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# Accumulation and stranding process of bryozoans and benthic microalgae on a beach in southern Brazil: Eutrophication and secondary succession case study

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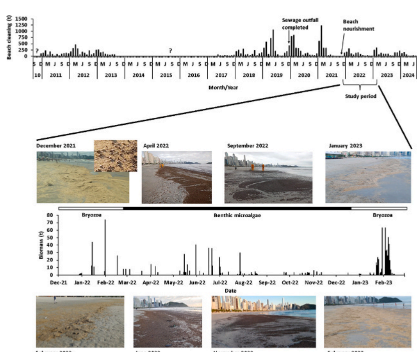
## HIGHLIGHTS

- Beach strandings are caused by bryozoans in summer and benthic microalgae in winter.
- Camboriú River is the source of nutrients and suspended particulate matter in the bay.
- The resuspension of sediments can also be a source of nutrients and organic matter.
- Bryozoans and benthic microalgae occurs mainly with the action of waves and tidal currents.
- The bay is considered eutrophic due to the high densities of plankton.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Strandings of bryozoans and benthic microalgae (*Arribadas*), with biomasses >200 tons, have been monitored in Balneáriu Camboriú, southern Brazil since 2003. Starting in 2021 after beach nourishment, the occurrences of strandings were interrupted for five months, and then restarted in 2022. To study these events and evaluate a secondary succession process, physical, chemical, and plankton data were sampled in the bay's surf zone, surface, and bottom water for a period of one year (2022 to 2023). The results showed that the organisms that make up the strandings are dominated by bryozoans in the warm months, and benthic microalgae in the cold months. However, the succession of species occurs due to other forcings such as substrate availability (the biomass of organisms itself) and physical and chemical changes in the environment. The Camboriú River, located in the south of the bay, is responsible for the entry of nutrients into the system, adding suspended particulate matter to the sediment in the northern part of the bay. The accumulation of bryozoans and benthic microalgae also occurs in the northern region, with the action of waves and tidal currents being determining factors. The resuspension of sediment in the north of the bay can also be considered a source of nutrients (ammonium) and organic matter serving as a food item for bryozoans. The bay is considered eutrophic due to the high densities of phytoplankton and zooplankton.

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## 1. Introduction

The accumulation of organisms in the water column and/or associated with the bottom is common in coastal environments, mainly in response to human activities that can directly affect the balance of the ecosystem, modifying the intensity and frequency of the natural processes (Schramm and Nienhuis, 1996; Schaffner et al., 2001). The growth of organisms in coastal and depositional environments is difficult to study because they are submerged in the shallows and energetic but record high rates of sediment accumulation. Depositional systems act as direct sinks for a vast amount of terrigenous sediments, organic carbon, and anthropogenic pollutants (Pellegrini et al., 2023). According to Trincardi et al. (2023), there are different anthropogenic impacts on coastal environments such as borrowing sites, and sand nourishment in places where environmental forcings such as waves and tides act.

The Balneário Camboriú Bay, where Central Beach is located, is an important tourist destination in southern Brazil and is typically sheltered by two rocky promontories that limit 5.8 km of beach in a NW-SE direction (Menezes, 2008). The Camboriú River (Fig. 1) is located in the southern portion of the bay, which is 40 km long and drains an area of 200 $km^2$. The river passes through several regions of agricultural activity and receives direct input of treated and untreated domestic sewage (Pereira Filho et al., 2002). As a result, variations in water quality in the bay are directly influenced by the Camboriú River estuary (Franklin-Silva and Schettini, 2003), characterizing it as a deposition area.

Since 2003, the central beach has recorded the accumulation and stranding of organisms (bryozoans, micro and macroalgae) in the intertidal region. This process, known as *Arribadas*, has generally been associated with the availability of excess nutrients (Pereira Filho et al., 2002; Costodio et al., 2006), eutrophication, and local hydrodynamics (Tocci et al., 2022) (Fig. 2). Since ecosystem services are fundamental to the well-being of society, the intensification of *Arribadas* on the central beach represents a problem for the local economy, namely the tourism sector. This is due to extensive beach cleaning carried out by sanitation companies, which remove >200 tons of stranded organic material per month (Tocci et al., 2022).

The first records of strandings on the beach showed that they were formed by a high biomass of the bryozoan species *Membraniporopsis tubigera* Osburn (Gordon et al., 2006; Pezzuto et al., 2006, 2007). Later, Rörig et al. (2017) described the strandings between 2011 and 2013 as blooms of the bryozoans *M. tubigera* and *Arbocuspis ramosa* Osburn (described as *A. bellula*), associated with the epibenthic diatoms *Amphitetras antediluviana* Ehrenberg and *Biddulphia biddulphiana* (J.E. Smith) Boyer. Rörig et al. (2017) also highlighted that the data from this period indicated a seasonal trend in these blooms, with greater bryozoan biomass in the warmer months. The later work of Tocci et al. (2022) highlighted, through photographic records, that these stranding events have been occurring since 1938, increasing in biomass and frequency due to eutrophication resulting from urban development (Fig. 2). These same authors presented a classification of *Arribadas* based on their color and texture in relation to their composition and dominance of organisms present in the beach strandings.

The most recent records still report the persistence of the microalgae species *A. antediluviana* and *B. biddulphiana*. However, from 2018 to

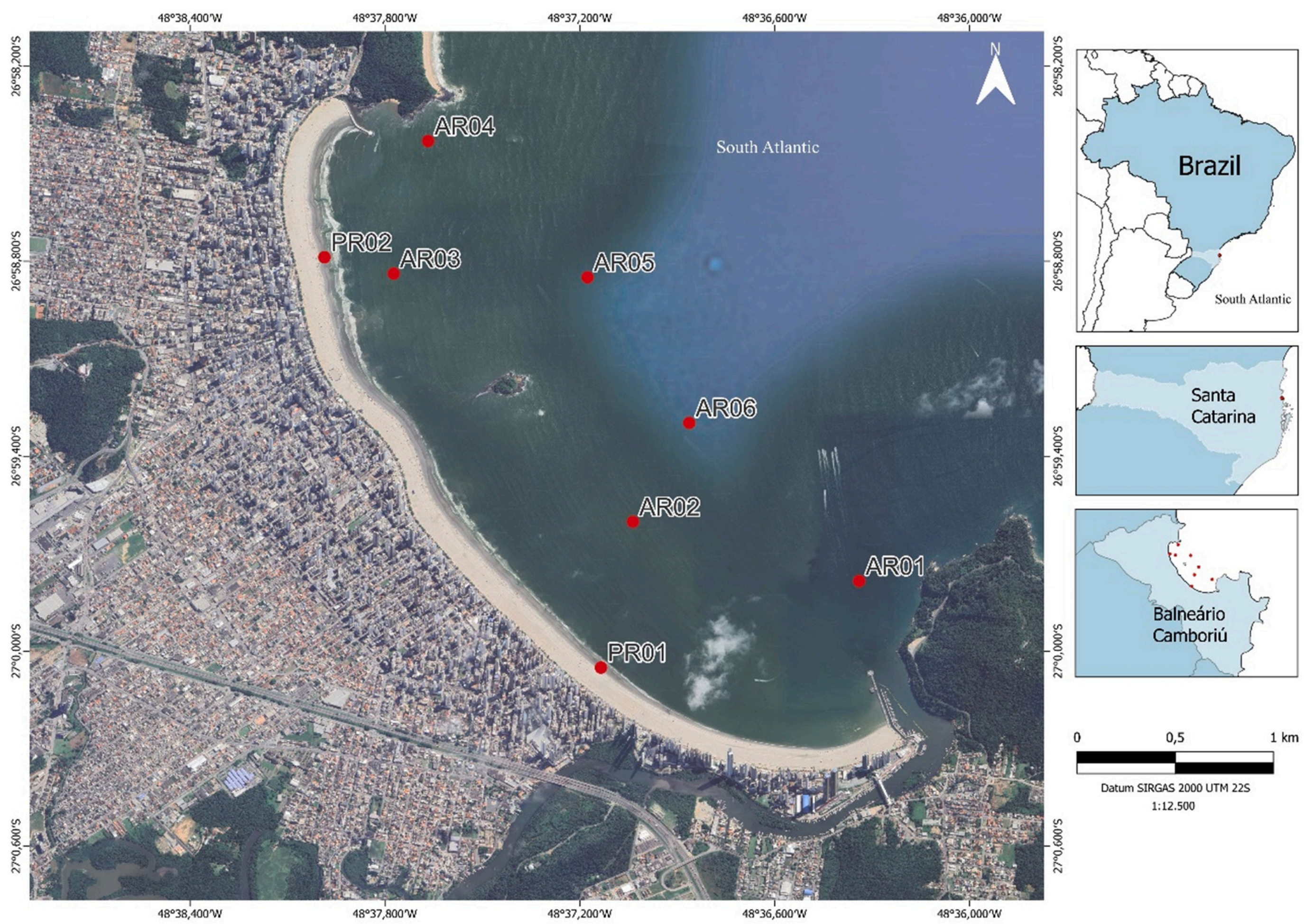



**Fig. 1.** Study area highlighting the Balneário Camboriú Bay and its location in southern Brazil. Central Beach, Balneário Camboriú with the location of sampling points in the surf zone (PR01 and 02) and in the bay, being AR1, AR2, AR3, and AR4 in the 5 m isobath, and AR5 and AR6 in the 10 m isobath.

2021, the macroalgae *Bryopsis plumosa* (Huds.) C. Agardh, 1823 was responsible for the substantial increase in the biomass deposited on the beach, especially in the warmer months (Tocci et al., 2022). In 2022, the presence of the bryozoan *Amathia alternata* Lamouroux was also detected in the strandings; however, despite being considered invasive, its occurrence was isolated to that year (Nascimento et al., 2022). The presence of *A. ramosa* has always been constant in these strandings.

