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Urticating macromedusae and stinging bathers on the South Atlantic coast: Oceanographic and climatological conditions of *Olindias sambaquiensis* (Müller, 1861) outbreaks

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A R T I C L E I N F O

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A B S T R A C T

Incidents of bathers being stung by jellyfish on the coast of southern Brazil have been monitored from 2012 to 2022 to identify the species involved and to search for patterns of behavior in different summer seasons. For 10 years of monitoring, data on occurrence, density and the crossing with the abiotic variables of temperature and salinity of the water and wind direction were obtained. During the investigated period, seven species of macro jellyfish were recorded out, four of them were urticating species, in wich *Olindias sambaquiensis* was the most frequent and abundant. Based on physical-chemical data on the seawater in this area, the cohorts, and consequently the success in the recruitment and the density of the *O. sambaquiensis*, may be related with years of low salinity of these Coastal Water. This hydrozoan was also the only species that showed a correlation between average annual density values and incidents of bathers being stung in subsequent summers. Likewise, on a monthly time scale, incidents of stings were correlated with winds from the south quadrant that could promote the transport of organisms to the beach region. A predictive model of the occurrence of jellyfish stinging events is presented and applied for the summer of 2023.

1. Introduction

Due to the importance in terms of public health, tourism and fisheries, the occurrence of high concentrations (outbreaks) of stinging cnidarians in the form of medusoid (jellyfish) and polypoid (Portuguese man o' war) species has been the subject of research (Cegolon et al., 2013). Furthermore, Increasing occurrences of outbreaks of these organisms have often been correlated with global climate change (Condon et al., 2012), encouraging the understanding and studies on predictive models of factors that induce the productivity of these organisms, as well as on the processes of transport and accumulation in coastal areas applied both in fishing and in the protection of bathers in different parts of the world (Boero, 2013; El Rahi et al., 2020; Zhang et al., 2022). This ecological modeling strategy has shown satisfactory results in predicting the occurrence of jellyfish in different parts of the world (Australia - Gershwin et al., 2014; Mediterranean - Benedetti-Cecchi et al., 2015 and Malaysia - Mubarak et al., 2021), but such results are only possible with information gathered from several years of study.

In Brazil, examples of species that occur in outbreaks, with beach strandings and hazardous stings, are the siphonophore *Physalia phylsalis* (Linnaeus, 1758) (Portuguese man o' war) (Haddad Jr. et al., 2013), the hydrozoan *Olindias sambaquienesis* Muller, 1861 (cigar jellyfish) (Resgalla Jr. et al., 2019) and scyphozoan *Chrysaora lactea* Eschscholtz, 1829 (jellyfish) (Marques et al., 2014).

Other species involved in beach outbreaks that do not pose a danger in terms of stings, or at least present low-activity toxins or nematocysts with a low ability to penetrate human skin, include *Lychnorhiza lucerna* Haeckel, 1880 and *Rhacostoma atlanticum* Agassiz, 1850, which cause clogging to artisanal and industrial fishing nets (Nagata et al., 2009; Schroeder et al., 2014). Representatives of the Cubozoa class, such as *Chiropsalmus quadrumanus* (Müller, 1859) and *Tamoya haplonema* (F. Müller, 1859), are known to cause serious injuries to bathers (Fenner, 1998; Haddad Jr. et al., 2010), but there are no records of their mass occurrence on beaches and/or population outbreaks. Other jellyfish species of the genus *Aequorea* (Nogueira Jr. et al., 2016), *Aurelia, Drymonema* and *Phyllorhiza* (Morandini et al., 2005; Haddad and Nogueira

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Jr., 2006; Nogueira Jr. and Haddad, 2006; Nogueira et al., 2010) present sporadic occurrences and their population dynamics require further investigation.

There are biological differences (life cycle, phenology and population growth rate, among other issues) between the jellyfish species that cause stings in bathers and questions about the participation of each species in these events remain to be answered. In addition, further research is needed to better understand the patterns of occurrence of these organisms in beach regions, such as their abundance, their relations with abiotic components and stinging events (Resgalla Jr. et al., 2019).

The temporal variation of occurrences of urticating macrojellyfish species in southern Brazil was investigated, and their possible relation with outbreaks of stinging occurrences in bathers. Once the species responsible for the outbreaks was determined, the oceanographic conditions that determine its abundance were analyzed, as well as the climatic conditions for the beach environment. This study was only possible with the type of sampling for macro and megaplankton as well as the compilation of information from ten years of study and the possibility of inferring a predictive model for jellyfish sting outbreaks.

2. Material and methods

2.1. Study area

The central state of southern Brazil is Santa Catarina, which has a coastline of 531 km with approximately 200 beaches and the largest fishing port in Brazil located in the estuary of the Itajaí-Açu river, which has an average discharge of 228 ± 282 $m^3 s^{-1}$ (Schettini, 2002). The Itajaí-açu River together with the Lagoa dos Patos estuary (average flow of the Jacuí River of 801 $m^3 s^{-1}$) consist in the two main basins that influence the continental contribution on Coastal Water in southern Brazil (South Atlantic Basin) and influenced by the ENSO phenomenon (Isla and Toldo, 2013). In the north, the state borders Paraná (25°57′41″ S), with 98 km of coastline, and in the south it borders Rio Grande do Sul (29°23′55″ S), with 623 km of coastline (Fig. 1).

