory variables) wind direction and wind speed. Hot-points were established according to the behaviour of the partial residuals of generalised additive models (GAMs) calibrated by Gutiérrez-Estrada et al. (2021) with the variation of the explanatory variables. The hot-points values were fixed into the FRBS and the results were compared with the GAM estimations.

3. Results

For a better comprehension of the fuzzy rules obtained in each analysed zone, the results have been exported to the format of the Fuzzy Logic Toolbox of Matlab (MathWorks®), with the goal of representing the rules in 3D surface format, so that be more readable and interpretable in natural language.

For the Set 1 of beach localities (Malaga city beaches), a total of 7 fuzzy rules were generated by the fuzzy logic-based methodology. The 3D surface representation of these 7 fuzzy rules is presented in Figure 3, where relative jellyfish abundance act as consequent. The highest incidence of jellyfish is shown when the wind direction is around 225° and the speed is 10.5 km h^{-1}. The incidence of jellyfish is null with a wind direction of 135° and 230-250° or a wind speed higher than 21 km h^{-1}. The results of the model when setting the input variables at the established hot-points are represented in Table 2.

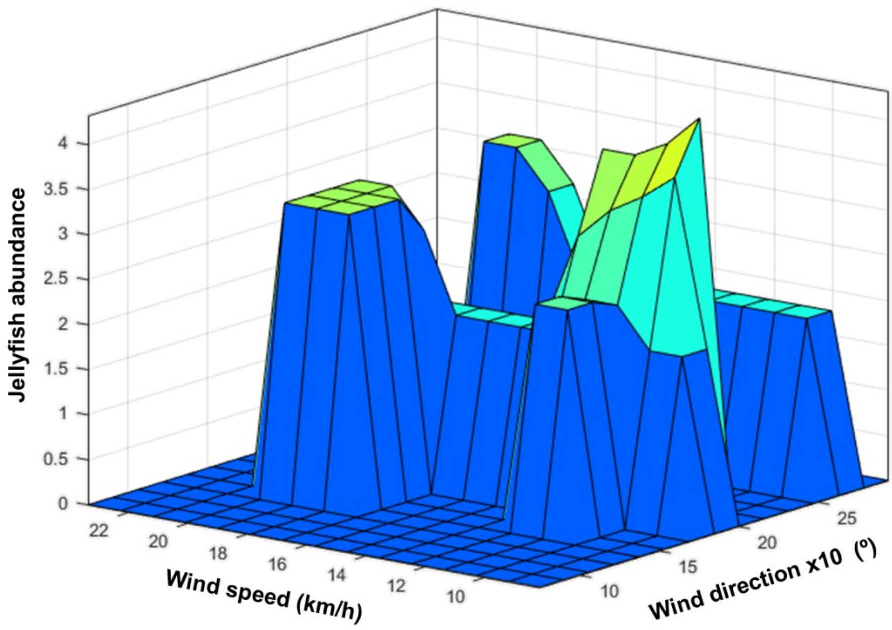
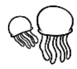
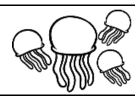
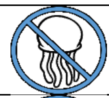
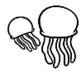
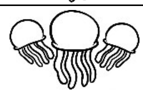
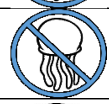
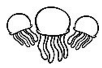
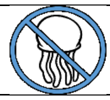
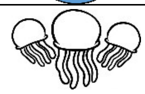


Figure 3. Surface view results of the Set 1 FRBS.

Table 2. Schematic results of the jellyfish incidence in Set 1 after setting the input variables in the Gutiérrez-Estrada et al. (2021) hotpoints.

	Wind direction hotpoints (° x10)		
Wind speed hotpoints (km/h)	**18**	**21**	**25**
10.5			
14			
19			

The results of fuzzy logic-based model show that a decrease of jellyfish incidence is driven by values of wind direction and wind speed around 250° or 10 km h^{-1}, respectively. However, the level of explained variance by the fuzzy approach is clearly lower than the reached by GAMs calibrated by Gutiérrez-Estrada et al. (2021) (GAM r^2=0.77; $Fuzzy_{presence}$ r^2=0.20, p<0.05).