At the end of 2021 a large-scale beach nourishment project was completed on a 5.8 km stretch of Central Beach in Balneário Camboriú, widening the sand strip with a landfill of approximately 2.7 million $m^3$ of sand (work carried out between August and November 2021, more details in Beltrão et al., 2023). During and after the work, the strandings of organisms associated with *Arribadas* did not occur, in contrast to the previous five years of continuous presence (Fig. 2). However, from December 2021 onwards, the strandings returned showing a clear pattern of color and temporal texture that are associated with the predominant species according to Tocci et al. (2022). In addition, recent occurrences of these same organisms in other locations, or even stranding features similar to those observed in the Balneário Camboriú bay, have attracted attention (Fig. 3). These events are unlikely to be related to each other, however, they indicate similarities in natural processes with different morphological responses from the colonial organisms involved.

Starting in 2022, a unique opportunity arose to monitor the processes of changes in the dominance of organisms involved in strandings in the intertidal region, following the system's alteration caused by the beach nourishment project (Fig. 2). The half-life of stranding events was studied by Rörig et al. (2017), and the more advanced stages by Tocci et al. (2022). However, little is known about the environmental factors that act in the initial phases of these strandings, which may promote a process of secondary succession of the organisms involved.

The present study monitored a secondary succession process of stranding after beach nourishment, evaluating the environment's seasonality and the spatial variations (parallel and perpendicular to the coast) of the occurrences. In addition, this study details the concentration of nutrients on the bay's surface and bottom, and seeks the use of biological indicators associated with the stranding processes. The objective, complementing the study by Tocci et al. (2022), was to visualize the bay's regions that initially presented accumulations of strandings; whether the seasonality of the environment determines the change in the composition of strandings; and whether the accumulation of strandings is limited to a certain depth in relation to the surf zone. By studying this process, the authors confirm the influence of nutrient inputs and the eutrophication process, the response of the planktonic community, and most importantly, which physical processes of the environment may be associated with stranding.

## 2. Material and methods

This study was conducted in Balneário Camboriú Bay, located on the north-central coast of Santa Catarina State (26°58′ to 27°00′ S; 48°37′ to 48°36′ W), southern Brazil. The bay is an important tourist spot, known nationally for its notable urban development and skyscrapers. Central Beach is 5800 m long and receives constant continental input from the Marambaia Canal (northern portion) and the Camboriú River (southern portion) (Pereira Filho et al., 2002) (Fig. 1). Central Beach is classified as sandy (Menezes, 2008) and is therefore susceptible to morphological changes due to fluctuations in local energy levels, subject to the action of hydrodynamic and meteoceanographic processes. Between August and October 2021, in a large-scale coastal project, approximately 2.7 million $m^3$ of sand were deposited from a nearby deposit to extend the width of the sand strip from 25 to 70 m, over a distance of 5.8 km.

Prior to this engineering work, *Arribadas* of bryozoans and benthic micro and macroalgae were monitored since 2010. Biomass peaks were recorded in the summer months, with a maximum record of 1200 tons in February 2021 (Tocci et al., 2022). During the beach nourishment work, strandings of organisms were not recorded, only occurring again at the end of December 2021. The occurrences of *Arribadas* in the intertidal region of the beach were always monitored by the Environmental Urban Cleaning Company, which communicated directly the location, weight (biomass), and photographic record of the material removed from the beach on a daily basis, composing a time series of occurrences since 2010. The photographic records were used as visual control for potential variations in the taxonomic composition of the *Arribadas* community, as presented by Tocci et al. (2022) based on their coloration and texture.

In order to monitor the successional events after the widening process of Central Beach, monthly samplings were carried out for a period of one year (February 2022 to 2023). This was done at four points in the bay with an average depth of 5 m (AR01, AR02, AR03 and AR04), two points in the 10 m (AR05 and AR06) isobath, and two points in the surf zone (PR01 and PR02). The points were classified as south (AR01, AR02, AR06 and PR01) and north (AR03, AR04, AR05 and PR02) of the bay and separated by the presence of a small island and associated cusps (Fig. 3).

Sampling in the bay was carried out with a 16-foot boat with a 60 HP engine to obtain data on temperature (°C), salinity, turbidity (NTU), and dissolved oxygen (mg $L^{-1}$), using a multiparameter probe (YSI) at the surface and bottom. Data on suspended particulate matter (SPM - mg $L^{-1}$), ammoniacal N ($NH4^{+}$ – mg $L^{-1}$), and chlorophyll-a (Cla-a - μg $L^{-1}$) were obtained by gravimetry and spectrophotometry in the laboratory (Strickland and Parsons, 1972). Water samples were collected using a Niskin bottle (5 L), also at two depths. At the points in the surf zone, temperature and salinity data were also collected using the YSI probe, and surface water and groundwater samples (obtained using an auger) on the sand strip were collected for analysis of ammoniacal-N ($NH4^{+}$) by spectrophotometry (Spectroquant® Merck Millipore). Groundwater samples on the beach were taken to evaluate the contribution of organic matter from clandestine effluents in the city.

In order to detect the presence, and spatial and temporal distribution of the species of interest (the bryozoan *Arbocuspis ramosa*, and the benthic microalgae *Amphitetras antediluviana* and *Biddulphia biddulphiana*) within the bay and in the surf zone, the phytoplankton,

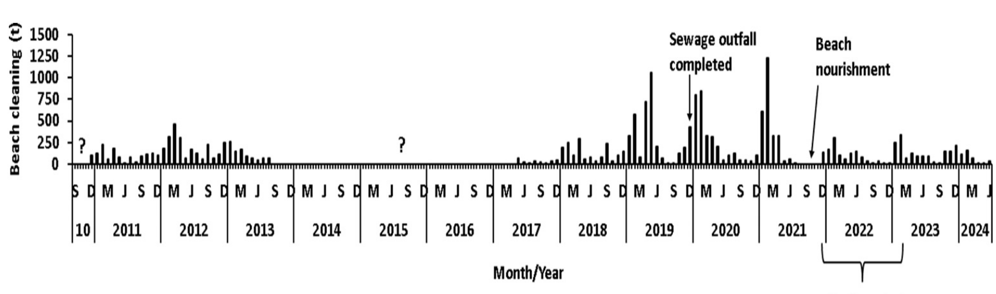



**Fig. 2.** Monthly variation in biomass (t) of strandings (*Arribadas*) of organisms collected on the beach of Balneário Camboriú (SC) according to the Environmental Urban Sanitation Company.

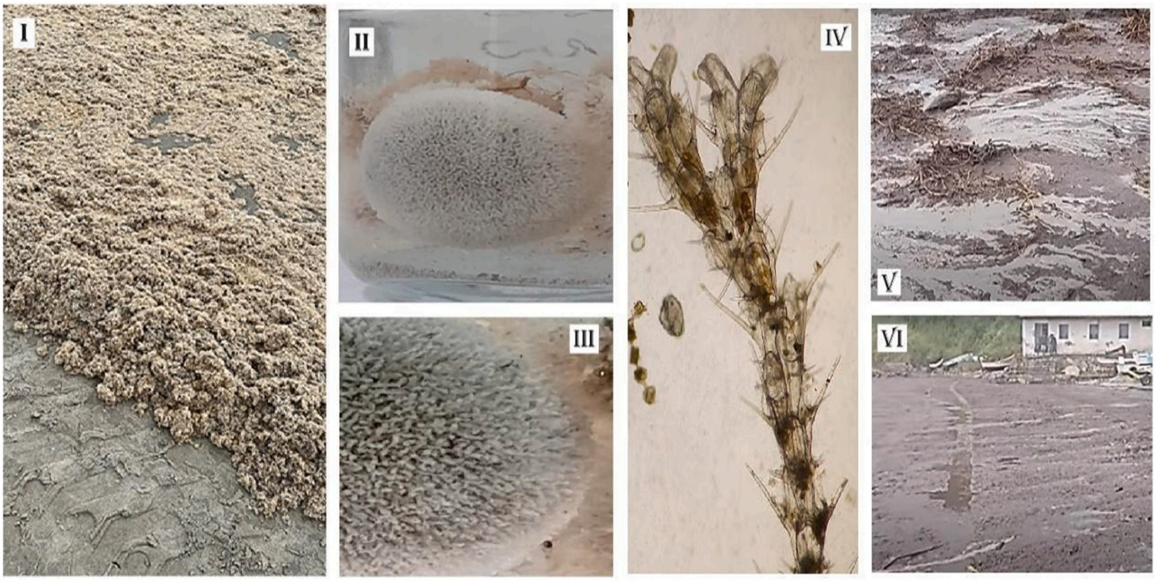



**Fig. 3.** Occurrence of different types of stranding features on the coast of Santa Catarina: I – typical agglomeration of the erect and branched colony of *Arbocuspis ramosa* on Central Beach in Balneário Camboriú (January 2023); II and III – massive structures in the form of a circular colony (1 to 3 cm in diameter) of *A. ramosa* on Perequê beach in Itapema (February 2023); IV – erect and branched colony of *A. ramosa*; V and VI – occurrence of litter and biomass strandings in Garopaba (April 2024), similar to those recorded in Balneário Camboriú with the dominance of epibenthic microalgae and bryozoans, but in this case without confirmation of the composition.

zooplankton, and benthopelagic communities (only for the bay) were analyzed at the same sampling points presented for the physicochemical parameters. The phytoplankton community samples were collected using Niskin bottles (5 L), fixed with Lugol solution and analyzed according to Utermöhl (1958) in a sedimentation chamber, under an inverted microscope, with the densities expressed in cells per liter (cell $L^{-1}$). To collect the zooplankton community, horizontal trawls were performed using a zooplankton net (220 μm mesh and 30 cm diameter), equipped with a flowmeter (average filtered volume of 1.5 $m^3$). To collect the benthopelagic community, bottom trawls were performed using an epibenthic sledge coupled to a cylindrical-conical net with 220 μm mesh, and equipped with a flowmeter (average filtered volume of 4.6 $m^3$). Both the zooplankton and benthopelagic community samples were fixed in 4 % formalin, and analyzed under a biological and stereoscopic microscope in a Bogorov-type chamber after total sample fractionation (Boltovskoy, 1981). Density estimates of the target species were expressed in cells per liter (cell $L^{-1}$) for the diatoms *Amphitetras antediluviana* and *Biddulphia biddulphiana*, and in the number of live zooids $L^{-1}$ for *Arbocuspis ramosa*. For the other zooplankton organisms, density was expressed in organisms per cubic meter of water filtered by the net (org $m^{-3}$).