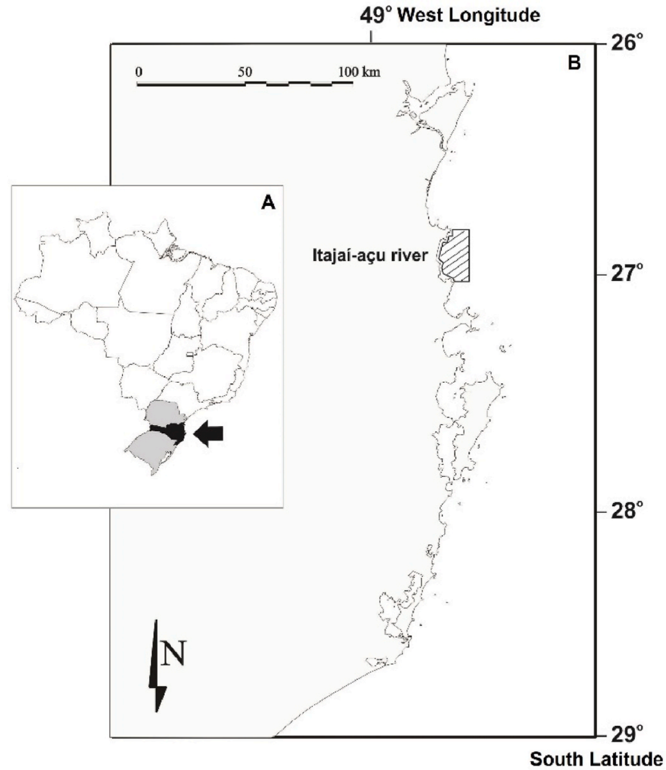

Fig. 1. Location of the southern region of Brazil (three states highlighted), the state of Santa Catarina (black) (A) and the area surrounding the coastal region at the mouth of the Itajaí-Açu river (hatched area) (B).

2.2. Sampling

Samples of jellyfish were obtained over a period of 96 months; from February 2012 to November 2021 (monthly from 2012 to 2018 and bimonthly from 2019 to 2021) as bycatch of artisanal shrimp fishing. The sample area comprised the north coast of Santa Carina and in the region surrounding the mouth of the Itajaí-Açu river and between the isobaths of 8–25 m, within 25 km of the coast (26°45′ to 27° 00′ S) (Fig. 1). The trawls were performed from a motorized boat using a fishing net with a mesh size of 23 mm between opposite knots in the body and in the bagger, with a length of 6 m, worked with a mouth opening of 7 m in length and 1 m in height, covering between 500 and 700 m of the distance (approximate volume of filtered water ranging from 3500 to 4900 m^3). On each field trip, two to four trawls were carried out depending on the environmental conditions and the occurrence of organisms in the nets. Density data were standardized as the average number of organisms per 100 m^3 of water filtered by the net based on the average distance covered in the hauls and as density index the number of organisms captured per 10 min of trawl (average between the number of trawls). Organisms smaller than 23 mm (net mesh size) were frequent in the samples due to mesh opening changes (shrimp net) as well as network clogging. In any case, records of small specimens (in frequency of occurrence) are important for interpretation in cohort analysis, particularly for *O. sambaquiensis*. In parallel, temperature and salinity data (oceanographic data) were obtained at a depth of 2 m at each initial point of the trawls using a Yellow Springs® thermosalinometer (model 30/10 F T).

The organisms obtained were placed in coolers and taken to the laboratory (Polytechnic School/UNIVALI) where they were weighed with a Shimadzu balance (wet weight) and measured individually with a ruler and a pachymeter (De Barba et al., 2016; Resgalla Jr. et al., 2019). Umbrella diameters were measured for Hydrozoa and Scyphozoa and width and height for Cubozoa.

2.3. Cohort analysis of *O. sambaquiensis*, *C. lactea*, *C. quadrumanus* and *T. haplonema*

The biometric data were grouped into size classes, and the percentages of juveniles (umbrella diameter <2.0 cm for *O. sambaquiensis* and <3.0 cm for *C. lactea* and width <5.0 cm for *C. quadrumanus* and *T. haplonema*) and adults (umbrella diameter >7.0 cm for *O. sambaquiensis* and >6.0 cm for *C. lactea* and width >10.0 cm for *C. quadrumanus* and >8.0 cm for *T. haplonema*) were estimated as the mean of 10 years of data, in order to evaluate the population dynamics of the species. The size classes presented for each species and defined as juveniles and adults were established based on lower and upper quartiles of size frequencies. Data were treated as averages to eliminate information gaps between months due to the random distribution of the species in the sample area and due to seasonal and interannual variability. Intermediate size classes, for all species, were not represented in the analyzes as they made it difficult to interpret the results as they were always present.

2.4. Data on injuries caused by jellyfish (ICJ - Santa Catarina State Fire Department)

The records of the number of bathers with injuries caused by jellyfish (ICJ) and number of bathers who received preventive warnings about sea conditions, drowning and attention from parents to their children on the beach (called Prevention) from the summer seasons between 2013 and 2022 were obtained from the database of the Military Fire Brigade of Santa Catarina State. Prevention was used as an estimate of the number of bathers present on the beach per summer season, and, on this time scale, to prove that the number of injuries caused by jellyfish is not dependent on the number of potential victims present on the beach. These records were generated from data surveys of sting occurrences quantified by lifeguards on the beaches, during the summer operation period. Data from January and February of each season, the period with the greatest occurrence of ICJ and numbers of bathers on beaches, were selected. Lastly, these data were reviewed and the duplicate information and occurrences with incomplete information were eliminated according to the data presented by Resgalla et al. (2019).

2.5. Wind data

The wind direction records were obtained from the database of the Instituto Nacional de Meteorologia (National Institute of Meteorology) – INMET (http://www.inmet.gov.br/portal/) referring to the station A866, Farol de Santa Marta, Laguna (Latitude: 28.60444444; Longitude: −48.81333333; Altitude: 34.36 m) in an hourly frequency. The data refer to the months of January and February for the years 2013–2022, however, the station did not provide meteorological records for the years 2016 and 2017.

2.6. Statistical analysis

Due to the reduction of information for annual averages, the density data of the stinging jellyfish species, accumulated number of bathers with jellyfish stings and the frequency of wind direction in the summer period were compared by linear regressions and nonlinear (significance of the correlation coefficient) as well as by t tests (Zar, 2010). The variances observed in the jellyfish density data limited more deterministic comparisons but allowed the observation of trends in the behavior of the species occurring in the samples.

2.7. Predictive model and validation

Summer seasons (January and February) with (>30,000 cases) and without (<10,000 cases) outbreaks of jellyfish stings in bathers were grouped into two treatment sets. From these sets, the minimum and maximum values of the annual average seawater salinity and the average annual densities of *O. sambaquiensis* were determined for the year before the summer, thus establishing a range of these parameters for the conditions of occurrence and non-occurrence of outbreaks. The same criterion was used for the range of frequencies of southerly winds in summer (January and February) with and without outbreaks of jellyfish stings for the coast of the state of Santa Catarina.