For the Set 2 of beach localities (beaches from Nerja to Rincón de la Victoria), a total of 6 fuzzy rules were generated by the fuzzy logic-based methodology. The 3D surface representation of the resulting fuzzy rules (Fig. 4) show a relatively low presence of jellyfish for the whole study period, although the highest presence was concentrated in winds from the south (180-200°). Jellyfish only appeared at wind speeds between 9 and 21 km h^{-1}. Similar to the results of Gutiérrez-Estrada et al. (2021), wind directions above 230° lead to a decrease of jellyfish incidence (Table 3). Again, GAMs for the Set 2 provided better fits versus FRBS (GAM r^2=0.75; $Fuzzy_{presence}$ r^2=0.24, p<0.05).

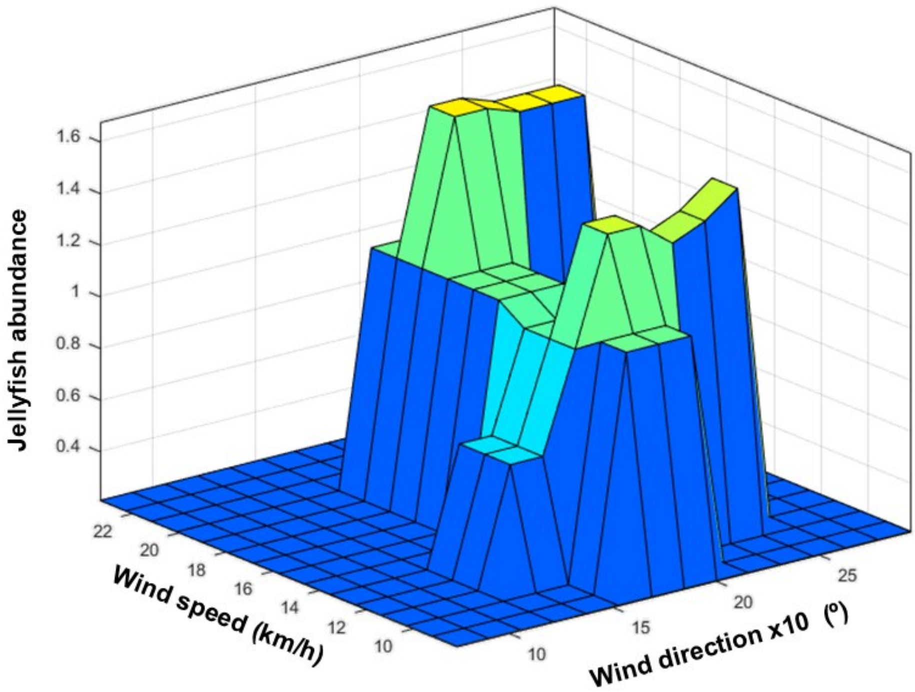
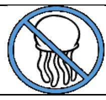


Figure 4. Surface view results of the Set 2 FRBS.

Table 3. Schematic results of the jellyfish incidence in Set 2 after setting the input variables in the Gutiérrez-Estrada et al. (2021) hotpoints.

	Wind direction hotpoints (° x10)		
Wind speed hotpoints (km/h)	**17.5**	**21.5**	**26**
10			
13			
18			

For the Set 3 of beach localities (beaches from Torremolinos to Fuengirola), a total of 4 fuzzy rules were generated by the fuzzy logic-based methodology. In this case, GAMs and FRBS provided the worst fit capacity which was reflexed in a low level of explained variance (GAM r^2=0.37; Fuzzy$_{presence}$ r^2=0.12, p<0.05). The 3D surface representation of the obtained fuzzy rules is shown in Figure 5. The environmental variables analysed remained relatively constant for the whole study period, which makes it difficult to analyse the effect on jellyfish abundance. The recorded wind speed did not exceed 10 km h^{-1} as in the case of the previous areas, so the effect of this variable cannot be interpreted in a precise way. However, according to Gutiérrez-Estrada et al. (2021), the results of the FRBS show how the incidence of jellyfish starts to decrease when the wind direction is higher than 225° (Table 4).