The target species, including *Arbocuspis*, *Amphitetras* and *Biddulphia*, were treated separately for observations of temporal and spatial patterns of occurrence, both in the surf zone and in the bay (surface and bottom). The same treatment was performed for the total phytoplankton and four zooplankton species. The phytoplankton community was treated only by the total number of cells per liter, with the genera *Skeletonema, Pseudo-nitzschia, Thalassiosira, Cryptomonas* and *Gymnodinium* being the most frequent. For the zooplankton community, the copepod species *Paracalanus quasimodo* Bowman, 1971; *Temora turbinata* (Dana, 1849–1852); and *Acartia lilljeborgi* Giesbrecht, 1889 were treated due to their high frequency of occurrence and relative abundance, and because they range from 0.65 (*Paracalanus*) to 1.30 mm (*Acartia*) in total length. This size range for copepods may be associated with the size spectrum of phytoplankton that are used as food. Together, these zooplankton species represent >80 % of the density of the zooplankton community in the bay. In addition to these holoplankton organisms, cnidarian polyps of the *Clytia* group were used as indicators because they also belonged to the *Arribadas*, and they survive in the water column after their fragmentation or detachment from the substrate (Cabral et al., 2015).

In total, 168 water samples and 168 plankton samples (phytoplankton and zooplankton separately) were obtained, involving two points on the beach and six in the bay at two depths every month, for 12 months. The abiotic (physical and chemical parameters) and biotic (plankton) variables of the sampled points were statistically compared between the surface and bottom samples using Student's *t*-test. The objective of this was to observe significant differences between the bay samples ($p < 0.05$). Spatial (south and north) and temporal (from summer 2022 to summer 2023) comparisons were performed by grouping the points and collection months and applying an ANOVA ($p < 0.05$) (Zar, 2010). The verification of data normality was performed using the Shapiro-Wilk test ($p < 0.05$). The relationships between biotic and abiotic variables at the beach and bay points (surface and bottom) were investigated using principal component analysis (PCA) (Pielou, 1984) with data normalization by log transformation, centering, and weighting.

## 3. Results

### 3.1. Overview of the accumulation and stranding process

The records of *Arribadas* indicated that the occurrences ceased in August 2021, returning only at the end of December of the same year (Fig. 4). The beach cleaning data indicated a large volume and biomass in the summer, with maximums of 74.3 tons in January 2022 and 63.43 tons in January 2023. The incidence of events increased over the months, with a higher frequency of occurrence in the summer of 2023, totaling 99 days with *Arribadas* for the entire period of one year and two months.

Initially, the temporal variation demonstrated an alternation in the predominance of indicator species according to the color of the stranding features (Tocci et al., 2022) observed in the photographic records. In summer, the lighter color and large biomass demonstrate the dominance of bryozoans (*Arbocuspis*), while in the colder months (autumn, winter, and spring), the darker color and low biomass indicate the predominance of benthic microalgae (*Amphitetras* and *Biddulphia*) (Fig. 4). At the

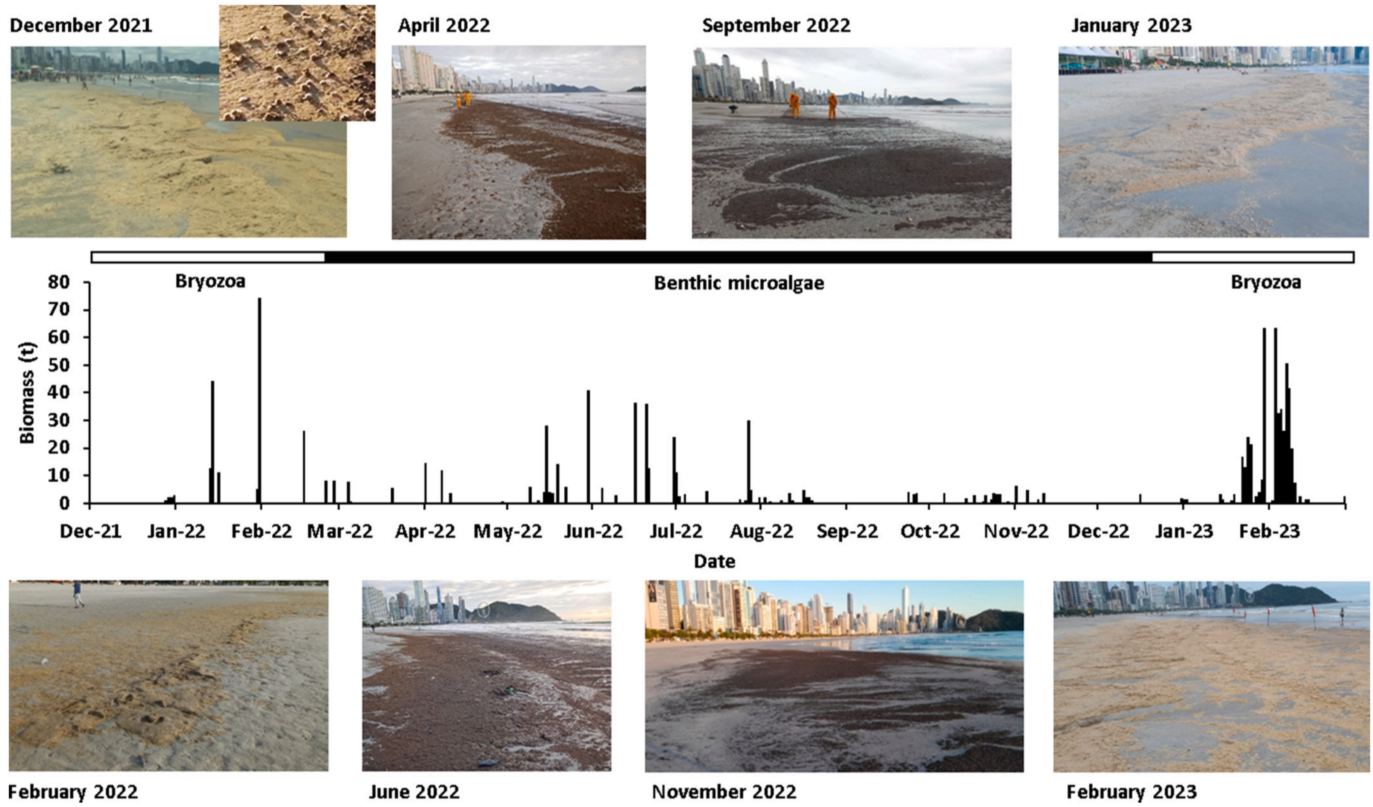



**Fig. 4.** Time series of wet biomass (in tons) of the strandings between December 2021 (post-widening) and February 2022. The images refer to the different features of strandings, with variations in color and texture according to the scale proposed in Tocci et al. (2022), indicating differences in composition. Lighter coloration indicates dominance of the bryozoan *Arbocuspis ramosa*, darker coloration indicates predominance of the benthic microalgae *Amphitetras antediluviana* and *Biddulphia biddulphiana* with the presence of the bryozoan. Additional photo in December 2021 - detail of the shape of bryozoans in spheres observed only in that month.

beginning of the process (December 2021), the bryozoan colonies showed a tendency toward erect forms with circular or spherical colonial formation (detail of the December 2021 photo in Fig. 4) but with low biomass. From January 2022, the colonies of *Arbocuspis* were observed in a scattered or continuous and spongy form, typical for the bay according to Tocci et al. (2022). It was observed that the color of the stranding on the beach varied with the oscillation of the bryozoan biomass: the greater the biomass, the lighter the accumulated material.

The biomass collected by the cleaning company showed spatial variation in the bay, demonstrating a higher frequency of events in the northern portion of the beach (Fig. 5). Proportionally, the records indicated that 24 % of the occurrences of accumulation of biological material were recorded only in the southern portion, 58 % only in the northern portion, and 18 % on both sides for the period considered.

### 3.2. Target species in surf zone

The presence of species stranded in the surf zone varied throughout

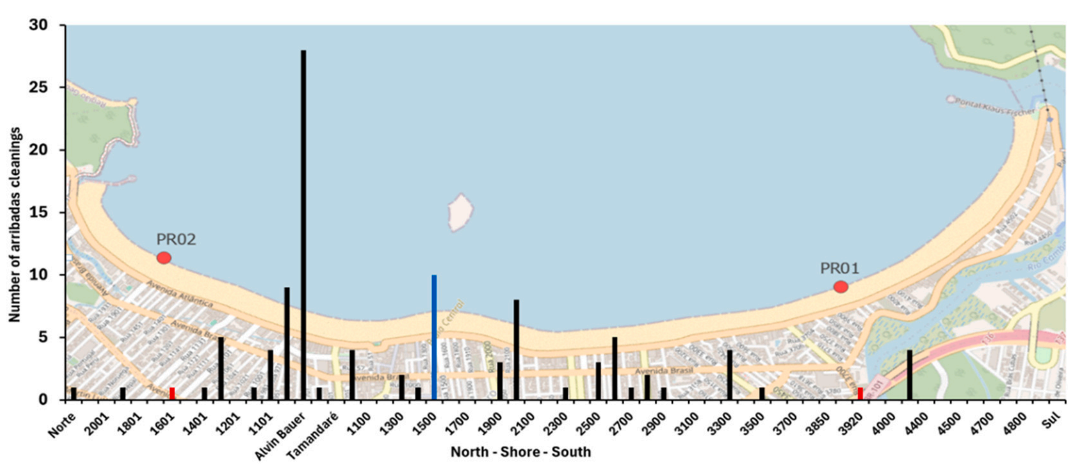



**Fig. 5.** Spatial distribution of the number of occurrences of *Arribadas* for the period from December 2021 to February 2023. The northern portion is to the left of the cusp of Cabras Island and the southern portion is to the right of the cusp of the island. The red bars in the graph indicate the location of the collection points of the surf zone parameters (PR01 and PR02), and the blue bar indicates the cusp of Cabras Island. The x-axis of the graph illustrates the spatial distribution referenced by the location of the streets (numerical in most cases) and limited by the northern (Marambaia channel) and southern (Camboriú River) breakwaters.

the net sampling and followed the variations observed in the photographic records described in Fig. 4. In general, the northern and southern portions of the bay presented different behavior in the density of organisms. Bryozoans, benthic microalgae, and polyps were the most representative and frequent in the northern portion. Bryozoans were not more abundant due to the peak density of 258 zooids $L^{-1}$ in April 2022 in the south (Fig. 6).