Once these intervals have been established, the predictive model can be used by placing new data on average annual salinity and average annual density of *O. sambaquiensis* for a given year, indicating the reproductive success of the species. In the summer following this data, wind information or forecast for southerly winds may indicate the possibility of jellyfish sting outbreaks. Salinity and *O. sambaquiensis* density data from 2022 and wind data for the summer of 2023 were used to validate the model based on the number of cases of jellyfish stings. The origin of these data is the same as presented in the previous items and were not used to adjust the model.

3. Results

3.1. Temporal variation and life cycle of urticating jellyfish species

In 10 years of sampling, 7 species of macromedusae occurring in the shrimp trawls were identified, by abundance: *Olindias sambaquiensis*, *Rhacostoma atlanticum*, *Chrysaora lactea*, *Chiropsalmus quadrumanus*, *Lychnorhiza lucerna*, *Tamoya haplonema* and *Aequorea* sp. Despite the importance of *R. atlanticum* in terms of density and frequency of occurrence it will not be considered herein because it is not a stinging species (Resgalla Jr. et al., 2019). Likewise, the species *L. lucerna* (Scyphozoa) and *Aequorea* sp (Hydrozoa) were not included in this study.

The hydrozoan *O. sambaquiensis* was the most abundant and frequent of the species considered, with a maximum of 11 org. 100 m^{-3} (470 organisms per 10 min of trawling) in December 2018 (Table 1). In terms of potential accidents with bathers, this species is followed by *C. lactea*, occurring at high densities on some sampling occasions (maximum of 4 org. 100 m^{-3} or 176 organisms per 10 min of trawling in August 2017). *C. quadrumanus* had the third highest frequency of occurrence among jellyfish species and a maximum density of 0.6 org. 100 m^{-3} or 25 organisms per 10 min of trawling in December 2020. Lastly, *T. haplonema* was relatively rare in the sampling.

The annual and monthly density variations for *O. sambaquiensis* determine the temporal patterns of macromedusae on the northern coast of Santa Catarina, since this is the dominant species. For the years 2014–2019 and 2021 this species presented, in annual average, densities greater than 0.14 org. 100 m^{-3} or 6 organisms per 10 min of trawling (Fig. 2) while the monthly averages showed two density peaks, one between autumn and winter (June and July) and the other at the end of spring (December) (Fig. 3). These peaks were accompanied by the dominance of juveniles in the samples (diameter <2.0 cm) and later the frequency of adults (diameter >7.0 cm), indicating a well-defined reproductive cycle of two cohorts per year, with winter being the period of emergence of a new cohort (Fig. 3).

Limited to the study period, *C. lactea* showed an increase in density from 2017 onwards (>0.02 org. 100 m^{-3} or 1 organism per 10 min of trawling) (Fig. 2). The average monthly distribution of this species suggests a reproductive cycle with seasonal characteristics, that is, low density in late autumn and early winter (disregarding the density peak in August 2017). The distribution of the different size classes during the year characterizes it as a species with reproductive behavior throughout the year but with a peak number of juveniles in the population in the spring (Fig. 3).

In the case of the cubozoans, the frequency of *C. quadrumanus* presented low interannual variability (densities <0.02 org. 100 m^{-3}) with one density peak in 2020 (Fig. 2). The distribution of the density and size classes suggests the occurrence of adults throughout the year, the dominance of adults from autumn to spring and the occurrence of juveniles in the spring (Fig. 3). On the other hand, the behavior of a single cohort limited to the coldest months of the year was more evident for *T. haplonema* despite its greater interannual variability with years of absence in the samples (Figs. 2 and 3).

Table 1
Species occurring in shrimp trawls, mean density, mean density index, standard deviation of the mean and frequency of occurrence for 10 years (between 2012 and 2021) of sampling on the northern coast of Santa Catarina. *Stinging species.

Species	Average density (Number of organisms per 100 m^3)	Average density index (Number of organisms per 10 min of trawling)	Frequency of occurrence (%)
*Olindias sambaquiensis**	0.32 ± 1.14	13.56 ± 48.12	86.14
Rhacostoma atlanticum	0.23 ± 0.86	9.54 ± 36.12	79.21
*Chrysaora lactea**	0.11 ± 0.59	4.53 ± 24.64	44.55
*Chiropsalmus quadrumanus**	0.02 ± 0.07	0.93 ± 2.77	58.42
Lychnorhiza lucerna	0.008 ± 0.03	0.35 ± 1.37	27.72
*Tamoya haplonema**	0.003 ± 0.01	0.13 ± 0.45	18.81
Aequorea sp	0.0002 ± 0.001	0.01 ± 0.06	0.99