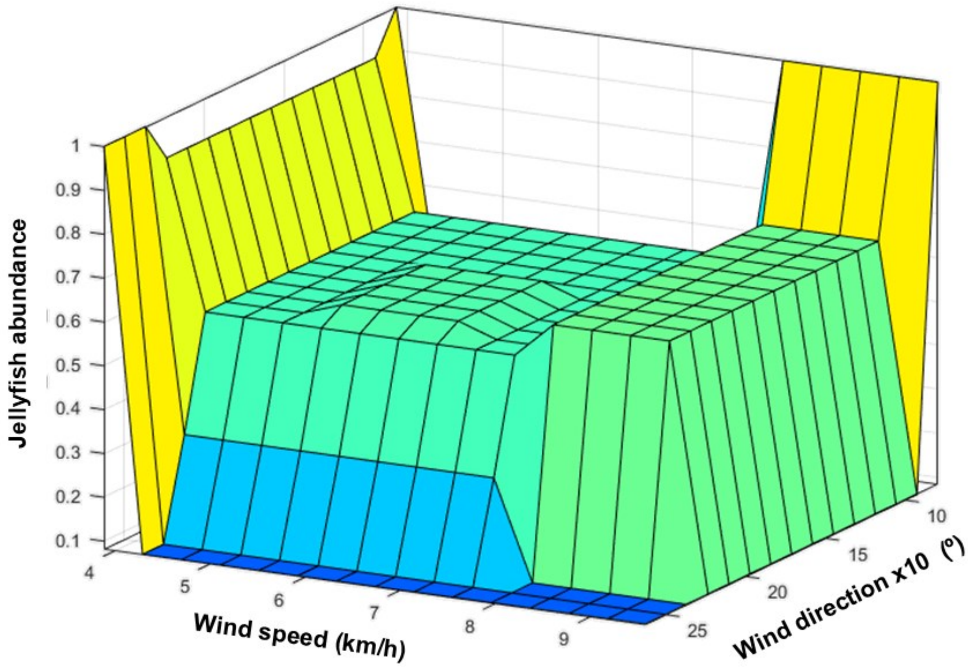
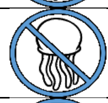


Figure 5. Surface view results of the Set 3 FRBS.

Table 4. Schematic results of the jellyfish incidence in Set 3 after setting the input variables in the Gutiérrez-Estrada et al. (2021) hotpoints.

	Wind direction hotpoints (° x10)		
Wind speed hotpoints (km/h)	**17**	**21**	**22.5**
5			
5.5			
6			
6.5			
7			

For the Set 4 of beach localities (Marbella beaches), a total of 12 fuzzy rules were generated by the fuzzy logic-based methodology which implied a significant improvement respect to the Sets 1, 2 and 3 and provided better results than GAMs (GAM r^2=0.41; Fuzzy$_{presence}$ r^2=0.53, p<0.05). The 3D surface representation of the FRBS is shown in Figure 6. The results show that the lowest number of jellyfishes events are recorded when the wind speed is set at around 15 km h^{-1} (medium-high in the time series analysed) with a wind direction of 180°. The highest incidence of jellyfish is recorded with a wind direction of 90° and a wind speed of 10.4 km h^{-1}. The incidence of jellyfish remained at a medium value (around 2, on a scale 0-5) for all cases of wind directions and speeds. Results of the FRBS with the established hot-points are shown in Table 5.

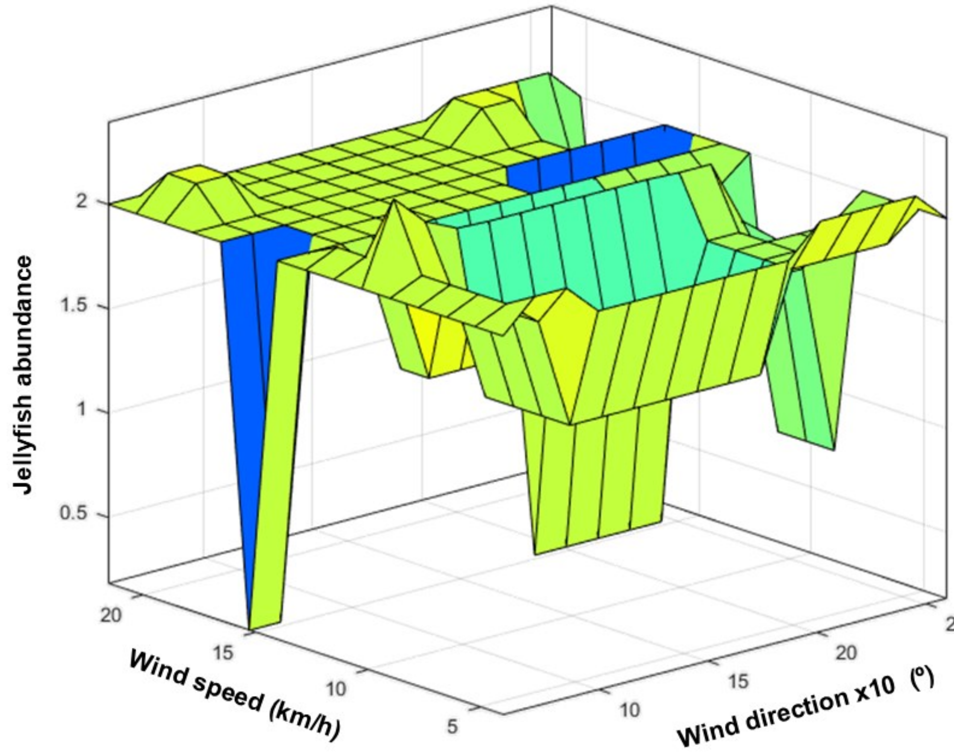
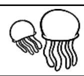
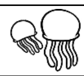
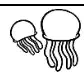
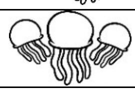
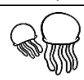
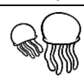
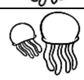
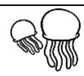
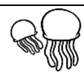
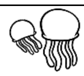
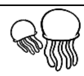
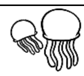