The temporal variation among the species of *Arribadas* showed that the bryozoan *Arbocuspis* and the microalgae *Biddulphia* tend to occur in higher densities in the same period, indicating a positive correlation in the southern portion (rs = 0.958; $p < 0.05$) and in the northern portion (rs = 0.532; p < 0.05). *Amphitetras* indicated a positive correlation with *Biddulphia* (rs = 0.622; p < 0.05) only in the northern portion. The polyps followed the peaks of bryozoans and microalgae in the northern portion, but with similar occurrence to the microalgae in the southern portion.

The highest densities of the bryozoan and the diatom *Biddulphia* in the surf zone were observed in the months with the highest water temperature (03/2022 = 24.3 °C; 04/2022 = 25.3 °C; 02/2023 = 29.6 °C), while *Amphitetras* showed preference for the months with the lowest water temperature (05/2022 = 20.9 °C; 07/2022 = 19.7 °C) (Fig. 7). Despite these observations, no significant correlations were observed between temperature and the densities of the organisms in the surf zone. For salinity, a decreasing trend was observed between the summers of 2022 and 2023.

The temperature ($p = 0.90$) and salinity ($p = 0.96$) of the water in the surf zone did not present significant differences ($p > 0.05$) between the northern and southern portions of the bay. Likewise, the ammoniacal nitrogen (N-$NH^4$), both in the water of the surf zone ($p = 0.86$) and in the groundwater ($p = 0.57$), did not present spatial differences (means $N$ = 0.66 mg $L^{-1}$; S = 0.92 mg $L^{-1}$; sd = 0.9) despite the high values observed (Fig. 7).

### 3.3. Presence of target species in the bay

The presence of the species of interest (from *Arribadas*) in the benthopelagic community (bottom) of the bay was more representative in the 5 m isobath, and mainly in the northern portion (Fig. 8). The microalgae *Amphitetras* and polyps were present in the surface trawls,

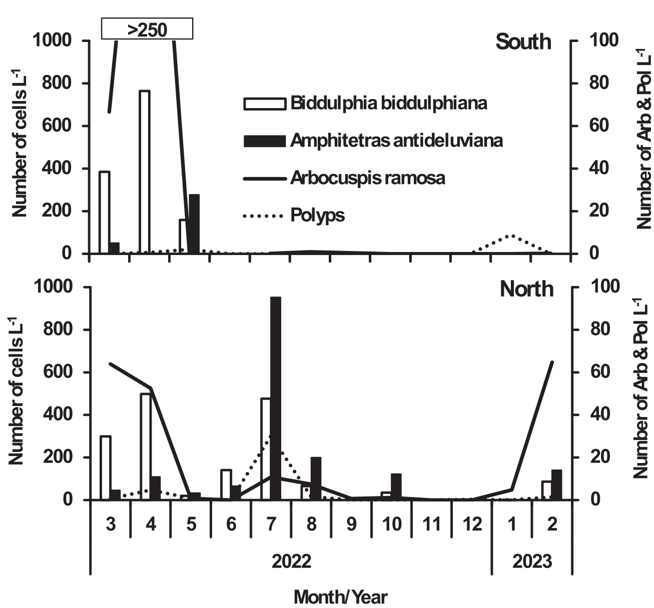



**Fig. 6.** Temporal variation of the predominant species in the surf zone for the southern (PR01) and northern (PR02) portions of the beach: *Arbocuspis ramosa* (zooids.$L^{-1}$), *Amphitetras antediluviana* (cells.$L^{-1}$), *Biddulphia biddulphiana* (cells.$L^{-1}$), and Polipos (Org. $L^{-1}$).

but in general, both the distance from the surf zone and the water column were not environments with high densities of the species that accumulate in the surf zone and strand in the intertidal region.

### 3.4. Spatial and temporal variations in the bay

Considering the samples from the 5 m isobath points (AR01 to AR04) with occurrences of stranded organisms on the beaches, two groups were observed for the abiotic and biotic parameters based on the highest values on the surface or at the bottom, according to Tables 1 and 2 and interpreted in Fig. 9.

At the surface, the variables temperature, dissolved oxygen (DO), phytoplankton, chlorophyll, and ammonia presented the highest average values. Temperature and DO did not indicate spatial variations, although did so for seasonality with the lowest values in winter (18.0 to 18.3 °C) for temperature, and oxygen below 6.0 mg $L^{-1}$ in the summer of 2022. However, surface ammonia (high values in the south) presented inverse spatial variation with chlorophyll and phytoplankton density (high values in the north), all with high values in the summer of 2023.

For the variables with higher averages at the bottom, salinity showed similar behavior to temperature, without spatial variations but with higher averages in the summer of 2022. It is noteworthy that ammonia (bottom), turbidity, and suspended particulate matter (SPM) showed higher averages in the northern region of the bay in the winter of 2022 and summer of 2023.

The organisms that make up the *Arribadas* showed similar behavior at the bottom, concentrating in the northern region, but with the highest averages in the two summers of 2022 and 2023.

Zooplankton organisms (copepods) occurred in the central portion of the bay, but with a seasonality or alternation of dominance between the seasons, starting with *Acartia* in the summer of 2022—albeit without repetition in 2023—*Paracalanus* in the fall, and *Temora* in the winter. Unlike this pattern, hydrozoan polyps followed the distribution of *Arbocuspis* (bryozoan), being abundant in the fall of 2022 and in the summer of 2023.

PCA analyses were performed to confirm the previous results (secondary validation) and to observe other patterns in the abiotic and biotic data, in the surf zone and in the bay. For this purpose, the sampling points of the south/north profile of the bay (points AR1 to AR4) were treated separately in surface and bottom water, as well as the two points in the surf zone. The three PCA analyses presented explainability percentages between 41.5 and 50.8 %, and variables with a minimum frequency of occurrence of 5 % were used.

The results indicated that the bay's surface water presented an inverse correlation between salinity, and indicators of phytoplankton biomass and density (chlorophyll and phytoplankton) involving hydrozoan polyps. For the other zooplankton indicators, a positive correlation was observed with the genus *Acartia* and temperature (Fig. 10).

The bay's bottom water showed an inverse correlation between DO and the organisms of the *Arribadas*, ammonia, temperature, salinity, chlorophyll, and density of the phytoplankton community. In the second axis, the benthic microalgae (*Biddulphia* and *Amphitetras*) as well as polyps showed an inverse relationship with turbidity (Fig. 10).

Finally, in the surf zone, temperature and salinity lose importance to ammoniacal nitrogen, which is related to the members of the beach strandings (bryozoans, microalgae, and polyps) (Fig. 10), and this fact possibly reflects the mixing between the bay's surface and bottom water.

## 4. Discussion

In summary, the results indicate a higher concentration of organisms from the *Arribadas* in the northern region of the bay. This region also presents a greater dispersion of organisms on the bottom, and on the surface up to the 10 m isobath. Due to the difference between the densities in the 5 m isobath and the surf zone for organisms from the *Arribadas*, their concentration occurs near and behind the depth of closure

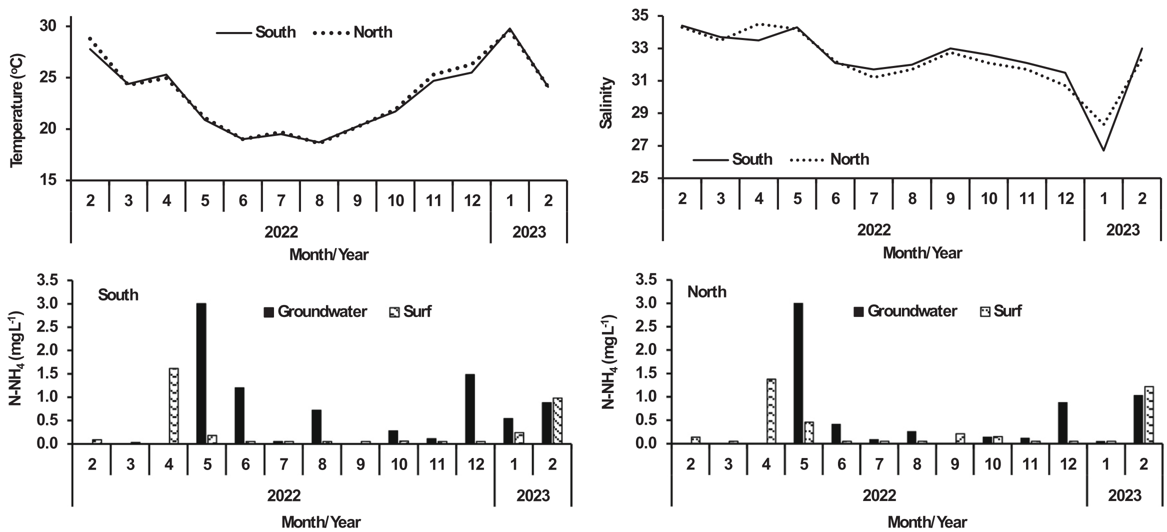
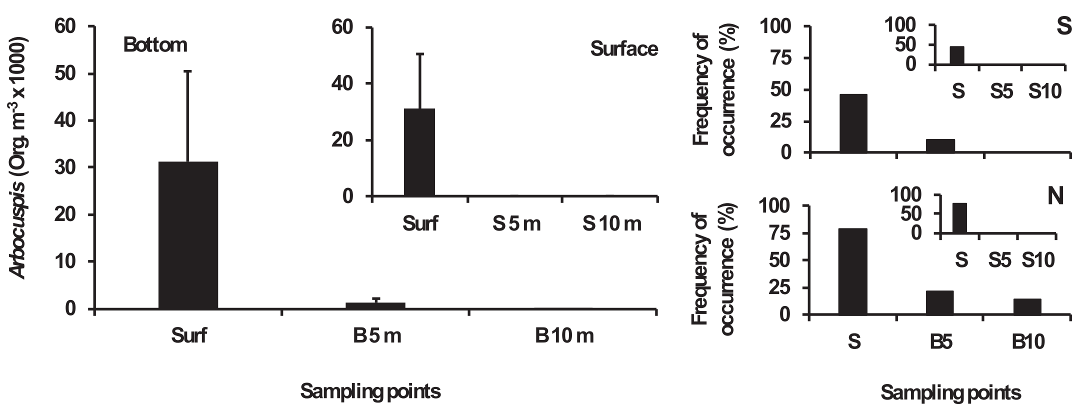



**Fig. 7.** Temporal variation of temperature (°C), salinity, and ammoniacal nitrogen (mg $L^{-1}$) of the southern (PR01) and northern (PR02) portions at the points of the surf zone. There is information for the water table between the period from February to April 2022.