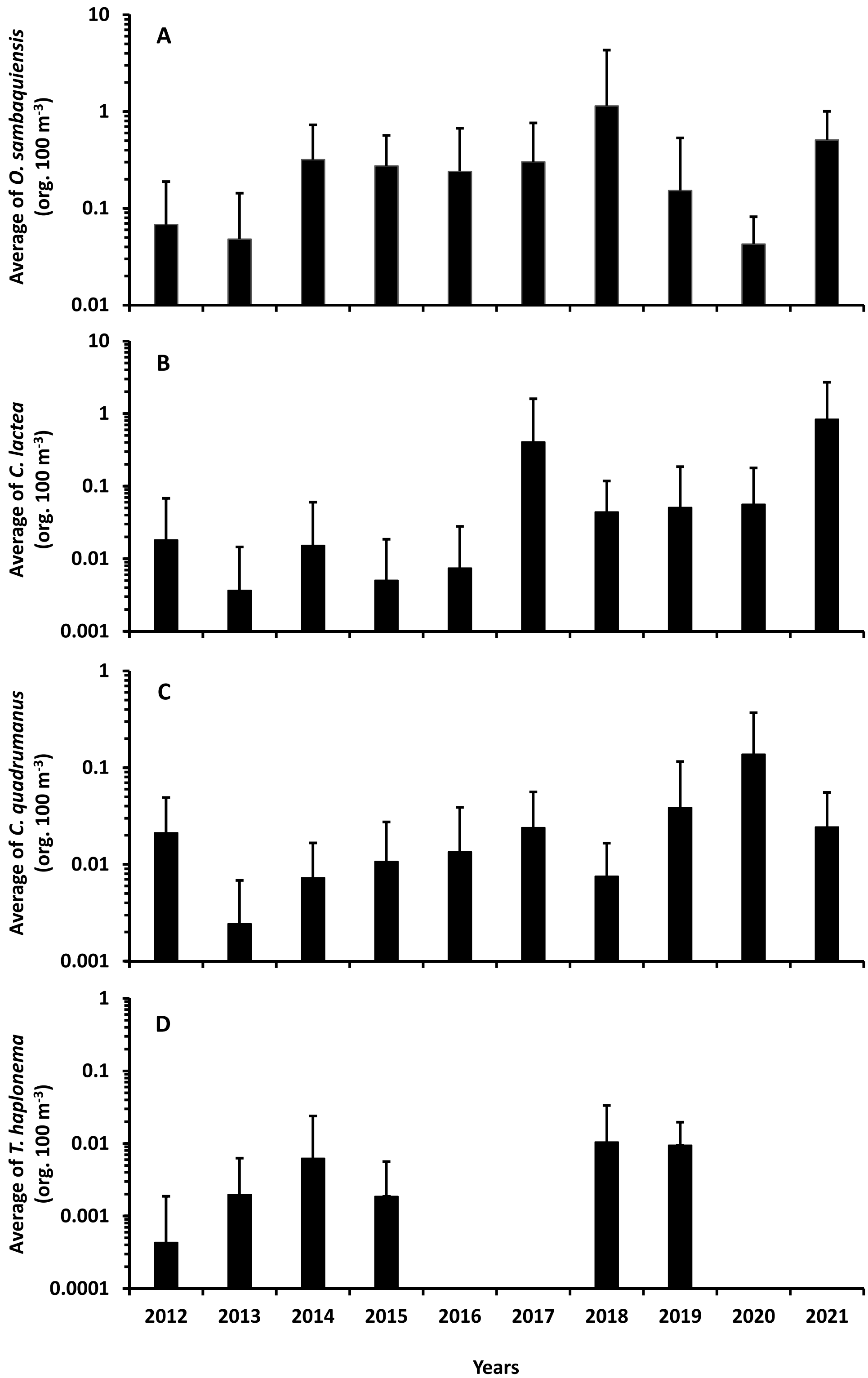

Fig. 2. Annual mean density (organisms per 100 m^3) (column) and standard deviation (bar) for (A) *Olindias sambaquiensis*, (B) *Chrysaora lactea*, (C) *Chiropsalmus quadrumanus* and (D) *Tamoya haplonema* between 2012 and 2021 for the north coast of Santa Catarina. Y axis in log scale.

3.2. Oceanographic conditions and jellyfish species

The water temperature showed a very marked seasonality with high values in January and February (maximum of 28.72 °C in February 2015) and minimum in July and August (minimum of 16.75 °C in July 2018). The overall average salinity was 31.5 and no pattern was observed during the year, except for low salinity in August (minimum of 22.25 in August 2015).

In general terms, *O. sambaquiensis, C. lactea* and *C. quadrumanus* showed reproductive peaks in the spring, indicating a response to the increase in water temperature. However, the Coastal Water salinity also seems to influence the reproductive cycle of the species, mainly for the