Figure 6. Surface view results of the Set 4 FRBS.

Table 5. Schematic results of the jellyfish incidence in Set 4 after setting the input variables in the Gutiérrez-Estrada et al. (2021) hotpoints.

	Wind direction hotpoints (° x10)		
Wind speed hotpoints (km/h)	**8**	**20**	**24**
7.5			
10.5			
12.5			
14.5			
16			

According to Gutiérrez-Estrada et al. (2021), wind directions higher than 200° tend to have a reducing effect on the incidence of jellyfish at certain wind speeds. The results for the wind speed set at 16 km h^{-1} are a particular case of null jellyfish incidence between 14 and 16 km h^{-1} at wind directions of less than 80° and 180-250° that has been generated by the FRBS.

Finally, the 6 fuzzy rules that were generated by the fuzzy logic-based methodology for the Set 5 of beach localities (beaches from Manilva to Estepona), were not enough to be able to explain more than 32% of variance. The 3D surface representation of the FRBS is shown in Figure 7. The results showed that jellyfish incidence is reduced by high wind speeds and is increased by wind directions between 70 and 140°. However, a specific case is presented in which the incidence of jellyfish may be favoured in this same range of directions if the wind speed is sufficiently intense. The results for this area are in agreement with Gutiérrez-Estrada et al. (2021), whose results show the existence of the same range of directions in which the number of jellyfish increases, as well as that high wind intensity decreases the jellyfish incidence (Table 6).

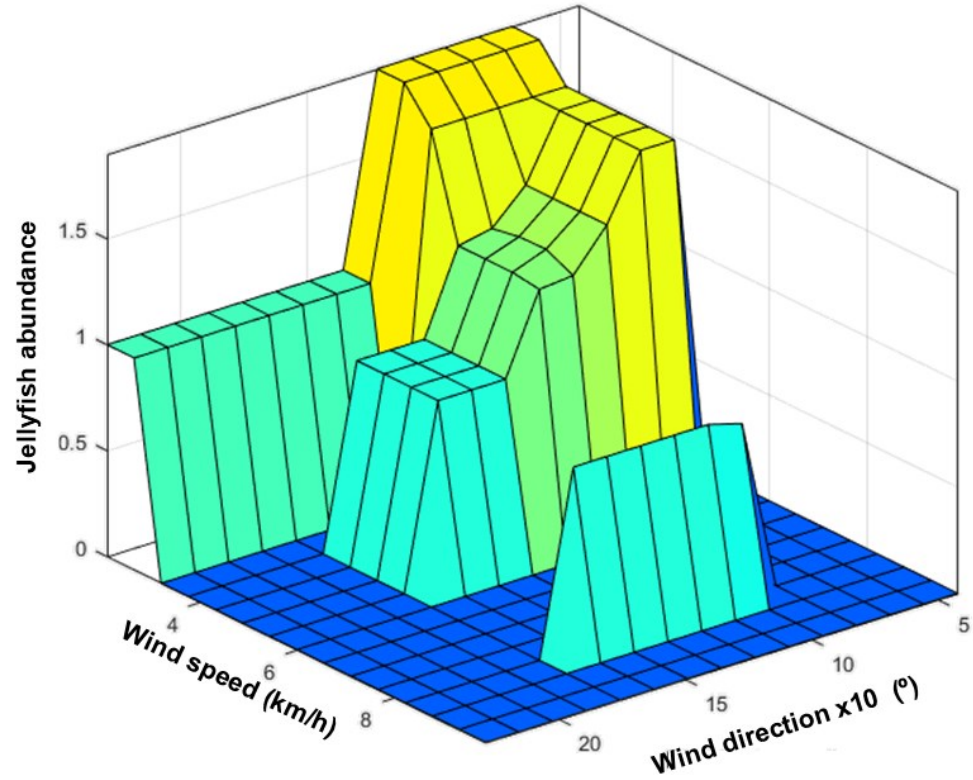
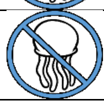
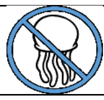
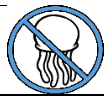
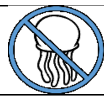


Figure 7. Surface view results of the Set 5 FRBS.