Relative abundance (% - Surf zone)

| | Arb | Bid | Amp | Pol |
|---|---|---|---|---|
| | Surf (zooide $L^{-1}$) | | | |
| Average | 31.26 | 15.53 | 78.65 | 2.10 |
| SE | 19.18 | 64.42 | 36.71 | 1.17 |
| | Surface (%) | | | |
| S 5 m | 0.00 | 0.00 | 0.01 | 0.08 |
| S 10 m | 0.00 | 0.00 | 0.00 | 0.16 |
| | Bottom (%) | | | |
| B 5 m | 3.88 | 2.84 | 2.73 | 2.3 |
| B 10 m | 0.05 | 0.52 | 2.72 | 0.00 |

Surf zone, 5 and 10 m isobath

Frequency of occurrence (%)

| | | Arb | Bid | Amp | Pol |
|---|---|---|---|---|---|
| Surf | South | 46.15 | 30.77 | 53.85 | 30.77 |
| | North | 78.57 | 78.57 | 100.00 | 78.57 |
| S 5 m | South | 0.00 | 0.00 | 3.57 | 7.14 |
| | North | 0.00 | 0.00 | 3.57 | 7.14 |
| S 10 m | South | 0.00 | 0.00 | 0.00 | 7.14 |
| | North | 0.00 | 0.00 | 0.00 | 7.14 |
| B 5 m | South | 10.71 | 10.71 | 10.71 | 0.00 |
| | North | 21.43 | 25.00 | 39.29 | 10.71 |
| B 10 m | South | 0.00 | 7.14 | 7.14 | 0.00 |
| | North | 14.29 | 14.29 | 28.57 | 0.00 |

**Fig. 8.** Graphs and table on the left: Densities of *Arbocuspis* zooids on the bottom (larger graph) and on the surface (smaller graph), and in different isobaths beyond the surf zone. In the table, the average and standard error (SE) of the densities of *Arbocuspis* zooids (Arb), the microalgae *Biddulphia* (Bid) and *Amphitetras* (Amp), and polyps (Pol) in the surf zone; and relative densities of the same species in the 5 and 10 m isobaths on the bottom (B) and on the surface (S). Graphs and table on the right are the frequencies of occurrence (FO) of the same organisms in the samples grouped by depth, isobath, and southern (S) and northern (N) regions of the study area.

(or depth where the wave touches the bottom). This depth of closure can be interpreted as the marginal growth limit of the organisms that make up the *Arribadas*, as once exceeded they can be resuspended by wave action and thrown into the surf zone. Temporally, there is a seasonality in the environment when considering variation in the biomass of organisms occurring on beach strandings. This can also be observed in the alternation of dominance between bryozoans and benthic microalgae, and between microalgae species.

The surface water of the bay maintains an inverse relationship between salinity and indicators of phytoplankton density and biomass (chlorophyll and phytoplankton), suggesting the influence of the Camboriú River which is the main source of nutrients. The work of Pereira Filho et al. (2001 and 2002) carried out at the Camboriú River mouth confirms that there is export of nutrients and chlorophyll by tidal

**Table 1**
Maximum, minimum, and average values of the abiotic and biotic parameters of the bay water between the south (AR01 and AR02) and north (AR03 and AR04) points (according to Fig. 1) on the surface (Sur) and bottom (Bot).

| | | South | | | | North | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | #AR01 | | #AR02 | | #AR03 | | #AR04 | |
| | | Sur | Bot | Sur | Bot | Sur | Bot | Sur | Bot |
| Temperature (° C) | Min. | 17.67 | 17.46 | 17.99 | 17.49 | 17.89 | 17.60 | 17.82 | 17.53 |
| | Max. | 27.93 | 24.88 | 28.36 | 24.73 | 28.44 | 24.85 | 28.59 | 24.60 |
| | Average | 22.23 | 21.48 | 22.49 | 21.46 | 22.51 | 21.59 | 22.48 | 21.42 |
| Salinity | Min. | 27.43 | 31.63 | 27.03 | 31.61 | 27.47 | 31.43 | 29.70 | 31.52 |
| | Max. | 33.98 | 34.73 | 33.90 | 34.68 | 34.11 | 34.68 | 34.02 | 34.62 |
| | Average | 31.94 | 33.14 | 31.91 | 33.16 | 31.79 | 33.01 | 31.82 | 33.07 |
| DO (mg $L^{-1}$) | Min. | 5.77 | 4.87 | 5.10 | 4.86 | 4.76 | 4.10 | 4.73 | 3.71 |
| | Max. | 8.45 | 7.54 | 9.24 | 7.31 | 9.84 | 7.74 | 8.27 | 7.57 |
| | Average | 7.29 | 6.27 | 7.12 | 6.16 | 7.29 | 6.13 | 7.22 | 5.67 |
| Turbidity (NTU) | Min. | 0.80 | 1.20 | 0.40 | 2.00 | 0.20 | 2.20 | 0.40 | 2.00 |
| | Max. | 6.20 | 11.30 | 6.40 | 19.80 | 18.00 | 15.85 | 12.80 | 23.00 |
| | Average | 2.24 | 5.79 | 2.74 | 9.45 | 4.12 | 7.03 | 4.67 | 11.84 |
| $NH_4$ (mg $L^{-1}$) | Min. | 0.08 | 0.05 | 0.09 | 0.04 | 0.07 | 0.05 | 0.06 | 0.07 |
| | Max. | 0.75 | 0.51 | 1.02 | 0.83 | 0.96 | 0.70 | 0.63 | 2.38 |
| | Average | 0.44 | 0.25 | 0.35 | 0.20 | 0.30 | 0.22 | 0.26 | 0.38 |
| SPM (mg $L^{-1}$) | Min. | 8.20 | 8.53 | 9.00 | 11.20 | 8.00 | 13.20 | 12.80 | 17.40 |
| | Max. | 39.20 | 48.80 | 87.60 | 46.90 | 38.53 | 37.20 | 46.21 | 75.60 |
| | Average | 19.16 | 20.55 | 25.24 | 24.39 | 19.31 | 23.13 | 22.82 | 34.24 |
| Chlorophyll (μg $L^{-1}$) | Min. | 1.58 | 0.68 | 2.08 | 1.16 | 1.75 | 1.18 | 0.87 | 1.64 |
| | Max. | 19.45 | 9.91 | 28.03 | 8.82 | 26.96 | 13.36 | 25.23 | 11.73 |
| | Average | 6.71 | 2.91 | 7.10 | 4.56 | 9.18 | 5.42 | 7.39 | 6.38 |
| Phytoplankton (Cel $L^{-1} \times 10^3$) | Min. | 253 | 9 | 264 | 30 | 137 | 29 | 124 | 11 |
| | Max. | 18,601 | 14,103 | 35,604 | 28,074 | 34,308 | 25,032 | 24,830 | 14,438 |
| | Average | 4784 | 2233 | 7736 | 4765 | 9160 | 4674 | 6450 | 3000 |
| *Acartia Lilljeborgii* (Org $m^{-3}$) | Min. | 0 | 0 | 0 | 21 | 0 | 94 | 0 | 0 |
| | Max. | 3858 | 27,577 | 1486 | 74,000 | 1266 | 45,417 | 3600 | 16,429 |
| | Average | 839 | 3411 | 440 | 6971 | 231 | 6342 | 459 | 2792 |
| *Paracalanus Quasimodo* (Org $m^{-3}$) | Min. | 80 | 400 | 0 | 156 | 17 | 140 | 36 | 25 |
| | Max. | 2010 | 7400 | 3086 | 20,247 | 3434 | 31,403 | 8321 | 9286 |
| | Average | 673 | 2336 | 802 | 6027 | 650 | 5663 | 926 | 2972 |
| *Temora Turbinata* (Org $m^{-3}$) | Min. | 7 | 0 | 31 | 0 | 18 | 80 | 0 | 0 |
| | Max. | 3016 | 14,368 | 2909 | 18,360 | 2798 | 7499 | 1743 | 2381 |
| | Average | 841 | 2254 | 1008 | 3003 | 672 | 2535 | 664 | 973 |
| Hydrozoan Polyp (Org $m^{-3}$) | Min. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Max. | 107 | 144 | 39 | 90 | 159 | 2716 | 99 | 1330 |
| | Average | 12 | 18 | 5 | 7 | 22 | 579 | 10 | 131 |
| *Arbocuspis ramosa* (Zooids $m^{-3}$) | Min. | – | 0 | 0 | 0 | – | 0 | – | 0 |
| | Max. | – | 390 | 23 | 26 | – | 21,980 | – | 4444 |
| | Average | – | 60 | 2 | 2 | – | 2984 | – | 385 |
| *Biddulphia biddulphiana* (Cell. $m^{-3}$) | Min. | – | 0 | – | 0 | – | 0 | – | 0 |
| | Max. | – | 1047 | – | 745 | – | 129,583 | – | 1524 |
| | Average | – | 87 | – | 79 | – | 17,864 | – | 153 |
| *Amphitetras antediluviana* (Cell. $m^{-3}$) | Min. | – | 0 | – | 0 | – | 0 | 0 | 0 |
| | Max. | – | 2732 | – | 2534 | – | 54,007 | 96 | 4299 |
| | Average | – | 235 | – | 211 | – | 8284 | 8 | 696 |

currents. Similarly, Schettini et al. (1998) highlights the association of the Itajaí-açu River (located north of the study area) with the increase in chlorophyll in the coastal region adjacent to its mouth. In the background, DO, ammonia, turbidity, and SPM explain the occurrence of organisms belonging to the *Arribadas*, indicating a process of accumulation and decomposition of organic matter as well as a high load of suspended particulate matter from the sediment by tidal action, as highlighted by Siegle et al. (2009).