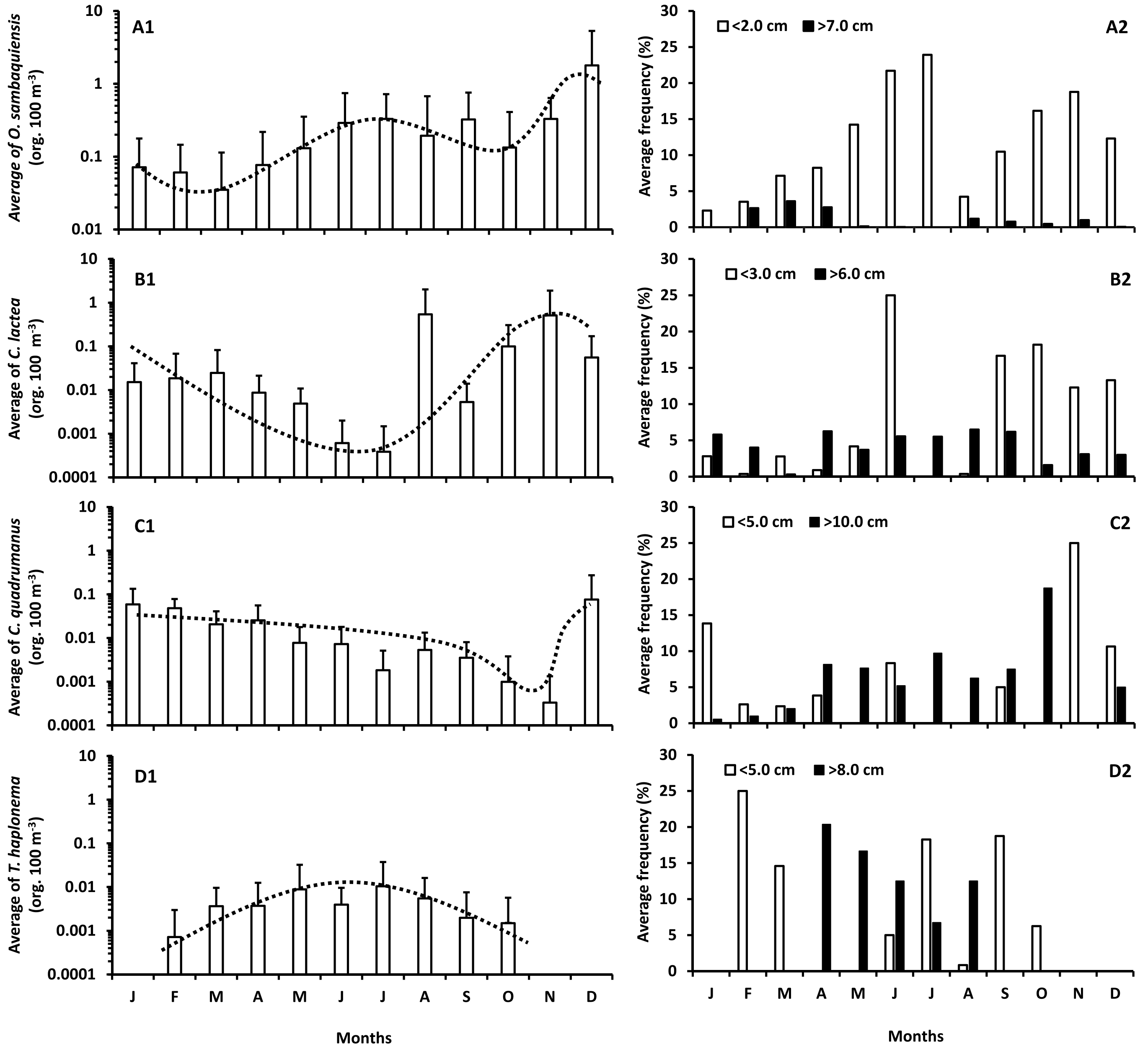

Fig. 3. Average density (organisms per 100 m^{-3}) (column) and standard deviation (bar) (1) and average monthly frequency of occurrence of the lower (juvenile) and upper (adult) size classes (2) for *Olindias sambaquiensis* (A1 and A2) and *Chrysaora lactea* (B1 and B2) based on diameter and *Chiropsalmus quadrumanus* (C1 and C2) and *Tamoya haplonema* (D1 and D2) based on umbrella width, for organisms obtained between 2012 and 2021 on the northern coast of Santa Catarina. ···· Moving average trend line. For density Y axis in log scale.

formation of the second cohort of *O. sambaquiensis* in August. *Tamoya haplonema* was the only species with the occurrence of adults in the autumn and winter months.

3.3. Stinging species, bathing accidents and environmental standards

The collection of data on accidents of bathers experiencing jellyfish stings along the coast of Santa Catarina recorded by the State Fire Department checked starting from the summer (January and February) of 2013. In previous years, the records show gaps and also overlapping of occurrences (Fig. 4). As part of the drowning prevention data, information on the number of bathers on the beach is traditionally included in the lifeguard reports. Based on the records obtained, it was observed that four seasons (2013, 2014, 2021 and 2022) had low incidences of jellyfish stings (below 10,000 cases) while for the years 2015–2020 the number of cases was higher than 30,000. It can be noticed that the number of people stung by jellyfish is not associated with the number of people present on the beaches (based on drowning prevention data) since there has always been a surplus of victims along the entire coast. Despite the time scale per season (2 months), a pattern of occurrences (stings and drowning prevention) was observed when considering the day of the week, with higher numbers of bathers on the weekends (Saturday and Sunday).

Considering the species of urticating macrojellyfish with cohorts from spring before the summer period, and consequently with a possible relation with stings on bathers at the beaches, the annual average of the densities of the three species with spring cohorts were correlated with the number of stinging cases in the summer season (Fig. 5). It was observed that the only species that showed a correlation ($p < 0.05$) between these parameters was *O. sambaquiensis*, with the exception of

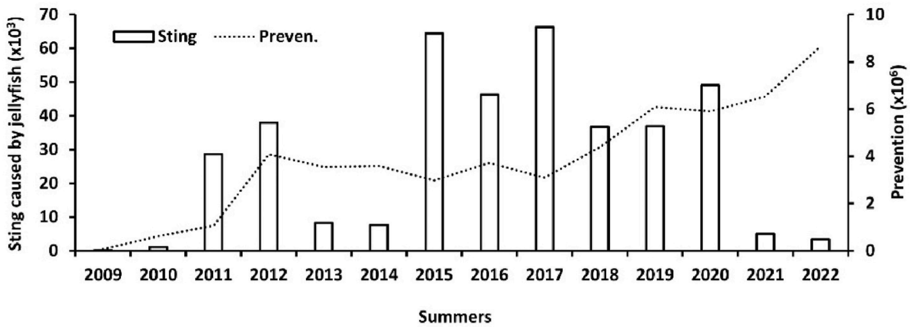

Fig. 4. Number of victims of jellyfish stings and number of downing preventions (population of bathers present on the beaches) per season (January and February) between 2009 and 2022 for the entire coast of Santa Catarina.

the average density/cases of stings for the summer of 2021/2022. The highest densities were observed for *O. sambaquiensis*, but the other species showed the cooccurrence of low density with a high number of victims of jellyfish stings.

As *O. sambaquiensis* is the most abundant and frequent species that has a strong association with the number of bathers who suffered stings from jellyfish observed on the beaches, the aim was to associate these events with oceanographic characteristics of Coastal Water and the wind conditions (Resgalla Jr. et al., 2005; 2011; 2019).

The annual peaks of *O. sambaquiensis* observed in the years 2014–2019 and 2021 showed lower average salinities than those observed in the years of low density (2012, 2013 and 2020) (Fig. 6) ($p < 0.05$). In regard to the action of the winds, crossing the data on jellyfish stings with the frequency of winds from the south quadrant only for years of high abundance of *O. sambaquiensis* (Fig. 7), it was observed that there is a need for a minimum frequency of winds from the south quadrant (>35%) for a high incidence of jellyfish stings to occur. This relation would explain the low correlation between stings by jellyfish in the summer of 2022 and the densities of *O. sambaquiensis* in 2021, as highlighted in Fig. 5 ($p < 0.05$ for significance of the correlation coefficient).

4. Discussion

In the south of Brazil, the species with a history of causing damage to bathers (with the exception of *Physalia physalis* which was not treated in this study) are, the hydrozoan *O. sambaquiensis, the scyphozoan Chrysaora lactea* and the two species of cubozoan *Chiropsalmus quadrumanus* and *Tamoya haplonema*.