Table 6. Schematic results of the jellyfish incidence in Set 5 after setting the input variables in the Gutiérrez-Estrada et al. (2021) hotpoints.

	Wind direction hotpoints (°x10)				
Wind speed hotpoints (km/h)	**6**	**9.5**	**11.5**	**13.5**	**17**
4.5					
5.5					
7.5					

4. Discussion

In this paper, a set of fuzzy logic-based models have been calibrated as an alternative to traditional statistic approaches for the analyses and interpretation of citizen science information on stranding of jellyfishes on Costa del Sol beaches. The proposed heuristic approach has been selected because FL allows to take intermediate membership values between data sets from information extracted from natural language reasoning, thus providing formal support for imprecise information (Martín del Brio and Sanz-Molina, 2006). This feature of FL is clearly very interesting from an ecological point of view because it allows to find non-linear relationships in multidimensional systems in a relatively easy way. This explains the increase in the last decade of applications of this heuristic technique to ecological applications of FRBS on ecology problems (Albajes-Eizagirre et al., 2011; Brotz et al., 2012; Gutiérrez-Estrada et al., 2013; Colbach et al., 2020; Balbuena et al., 2021).

On the other hand, the development of this study takes place in one of the most touristic places in Spain, which makes the study area a place of special interest for testing non-driven sources of information such as citizen science. Part of the time series of citizen comments analysed takes place in summer, which coincides with the peak of tourists in the area and with the period of highest incidence of jellyfish swarms (Hamner and Dawson, 2009) which supposes an opportunity to address the scarcity of temporal data on these gelatinous organisms.

The obtained FRBS have qualitatively agreed with the models calibrated by Gutiérrez-Estrada et al. (2021) although in 4 out of 5 groups of beaches, the explained variance levels were lower than those obtained by GAMs. This is in line with other works in which these approaches have been compared. For example, Gutiérrez-Estrada et al. (2012) modelling inflow rates for the water exchange management in semi-intensive aquaculture ponds in the south of Spain found that GAMs and fuzzy logic-based models provided similar response functions and different levels of explained variance. Also, Gutiérrez-Estrada et al. (2013) analysing the consistency of fuzzy rules to predict the water beetle diversity in temporary and fluctuating waters indicated that GAMs and FRBS had similar behaviours. However, these authors highlighted an important advantage of fuzzy approaches versus GAMs respect to the interpretation of the results. While in the case of GAMs the analysis of how the predictors are related to the dependent variable is carried out computing the partial residuals (which allow to evaluate the nature of the relationship between the predictor with the adjusted dependent variable value and hence the nature of the influence of the respective predictor in the overall model), in the FRBS the results are interpreted as rules associated to different linguistic categories which is very close to how humans solve everyday problems.

Given the planktonic nature of jellyfishes, the occurrence of these organisms swarms is increased or decreased by large-scale climatological factors (Bellido et al., 2020) and mainly can be driven by local climatological and oceanographical factors such as wind and sea currents (Zavodnik, 1987; Canepa et al., 2014). *Pelagia noctiluca* is the most common and conspicuous jellyfish species in the Mediterranean Sea (Canepa et al., 2014). According to citizen's comments, this species was the most frequent on the coast of Malaga and the only one species which appeared in high concentrations during the analysed time range. This species passive transport towards the coast is closely related to horizontal currents. Consequently, the spatio-temporal interpretation of their occurrences arises from the interaction between population dynamics and their dispersal by currents (Hamner and Dawson, 2009; Berline et al., 2013).