For zooplanktonic organisms, only polyps followed both a benthic and planktonic pattern, unlike copepods that showed a possible succession of seasonal dominance.

The beach nourishment project on Central Beach in Balneário Camboriú provided a unique opportunity to assess the *Arribadas'* evolution, a project that interrupted a historical evolution followed since 2018, and an opportunity to follow a secondary succession of events (Margalef, 1977). The strandings of organisms were interrupted between August and November 2021, and resumed at the end of December, almost a month after the beach nourishment project was completed. The return of strandings was characterized by low biomass, a clear succession of groups of organisms, and without the presence of macroalgae. In the summer of 2022, the shape of the colonies of the bryozoan *Arbocuspis* tended toward erect tufts, and formed balls similar to those observed in Figs. 3 and 4 in December 2021. It is believed that the interruption of organism strandings on the beach during and immediately after the beach nourishment is due to the beach profile's instability, which affected both the growth location of the organisms on the bottom, the wave action's stability, and the closure depth.

There are few studies that explain in detail the morphological variations in the growth of bryozoan colonies, and how erect growth with angles of arrangement between zooids can increase the efficiency of water circulation around the colony, for the filtration and feeding process (Mckinney and Mcghee, 2003). Other reasons for this morphological diversity, which can vary from erect, laminar, or foliate forms and even tufts, may be associated with lack of space or adaptation to specific substrates (e.g., unconsolidated substrates such as sand) and even local dynamics (turbulence). It is believed that these morphological advantages may be challenged in extreme environments such as the surf zone and shoreline, due to uncontrolled population growth and interference from high biomass of chain-forming benthic microalgae. These factors in the colony formation process may possibly result in the formation of the

**Table 2**
Maximum, minimum, and average values of the abiotic and biotic parameters of the bay water between the collection points (AR01, AR02, AR03 and AR04), grouped by collection months for each season: summers of 2022 and 2023 (Su), autumn (A), winter (W), and spring (Sp), on the surface and bottom.

| | | Surface | | | | | Bottom | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2022 | | | | 2023 | 2022 | | | | 2023 |
| | | Su | A | W | Sp | Su | Su | A | W | Sp | Su |
| Temperature (° C) | Min. | 26.12 | 19.58 | 17.67 | 21.56 | 24.00 | 24.20 | 20.00 | 17.46 | 20.94 | 23.42 |
| | Max. | 28.59 | 24.20 | 19.15 | 25.26 | 28.36 | 24.86 | 24.12 | 18.78 | 23.68 | 24.88 |
| | Average | 27.71 | 22.60 | 18.31 | 23.51 | 26.14 | 24.58 | 22.50 | 17.95 | 22.35 | 24.20 |
| Salinity | Min. | 33.51 | 32.37 | 30.00 | 30.45 | 27.03 | 34.33 | 33.97 | 31.43 | 31.80 | 33.31 |
| | Max. | 33.98 | 34.11 | 32.59 | 32.95 | 33.24 | 34.47 | 34.73 | 32.80 | 33.18 | 33.80 |
| | Average | 33.67 | 33.41 | 31.26 | 31.53 | 30.37 | 34.41 | 34.30 | 32.02 | 32.57 | 33.54 |
| DO (mg $L^{-1}$) | Min. | 4.73 | 5.40 | 5.89 | 5.77 | 6.88 | 4.27 | 4.69 | 5.97 | 4.45 | 3.71 |
| | Max. | 6.62 | 8.51 | 8.33 | 8.07 | 9.84 | 5.61 | 6.79 | 7.60 | 7.74 | 7.46 |
| | Average | 5.30 | 6.87 | 7.44 | 7.38 | 8.08 | 5.18 | 5.70 | 6.68 | 6.58 | 5.00 |
| Turbidity (NTU) | Min. | 3.00 | 0.20 | 0.40 | 0.20 | 0.80 | 11.00 | 2.20 | 1.20 | 2.00 | 1.20 |
| | Max. | 6.20 | 6.05 | 18.00 | 8.50 | 12.80 | 23.00 | 15.85 | 19.80 | 13.30 | 12.80 |
| | Average | 5.15 | 2.89 | 4.00 | 2.39 | 3.86 | 15.80 | 7.24 | 9.91 | 5.44 | 8.68 |
| $NH_4$ (mg $L^{-1}$) | Min. | 0.06 | 0.10 | 0.11 | 0.08 | 0.09 | 0.05 | 0.07 | 0.04 | 0.06 | 0.21 |
| | Max. | 0.37 | 1.02 | 0.69 | 0.42 | 0.96 | 0.47 | 0.70 | 2.38 | 0.58 | 0.83 |
| | Average | 0.15 | 0.31 | 0.41 | 0.21 | 0.51 | 0.17 | 0.24 | 0.31 | 0.18 | 0.36 |
| SPM (mg $L^{-1}$) | Min. | 20.93 | 12.40 | 8.20 | 8.00 | 21.80 | 18.34 | 14.00 | 9.60 | 8.53 | 24.80 |
| | Max. | 34.80 | 15.80 | 46.21 | 87.60 | 39.20 | 31.32 | 28.90 | 52.50 | 29.40 | 75.60 |
| | Average | 25.32 | 13.98 | 19.90 | 24.19 | 30.90 | 23.04 | 19.88 | 27.75 | 19.74 | 39.83 |
| Chlorophyll (μg $L^{-1}$) | Min. | 6.33 | 2.64 | 0.87 | 1.75 | 5.16 | 2.85 | 1.58 | 0.94 | 0.68 | 2.48 |
| | Max. | 13.40 | 17.04 | 12.65 | 25.23 | 28.03 | 7.84 | 6.15 | 6.70 | 13.36 | 13.35 |
| | Average | 9.03 | 6.70 | 4.53 | 8.02 | 13.71 | 5.12 | 3.91 | 3.00 | 6.19 | 7.61 |
| Phytoplankton (Cel $L^{-1} \times 10^3$) | Min. | 6845 | 761 | 124 | 394 | 9070 | 2529 | 357 | 11 | 223 | 1221 |
| | Max. | 27,548 | 9408 | 8239 | 9392 | 35,604 | 12,236 | 2056 | 7711 | 14,438 | 28,074 |
| | Average | 20,879 | 2699 | 2786 | 4072 | 19,543 | 5401 | 1068 | 1886 | 2895 | 11,424 |
| *Acartia Lilljeborgii* (Org $m^{-3}$) | Min. | 309 | 0 | 0 | 0 | 0 | 16,429 | 88 | 0 | 0 | 449 |
| | Max. | 2345 | 3858 | 237 | 252 | 1134 | 74,000 | 16,370 | 3578 | 691 | 7824 |
| | Average | 1245 | 1234 | 58 | 83 | 271 | 40,856 | 2438 | 1007 | 223 | 3345 |
| *Paracalanus Quasimodo* (Org $m^{-3}$) | Min. | 478 | 17 | 60 | 0 | 39 | 1958 | 556 | 140 | 25 | 561 |
| | Max. | 1220 | 8321 | 3086 | 405 | 794 | 14,000 | 9613 | 31,403 | 3880 | 2370 |
| | Average | 862 | 1874 | 595 | 150 | 215 | 8394 | 4514 | 7569 | 1151 | 1448 |
| *Temora Turbinata* (Org $m^{-3}$) | Min. | 43 | 83 | 0 | 22 | 7 | 0 | 27 | 80 | 64 | 0 |
| | Max. | 378 | 1421 | 3016 | 2909 | 169 | 2381 | 5400 | 18,360 | 7375 | 313 |
| | Average | 228 | 697 | 1198 | 1157 | 86 | 904 | 1752 | 4387 | 2260 | 97 |
| Hydrozoan Polyp (Org $m^{-3}$) | Min. | – | 0 | – | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Max. | – | 16 | – | 61 | 159 | 417 | 2402 | 400 | 541 | 2716 |
| | Average | – | 1 | – | 13 | 50 | 104 | 207 | 37 | 74 | 573 |
| *Arbocuspis ramosa* (Zooids $m^{-3}$) | Min. | – | – | – | – | – | – | 0 | 0 | – | 0 |
| | Max. | – | – | – | – | – | – | 21,980 | 390 | – | 13,267 |
| | Average | – | – | – | – | – | – | 2277 | 35 | – | 1680 |
| *Biddulphia biddulphiana* (Cell. $m^{-3}$) | Min. | – | – | – | – | – | 0 | 0 | 0 | 0 | 0 |
| | Max. | – | – | – | – | – | 129,583 | 28,822 | 9299 | 3517 | 43,143 |
| | Average | – | – | – | – | – | 32,396 | 2402 | 775 | 595 | 5418 |
| *Amphitetras antediluviana* (Cell. $m^{-3}$) | Min. | – | 0 | – | – | 0 | 0 | 0 | 0 | 0 | 0 |
| | Max. | – | 96 | – | – | 23 | 21,667 | 7205 | 14,098 | 2732 | 54,007 |
| | Average | – | 8 | – | – | 3 | 5417 | 638 | 1533 | 541 | 7046 |

bryozoan “carpet” observed in the study area.

In addition to morphology, the *Arribadas’* coloration, as presented by Tocci et al. (2022), is mainly controlled by the biomass of bryozoans and not by the biomass of benthic microalgae, as previously highlighted. The results of the analyses of the organisms in the surf zone confirm that the presence of benthic microalgae is constant, but the dark strandings observed on the beach’s sand strip are the result of the reduction in the biomass of bryozoans. The change in the biomass of bryozoans is reflected in the bottom, as a result of seasonality, temporal succession, and the accumulation of organic matter (PCA analysis), but not of the “mixing” water between the surface and bottom observed in the surf zone.