Cubozoans in particular are the most dangerous jellyfish in terms of stinging bathers (Fenner, 1998; Fenner and Williamson, 1996). This group are poorly studied organisms due to the difficulties associated with cultivation in the laboratory, but it is known that they have a short life cycle (Gordon et al., 2004). It is believed that the absence of massive strandings of these organisms on beaches is due to the well-developed orientation system and their superior locomotion capacity compared to other groups of jellyfish (Kingsford and Mooney, 2014). Particularly, in this study, *C. quadrumanus* presented an abundance in the summer period, but it was mainly constituted by juvenile forms, possibly due to the metamorphosis of polyps in the spring period. The population growth strategy is even more limited in the case of *T. haplonema*, with no spring/summer interface and limited autumn/winter adults, indicating that the temperature possibly influences and limits the period of metamorphosis of the species. These characteristics associated with the weak relation between density and the number of cases of bathers being stung on the beaches in the state of Santa Catarina indicate that cubozoan species do not represent a public health issue. However, Leoni et al. (2016) have warned of an increase in the occurrence of *T. haplonema* along the coast of Uruguay and the possible effects on tourism in the summer period. Due to the occurrences of *T. haplonema* on the coast of Uruguay, the discontinuity of its occurrences in southern Brazil and its more stenothermal characteristics of low temperatures, it can be suggested as a good indicator of tropicalization of the waters, justifying its monitoring on the coast of South America (Dutra et al., in preparation).

In the Coastal Water off southern Brazil, *C. lactea* form an important component of urticating macromedusae (Morandini et al., 2005). Of the species considered in this study, this is a slow growing jellyfish (Morandini et al., 2003), characteristic of the Scyphozoa. However, despite showing peaks of recruitment of meduzoid forms in late autumn and spring, the species showed the most erratic behavior, possibly due to the lower frequency of occurrence in the sampling events. However, the adult form was present in all samples collected and its density seems to oscillate with the water temperature, responding to the thermal phenology of the environment. There are records of patches of the species resulting in concentrations at high density (e.g., 4.2 org. 100 m^{-3} or 176 organisms per 10 min of trawling) in Coastal Water and massive beach strandings are relatively rare. The poor correlation between the density of this species and the number of bathers stung in the state also suggests that it is not associated with years of high incidence of stings, although it has been indicated as responsible for an outbreak on the coast of Paraná, also in the south of Brazil, in 2011/2012 (Marques et al., 2014).

Of the urticating jellyfish species present in the samples collected, *O. sambaquiensis* was the most abundant and frequent. Its seasonal variation clearly indicated two cohorts during the year, with density peaks in early winter and late spring being related to peaks in the number of juveniles in the population. The alternation of cohorts during the year seems to reflect the salinity patterns of the coastal region, coinciding with the lowest salinity values recorded for the month of August. The behavior of Hydrozoa reproduction has not been frequently studied, but Kinne and Paffenhöfer (1966) noted that for the species *Clava multicornis*, stolon length, polyp production and budding are stimulated by salinity between 24 and 32. Likewise, Dańko et al. (2020) observed a strong influence of salinity on the life cycle of the hydrozoan *Eleutheria dichotoma*, where cultivation of the species in low salinity (25) showed an earlier onset, higher budding rates and higher production of planula larvae.

As noted, the highest densities of *O. sambaquiensis* were recorded in years of lower salinity (<31) compared to years with salinity greater than 33 for Coastal Water. This pattern suggests that the continental contribution to the oceanographic conditions of the coastal region directly influence the success of the species recruitment. The continental contribution of the Lagoa dos Patos estuary, together with the Itajaí-açu river, involves the main tributaries of the South Atlantic Basin. On the other hand, the Plata plume (Piola et al., 2005) would possibly not have influenced the process of low salinity on the coast, since lower water temperatures were not observed under conditions of high densities of the species in the studied period. Anyway, the hydrodynamics of Coastal Water has been little investigated, presenting contributions from both the southeast and the south of Brazil, varying seasonally and without

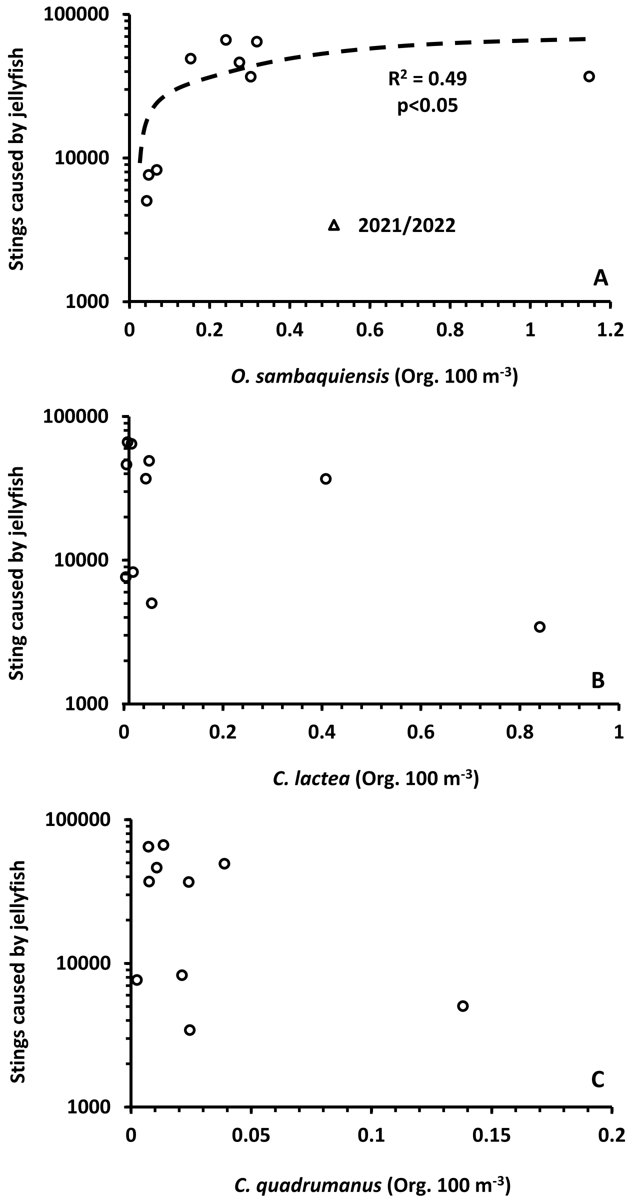

Fig. 5. Relation between the average annual density of stinging species on the northern coast of Santa Catarina and the number of victims of jellyfish stings for the entire coast corresponding to the subsequent summer (January and February). (A) *Olindias sambaquiensis* with logarithmic regression and coefficient of determination (R^2) without considering the 2021/2022 data (△) to $p < 0.05$; (B) *Chrysaora lactea*; and (C) *Chiropsalmus quadrumanus*. Y axis in log scale.

estimates of the continental contributions in its formation process (Piola et al., 2018). According to Schroeder et al. (2014), *O. sambaquiensis* has a wide distribution along the south and southeast coast of Brazil (from Rio de Janeiro to Rio Grande do Sul, and with a bathymetric distribution range from 10 to 70 m) and a tendency for currents to shift from north to south due to the friction of winds (Campos et al., 2013), displacing the populations along the coast.