The Mediterranean thermohaline circulation is the main driven of the Alboran Sea currents and the Atlantic Jet dominates the circulation in the first 200 m. When the Atlantic Jet flows through the Strait of Gibraltar and passes close to the Spanish coast, it generates two cyclonic circulation cells, one coinciding with this study the sets of beaches 1-3, and the other one with the sets of beaches 4 and 5 (Vargas-Yáñez et al., 2021). These cyclonic cells produce divergence of surface waters at the inner part of the gyres, resulting the upwelling of deeper, colder, and nutrient-rich waters on the coast (Ramírez et al., 2021). But this surface circulation is also subject to seasonal changes. This way, in our study area westerly winds prevail during the spring and easterlies of lesser intensity prevails during summer (Vargas-Yáñez et al., 2021). The summer wind condition strongly influences on the stranding of jellyfishes on Costa del Sol beaches and significantly increase the probability that a user of Infomedusa records a jellyfish sighting. This is because the coast line will be perpendicular to the resultant force of summer east wind and the currents generated by the two cyclonic circulation cells. The probability of jellyfish stranding clearly will decrease in winter and spring because the prevailing winds will force the jellyfish to move offshore.

This general behaviour not fulfilled for all sets of beaches. For example, for the set of beaches 4 and 5 (western beaches of study area), our results indicate that the incidence of jellyfish is increased when the winds are parallel to the coast. These results confirm the findings of Bellido et al. (2020), who suggested that in the western Costa del Sol an accumulation of jellyfish occurs due to the Western Anticyclonic Gyre and then jellyfish are transported eastwards by lateral winds. These authors also determined that the climatic indices North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) have an effect on the incidence of jellyfish swarms by influencing their reproduction and primary production in the area. Jellyfish swarms have a different response to changes in temperature depending on the area: in colder areas, it is the extreme cold events that promote these swarms, while in warmer areas such as our study area, there are the warmer events (Purcell, 2005; Bellido et al., 2020). The effect of high temperature events has been shown to favour the appearance of different jellyfish species in the Atlantic margin of the Iberian Peninsula (Rodríguez-García et al., 2021), so this variable should be taken into account in future work.

Prediction of these swarming events can be elusive due to the evasive behaviour of these species, which are able to swim upstream or dive to avoid them (Zavodnik, 1987; Malej, 1989; Fossette et al., 2015; Bellido et al., 2020). The occurrence of swarms of this jellyfish species has been shown to have a negative effect on small pelagic fisheries in the Spanish Mediterranean (Baez et al., 2021). Moreover, *Pelagia noctiluca* stings have been the cause of most cases of jellyfish stings on the Malaga coast (Canepa et al., 2014; Templado et al., 2021), so the use of intelligent models such as FL systems for improve the management of jellyfish swarm events are very useful tools for both the health of bathers and the economy of coastal touristic sites (Gutiérrez-Estrada et al., 2021). Nevertheless, jellyfish are key component for marine ecosystems, which implies that should be managed as organisms delivering both risks and benefits to society (Hamner and Dawson, 2009; Duarte et al., 2014). For this purpose, citizen science could have an important role to complement and enhance scientific studies and governments in actions for which they have not enough resources (Lee et al., 2006).

5. Conclusions

The results of the study developed, show that the use of artificial intelligence techniques such as FL, can address the scarcity of data on the incidence of jellyfish on the coast. The obtained fuzzy rules-based systems have made it possible to modelize the knowledge of citizens' natural language comments in the Infomedusa app. It has also been confirmed that local environmental variables such as wind direction and wind speed play a key role in the occurrence of jellyfish swarms in the province of Malaga. For the central and easternmost areas of the province, winds perpendicular to the coast lead to a higher occurrence of jellyfish swarms. However, for the westernmost areas the highest occurrence happens with winds parallel to the coast. Depending on the area and wind direction, high wind speed can favour or diminish the appearance of jellyfish.

From this study as a starting point, the application of FRBS and their use with the data obtained from the Infomedusa app, allows to use citizen collaboration to understand the climatic factors which drive the upwelling of these gelatinous organisms on the coasts. Future studies would allow to address the socio-economic impact of jellyfish on areas economically dependent on sun and beach tourism.

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Conflict of interest

The authors have no conflicts of interest to declare.

Author contributions

Castro-Gutiérrez, J., Gutiérrez-Estrada J.C., Aroba, J.: Conceptualization, Methodology, Software, Validation, Formal Analysis; Data Curation, Writing-Original Draft; **Pulido-Calvo, I., Peregrín, A.:** Conceptualization, Methodology, Formal Analysis, Writing-Review and Editing; **Báez, J.C.:** Investigation; Writing-Review and Editing; **Bellido, J.J., Souviron-Priego, L.:** Investigation, Resources.

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