The spatial variation observed in the bottom layer for bryozoans confirms that the growth and accumulation site of *Arribadas* organisms possibly occurs at the closure depth. Likewise, the occurrence of these organisms along the bathymetric profile also indicate that the biomass occurring in the surf zone is not beyond the bay’s 5 m isobath. The closure depth, located behind the beach break line, is a difficult place to access and sample, but a previous survey carried out by scuba diving in 2020 indicated the presence of high densities of organisms belonging to *Arribadas* (Univali/Semam, 2020). In addition, the erect growth form of bryozoans indicates growth without substrate (tufts), and all biomass (bryozoans and microalgae) can be considered to be demersal and episamic (associated with the sandy bottom). In fact, microalgae use bryozoans as substrate, but it can be stated that this development trigger is fed back to serve as substrate when there is a reduction in bryozoan biomass in the cold months, confirmed by the darker coloration of the *Arribadas*.

The physical and chemical parameters of the bay’s surface water indicate a greater influence of the Camboriú River (south of the bay), with an average flow rate of 3.1 $m^3 s^{-1}$ (Siegle, 1999). Meanwhile, the Marambaia Channel (north of the bay) has a flow rate of $<0.3$ $m^3 s^{-1}$. The differences observed between the bay’s northern and southern regions, mainly associated with the bottom water, reveal that in the northern portion of the bay, the dynamics are greater due to the resuspension of the bottom sediment, identified by the greater turbidity and SPM. The northern region is known to receive southerly waves directly, in addition to refraction of northeasterly waves due to the northern promontory. Variations in the mode height of between 1.25 and 1.75 m, and above 1.5 m in the autumn and winter months have also been

| | Water column* | | Spatial variation** | | | | Temporal variation** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | South | | North | | 2022 | | | | 2023 |
| | Surface | Bottom | 1 | 2 | 3 | 4 | Su | A | W | Sp | Su |
| Temperature | | | | | | | | | | | |
| DO | 0.00 | | | | | | | | | | |
| Phtoplankton | 0.02 | | | | | | | | | | |
| Cla-a | 0.01 | | | | | 0.01 | | | | | |
| NH4 | 0.02 | | | | | | | | | | 0.03 |
| | | | | | | | | | | | |
| Salinity | | 0.00 | | | | | | | | | |
| SPM | | | | | | 0.01 | | | | | |
| Turbidity | | 0.00 | | | | 0.00 | 0.05 | | | | |
| Arbocuspis | | 0.00 | | | | | | | | | |
| Biddulphia | | 0.00 | | | | | | | | | |
| Amphitetras | | 0.00 | | | | | | | | | |
| Acartia | | 0.02 | | | | | | | | | |
| Paracalanus | | 0.00 | | | | | | | | | |
| Temora | | 0.00 | | | | | | | | | |
| Polyp | | 0.03 | | | | | | | | | |

Probability (*p*) *t-Test, **ANOVA

**Fig. 9.** Compilation of the main results of Tables 1 and 2. Stained areas indicate higher values of the variables. The values highlighted in the areas indicate statistical differences (t-test and ANOVA) of the observed trends. Comparisons of the variables between surface and bottom, higher values in spatial terms (south for AR01 and AR02 and north for AR03 and AR04) and higher values in terms of temporal variations with the classification in times of the sampled year. Total of 168 water and plankton samples.

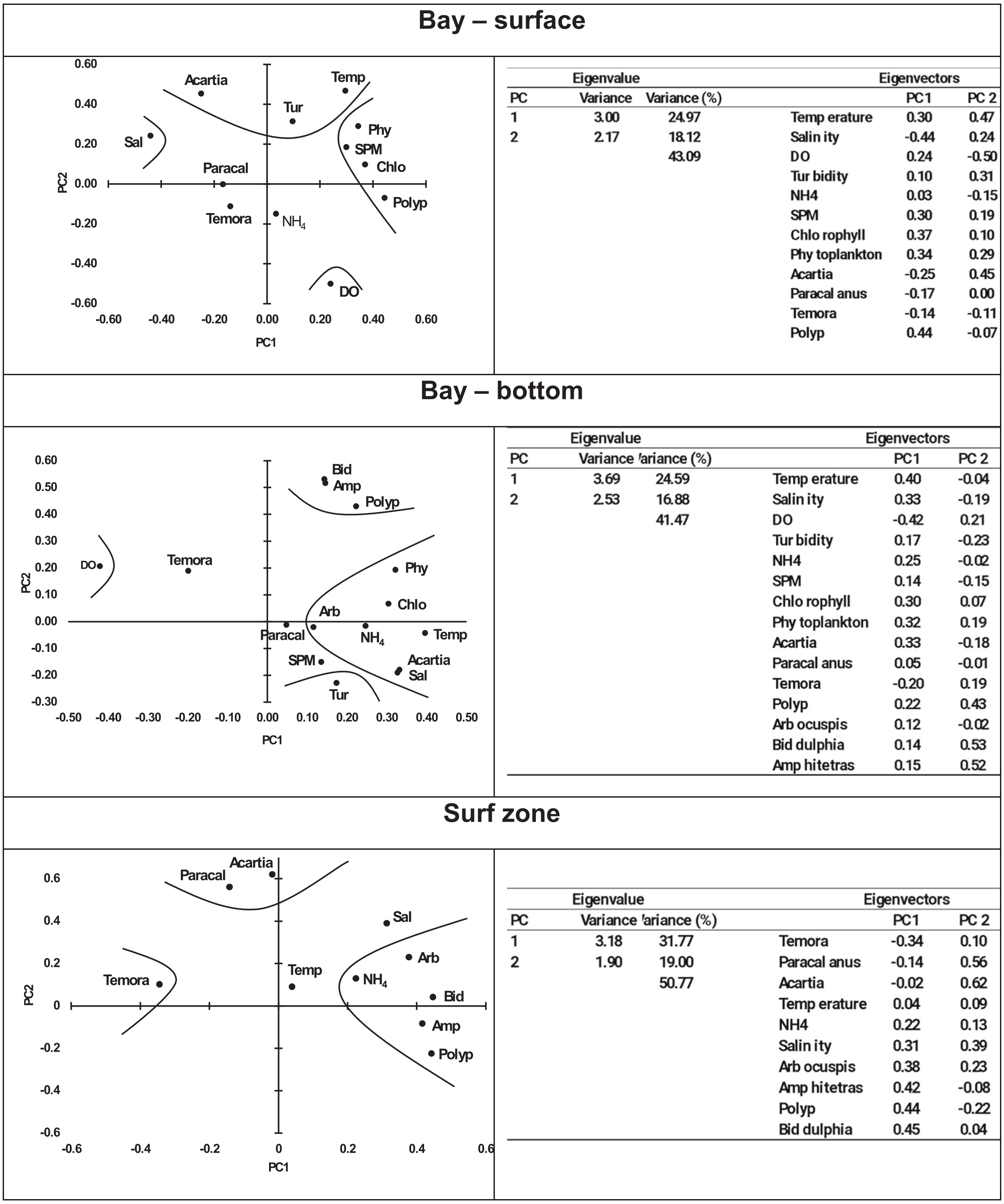
observed in this region (Menezes, 2008). The Camboriú River is known to export fine sediments to the bay (Siegle, 1999), and the resuspension of river sediment and residual nutrients is carried out by the spring tide (Pereira Filho et al., 2001, 2002; Siegle et al., 2009). Pezzuto et al. (2006) highlighted that fine sediment originating from a landfill carried out in 2002 at the mouth of the Camboriú River was deposited in the northern region of the bay, confirming the possibility of displacement to this region where the *Arribadas* organisms are concentrated and develop. Studies on the hydrodynamics of the environment are still under development, but it is believed that tidal and wave currents have a great influence on this transport.

A preliminary analysis of the stomach contents of bryozoans found in the samples from the bay and surf zone (data not shown) confirms the use of SPM and phytoplankton as a food source. The limitation of the zooid opening through which the tentacles of bryozoans are extroverted is 60 to 120 μm, which limits the use of benthic diatoms as food (ranging from 80 to 150 μm on the major axis) (Rörig et al., 2017). From the contents examined, the dominance of aggregates of organic material and 2 μm bacteria stands out. However, planktonic diatoms such as *Skeletonema* sp. (25 μm), *Pseudonitsczhia* spp. (2.5 × 90 μm), *Chaetoceros* sp. (20 μm), benthic diatoms (Naviculaceae family of 10 × 25 μm and Dinoflagellates of 30 μm), and unidentified centric diatoms (10 μm), as well as planktonic ciliates (7.5 μm) and pedunculates, are also present. This analysis highlights the importance of SPM as well as its resuspension from the bottom sediment as a food source for bryozoans.

Benthic microalgae and phytoplankton behave differently. Phytoplankton follow seasonal patterns of temperature (and light) on the surface, serving as food for bryozoans and zooplankton (*Acartia*). Nutrient input is continuous from the Camboriú River, but tends to increase in the summer due to the increase in the floating population. This does not always result in an increase in nitrogen concentrations in the bay due to their high consumption, which is reflected in the increase in the biomass of primary producers and the mixing of the river input with the water from the bay. It is important to remember that the Camboriú River receives effluent from the domestic sewage treatment plant in Balneário Camboriú. In addition, it also receives surface runoff from the city of Camboriú, which does not have a collective collection and treatment system for domestic sewage.

The benthic microalgae *Biddulphia* and *Amphitetras* are related to the turbidity of the bay's bottom water, being controlled by this parameter despite benefiting from the ammonia nitrogen at the bottom. This nitrogen can originate both from the decomposition of organic matter in the bottom sediment, and from the excretion of bryozoans. The influence of turbidity on the luminosity of the benthic environment is not restricted to light intensity, but can influence the spectrum of incident light, filtered by the existing SPM, and the response of the microalgae according to the dominant pigments (Tait et al., 2014). The substrate offered by the bryozoans for the growth of benthic microalgae is reduced from the summer to the colder months, and the growth of the microalgae itself begins to support the community. However, the replacement between the two species of benthic microalgae appears to be a dynamic process, with *Biddulphia* initially dominating and then being replaced by *Amphitetras*. Rörig et al. (2017) observed the greatest abundance of *Amphitetras* in 2011 and 2012, while Tocci et al. (2022) highlighted the dominance of *Biddulphia* in the most advanced phase of the migratory process in 2019 and 2020, with the presence of the macroalgae *Briopsis* recorded during this period. In any case, the replacement between microalgae is not very clear. The data presented in this work suggests that temperature, and consequently luminosity, are influencing factors in the dynamics of the species. This may be altered by the effect of variation in the biomass of bryozoans, the effect of shading and transparency, as well as seasonal and interannual changes in the water of the bay, since both species have the same growth rate of 0.5 (UNIVALI/SEMAM, 2020) under laboratory conditions.