The connection between the number of victims of jellyfish stings for the summer period (January and February) and the average densities of the different species of urticating jellyfish in the previous year indicated that *O. sambaquiensis* could be responsible for jellyfish sting outbreaks. The conditions for outbreaks of jellyfish stings to occur in summer seem to result from two events on different time scales, one related to recruitment success associated with lower salinity Coastal Water and the other to wind conditions.

According to Resgalla Jr. et al. (2005 and 2011), the influence of southerly winds would favor Ekman transport or the convergence of shelf waters at the coast (Campos et al., 2013), a condition that could allow the organisms to enter the surf zone. The density peaks of *O. sambaquiensis* associated with outbreaks of jellyfish stings in the summer were correlated with a minimum frequency of 35% of winds from the south quadrant for the summer period (January and February). After reproductive success, *O. sambaquiensis* can present a distribution from the 10 m isobath. In the summer, possibly stimulated by the light intensity and the vertical migration, *O. sambaquiensis* can be transported to the coast by the action of winds from the south quadrant, reaching the surf zone. A similar process involving the vertical migration (Chiaverano, 2001) and transport of *O. sambaquiensis* to the beach by north winds has been previously noted by Brendel et al. (2017) at the tourist resort of Monte Hermoso in Argentina.

The predictive model of the occurrence of jellyfish sting outbreaks was idealized on the availability of *O. sambaquiensis* (reproductive success/recruitment) based on low salinities in Coastal Water and its transport to the beach zone by southerly winds. The limits of the variables used are based on the classifications obtained in the 10 years of monitoring (Fig. 8 - horizontal columns). As validation, the oceanographic, biological, meteorological and occurrence data on the number of victims of jellyfish stings for the year 2022 and summer 2023 were compared with the predictive model (Fig. 8 - dotted line and variables in the boxes). There is a certain agreement between the model and what was observed for the period 2022/2023 with a salinity below 33 of the Coastal Water, density of *O. sambaquiensis* above 0.15 org. 100 m^{-3} or 6.4 organisms per 10 min of trawling, frequency of winds from the south quadrant above of 35% and the number of victims of jellyfish stings close to 30,000. Greater variations and inaccuracies are expected in the model limits for the density of *O. sambaquiensis*, due to sampling and the grouped distribution of organisms in the environment, as well as in the number of cases of jellyfish stings due to the behavior of bathers. In any case, the framing of favorable conditions for outbreaks is relatively wide and suggests that they are natural environmental conditions, with salinity being a more restrictive factor for reproductive success. Added to this, the concentration of outbreaks in the south of the study area, possibly influenced by the slope of the coastline (Resgalla Jr. et al., 2019) can influence the results and restrict the use of the model. On the other hand, the entry of new data each year will allow adjustments in the forecast of outbreaks that, associated with climate models of precipitation, flow of continental inputs and wind patterns, will add time to the alerts for Life Guards and bathers on the southern coast of Brazil.

The results and the application of the model suggest that the normal conditions for the south coast of Brazil are the availability of *O. sambaquiensis* (70% of the years treated), as well as the frequency of southerly winds (80% of treated cases) in the summer. Draws attention to the fact that the conditions of jellyfish sting outbreaks are related on a smaller time scale, that is, with the number of bathers on the weekend associated with wind patterns of the previous week.

The participation of other species of urticating macromedusae in outbreaks observed in the state of Santa Catarina may be significant in isolated events, and more information is required for a correct diagnosis of the controlling factors in this regard. Outbreaks of occurrences of Portuguese man o' war (*Physalia physalis*), for instance, may be related to the strong influence of north winds, due to their neustonic behavior. The gregarious behavior of *C. lactea* may hinder its passive transport in low-intensity coastal currents. This type of displacement has been described for Scyphozoa (Nagata et al., 2016) but it may be more complex in the case of Cubozoa species (Kingsford and Mooney, 2014).

5. Conclusions

In trawler sampling, four species of urticating macromedusae out of a total of seven known species were collected, with the most abundant and

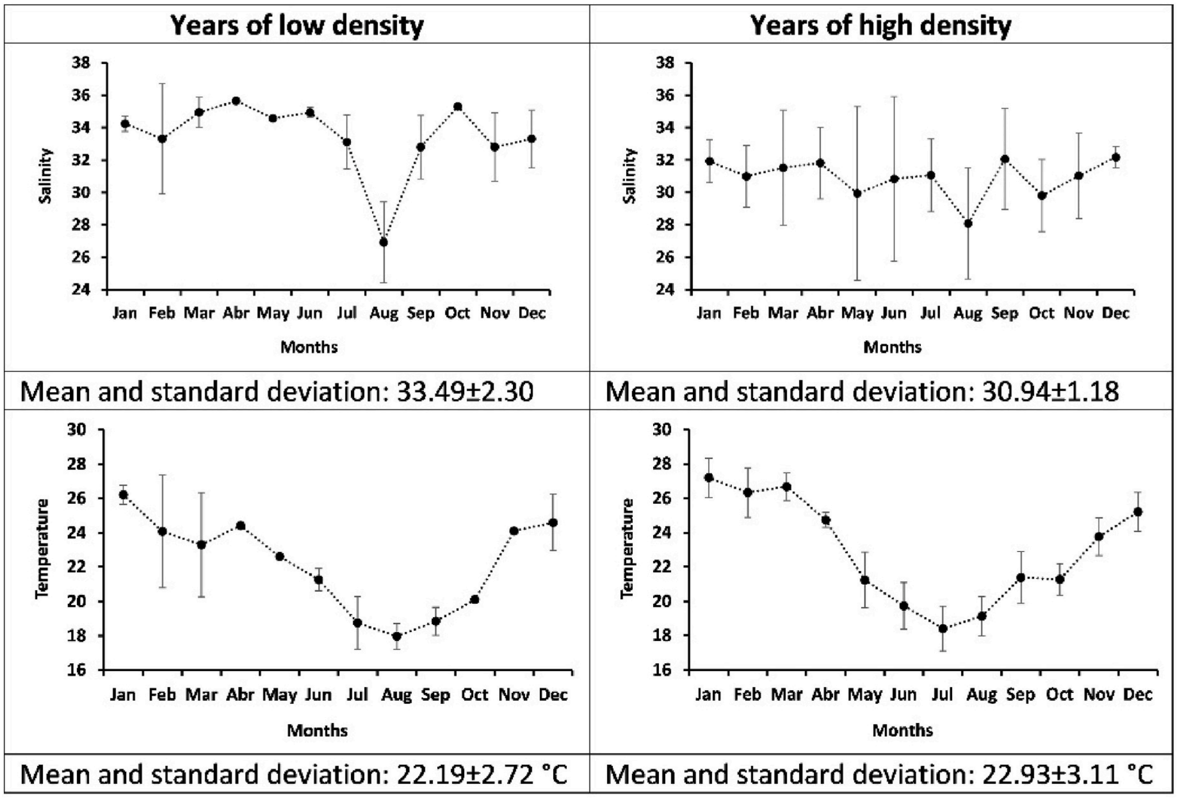

Fig. 6. Mean values for water temperature and salinity and standard deviations at jellyfish sampling points on the north coast of Santa Catarina classified as years of low (2012, 2013 and 2020) and high (2014–2019 and 2021) density of *Olindias sambaquiensis*. Water salinity for years with high densities is significantly lower than for years with low densities ($p < 0.05$).

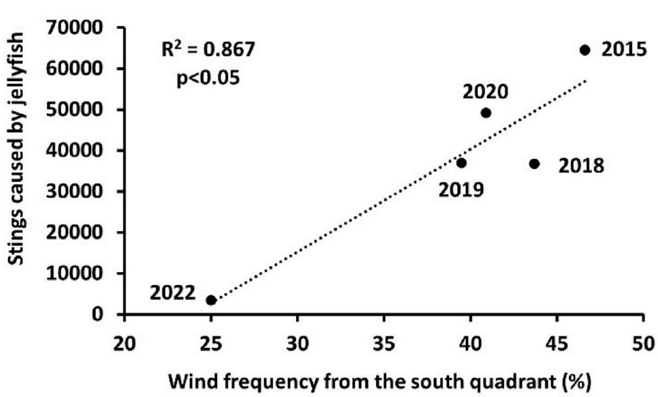

Fig. 7. Relation between the frequency of winds from the south quadrant and the number of cases of jellyfish stings, for the months of January and February, in the state of Santa Catarina and limited to cases of a high density of *Olindias sambaquiensis* in the year before the summer considered. For the summers of 2016 and 2017 no wind data were found for the Santa Marta Grande at INMET. The summers of 2014 and 2021 were not preceded by a year with a high density of *Olindias sambaquiensis*.

frequent being the hydrozoan *Olindias sambaquiensis*, followed by the scyphozoan *C. lactea* and cubozoans *C. quadrumanus* and *T. haplonema*. Based on a greater availability of information on the populations, the life cycle of *O. sambaquenesis* was characterized by two cohorts during the year, one in summer/autumn and the most abundant in winter/spring. The cohorts appear to be regulated by the low salinity of the southern Brazil Coastal Water. This was the only species that showed a correlation between density and outbreaks of bather stings in subsequent summers. Similarly, on a monthly scale, outbreaks of bather stings were correlated with winds from the south quadrant, pattern of winds that favored the transport of jellyfish to the beach region in summer. Finally, the need for continued monitoring of stinging jellyfish is highlighted in order to improve a predictive model.

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Consent to participate

Consensus.

Consent for publication

Consensus.

Authors' contributions

Charrid Resgalla Jr. (coordination, interpretation and writing), **Katlyn Christine Kruger** (data processing); **Marco Aurélio Lino Massarani Costa** (data processing); **Thiago Eloi Santos Sarraff** (data processing); **Andressa Leite da Silva** (data processing).

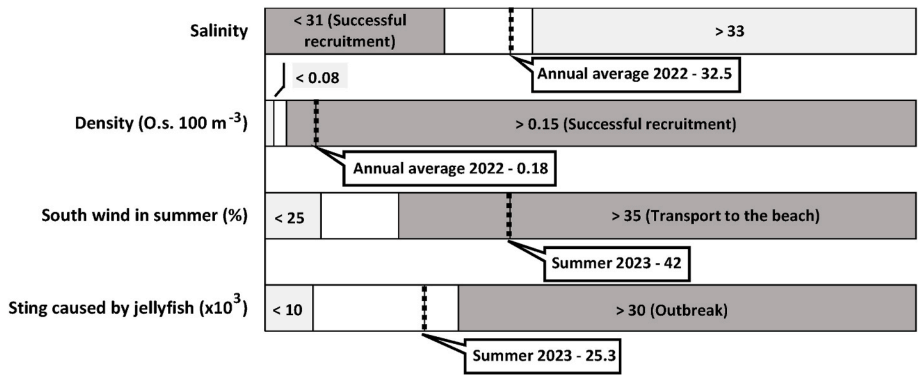

Fig. 8. Graphic representation of the predictive model of *Olindias sambaquiensis* outbreaks based on data between 2012 and 2021. The horizontal bars represent the lower and upper limits of seawater salinity (26.9 and 35.6), density of *Olindias sambaquiensis* (0.06 and 1.5100 m^{-3} or 2.5 and 63.9 for 10 min of travel) in the year before the summer season and the frequency of southerly winds (20 and 56.46%) and number of bathers with jellyfish stings (3.4 10^3 and 66.3 10^3) for the summer season. Darker bars refer to intervals favorable to outbreaks (according to the text) and white bars to intervals of uncertainty. Mean annual salinity and density data for *Olindias sambaquiensis* (0.18,100 m^{-3} or 7.7 for 10 min of travel) for 2022 and wind and outbreaks for summer 2023 are represented by dotted lines and were used for model validation.

Declaration of competing interest

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

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