These results, for bryozoans and benthic microalgae, and the availability of nutrients in the system, confirm the importance of turbulence in modulating the trophic state of the system (Alcaraz et al., 2002). In comparative terms, Guanabara Bay, known as a eutrophic system on the




**Bay – surface**

| PC | Eigenvalue: Variance | Variance (%) |
|---|---|---|
| 1 | 3.00 | 24.97 |
| 2 | 2.17 | 18.12 |
| | | 43.09 |

| Eigenvectors | PC1 | PC 2 |
|---|---|---|
| Temperature | 0.30 | 0.47 |
| Salinity | -0.44 | 0.24 |
| DO | 0.24 | -0.50 |
| Turbidity | 0.10 | 0.31 |
| NH4 | 0.03 | -0.15 |
| SPM | 0.30 | 0.19 |
| Chlorophyll | 0.37 | 0.10 |
| Phytoplankton | 0.34 | 0.29 |
| Acartia | -0.25 | 0.45 |
| Paracalanus | -0.17 | 0.00 |
| Temora | -0.14 | -0.11 |
| Polyp | 0.44 | -0.07 |

**Bay – bottom**

| PC | Eigenvalue: Variance | 'ariance (%) |
|---|---|---|
| 1 | 3.69 | 24.59 |
| 2 | 2.53 | 16.88 |
| | | 41.47 |

| Eigenvectors | PC1 | PC 2 |
|---|---|---|
| Temperature | 0.40 | -0.04 |
| Salinity | 0.33 | -0.19 |
| DO | -0.42 | 0.21 |
| Turbidity | 0.17 | -0.23 |
| NH4 | 0.25 | -0.02 |
| SPM | 0.14 | -0.15 |
| Chlorophyll | 0.30 | 0.07 |
| Phytoplankton | 0.32 | 0.19 |
| Acartia | 0.33 | -0.18 |
| Paracalanus | 0.05 | -0.01 |
| Temora | -0.20 | 0.19 |
| Polyp | 0.22 | 0.43 |
| Arbocuspis | 0.12 | -0.02 |
| Biddulphia | 0.14 | 0.53 |
| Amphitetras | 0.15 | 0.52 |

**Surf zone**

| PC | Eigenvalue: Variance | 'ariance (%) |
|---|---|---|
| 1 | 3.18 | 31.77 |
| 2 | 1.90 | 19.00 |
| | | 50.77 |

| Eigenvectors | PC1 | PC 2 |
|---|---|---|
| Temora | -0.34 | 0.10 |
| Paracalanus | -0.14 | 0.56 |
| Acartia | -0.02 | 0.62 |
| Temperature | 0.04 | 0.09 |
| NH4 | 0.22 | 0.13 |
| Salinity | 0.31 | 0.39 |
| Arbocuspis | 0.38 | 0.23 |
| Amphitetras | 0.42 | -0.08 |
| Polyp | 0.44 | -0.22 |
| Biddulphia | 0.45 | 0.04 |

**Fig. 10.** Principal Component Analysis (PCA) of the target species and biotic and abiotic variables, for the entire sampling period, separated for the surface water and bottom water of the bay and surf zone. The variables used were Temperature (Temp), Salinity (Sal), Dissolved Oxygen (DO), Turbidity (Tur), Ammonia (NH4), Suspended Particulate Matter (SPM), Chlorophyll (Chlo), Phytoplankton (Phy), *Acartia*, *Paracalanus* (Paracal), *Temora*, Polyp, *Arbocuspis* (Arb), *Biddulphia* (Bid) and *Amphitetras* (Amp).

Brazilian coast, presents ammonia (up to 8.09 mg $L^{-1}$) and chlorophyll (0.5 mg $L^{-1}$) levels higher than those observed in this study (Dias da Cruz, 2016). For Santos Bay, another eutrophic environment on the southeastern Brazilian coast, Braga et al. (2000) observed ammonia values of up to 0.85 mg $L^{-1}$, lower than those observed in this study. The same was found for the Lagoa dos Patos estuary with high N-$NH_4^+$ values, ranging from 0.5 to 0.6 mg $L^{-1}$ (Niencheski et al., 1999; Lemos et al., 2022).

According to Pereira Filho and Rörig (2016) in a study in the Itajaí-açu River estuary, the ammonia concentration was within the range observed in this study (0.02 to 1.4 mg $L^{-1}$) and considered the environment dominated by processes of organic matter mineralization and nitrification. However, the authors emphasize that nitrogen cycling is dependent on several processes that result in its consumption or production, in addition to the interconversion of the various forms of nitrogen in biogeochemical processes. The assimilation of phytoplankton and heterotrophic bacteria, and bacterial nitrification, occur simultaneously and dynamically, which limits the understanding of the system based solely on the concentrations of nitrogen compounds. This assimilation of nutrients by primary producers may explain the low concentrations of ammoniacal nitrogen observed in the bay in relation to the values of up to 2.36 mg $L^{-1}$ of N-$NH_4^+$ obtained by Pereira Filho et al., 2001, 2002 in the estuarine region of the Camboriú River.

In comparative terms, which can be used to confirm the eutrophication conditions of the bay, it is worth noting that the phytoplankton density values observed in this study were above $10^6$ cells per liter. These are similar to Guanabara Bay (RJ), but higher than Babitonga Bay in the north of the study area, whose values oscillate between $10^4$ and $10^5$ cells per liter (CENPES/PDEDS/AMA, 2013; Rörig et al., 1998). For zooplankton, high densities above $5 \times 10^3$ organisms per $m^3$ were frequently observed and higher than what is normally expected for coastal regions close to the study area (Resgalla Jr., 2011). Comparatively, the development of the plankton community in the Balneário Camboriú bay indicates a trophic chain and biological processes accelerated and stimulated by the entry of nutrients into the system, and by local dynamics.

For phytoplankton, the dominance of *Seletonema costatum* is already indicative of eutrophication (Gao et al., 2018). For copepods, no pattern of associated behavior was observed among the species responsible for the high densities found. However, a seasonal succession is suggested, starting with *Acartia*, moving on to *Paracalanus* and *Temora*. Only *Acartia* shows a relationship with the temperature and seasonality of the ambient water and is characterized by the influence of Tropical and Subtropical Waters typical of the continental shelf (warm continental shelf water) (Resgalla Jr., 2011). In zooplankton, polyps or representatives of the genus *Clytia* could be used as a tracer of the community of organisms mass accumulated on the bottom, and near the surf zone and closure depth. These free polyps indicate that they originate from the detachment of the mass of bryozoans and benthic microalgae, showing evolution with the arrivals and with greater biomass in the summer of 2023.

In contrast to the open ocean, allochthonous matter introduced by rivers, among other sources, is efficiently recycled in coastal environments such as bays. It is influenced by the energy of tides, currents, and waves, allowing coupling between the pelagic and, mainly, benthic compartments (Pellegrini et al., 2023). The high levels of primary production often observed in these systems are directly associated with the large supply of dissolved inorganic nutrients, both of natural and anthropogenic origin (Knoppers and Kjerfve, 1999).

According to Menezes (2008), the resuspension and transport of sediments in the Balneário Camboriú Bay are a result of the action of tidal currents and waves. These characteristics of Central Beach may explain the development of the organisms that make up the strandings or biomass strandings observed on the beach. The biogeochemical processes of the organic matter originating from the Camboriú River, which make nutrients available to primary producers (planktonic and benthic), could also be used by bryozoans in the process of degradation. The study carried out by Teixeira et al. (2022) of a tidal balance in the Camboriú River, for the same period as this study, estimated an export of approximately 980 kg of dissolved inorganic nitrogen (DIN) in two tidal cycles (25 h) into the Balneário Camboriú Bay.

The beach nourishment work must have buried the fine sediments in the submerged portion of the back line of the surf zone, interrupting the flow of organic matter and nutrients to the organisms of the *Arribadas*. However, the constant influx of fine sediments from the Camboriú River estuary allowed the return of the growth and accumulation of the *Arribadas* organisms in a short period of time (one to two months) for the new occurrences on Central Beach. On a temporal scale, the introduction of fine sediments with a high load of organic matter, linked to local urban development, is expected to lead to an increase in the biomass of the *Arribadas* observed. The increase in the biomass of bryozoans and microalgae may favor a feedback on the availability of substrate for macroalgae, as was observed between 2019 and 2021.

It is considered that the organisms of the *Arribadas* are classified as opportunists after the deposition of inadequate sediments in 2002, as presented by Pezzuto et al. (2006). The organisms of the *Arribadas* possibly benefited from the exclusion of other filter-feeding suspension feeders (e.g. bivalvia) due to the granulometric change of the bay, but not by their emergence. As demonstrated by Tocci et al. (2022), bryozoans and microalgae have always been present in the bay, and even after this process of inadequate sediment filling in the south of the study area and the acute mortality of bivalves, the recovery of suspension feeder populations in the study area was observed (Pezzuto et al., 2007). This demonstrates that the contribution of fines by the Camboriú River is a characteristic of the environment. However, monitoring of this SPM load, as well as the sediment and benthic community of the bay, has not been scientifically evaluated since then.

## 5. Conclusions

According to the results obtained, the organisms that make up the strandings of biological material (*Arribadas*) on Central Beach in Balneário Camboriú have a constant composition of bryozoans, benthic microalgae, and hydrozoan polyps. The proportion of bryozoans is the determining factor for the coloration of the *Arribadas*.

In a process of occupation of the environment, specifically in secondary succession, bryozoans predominate in the summer while benthic microalgae predominate in the cold months, with hydrozoans having no seasonality. Spatially, the cluster of organisms accumulates and grows near the bottom of the bay, and between the surf zone and the 5 m isobath, possibly at the closure depth, and are thrown onto the beach by the action of waves and tidal currents. This hypothesis, based on the presence and absence of *Arribadas* organisms at the bottom of the bay, needs to be confirmed by hydrodynamic studies.

The northern region of the bay is where the greatest accumulation and growth of organisms from the *Arribadas* occurs, and is the region with the greatest wave action and deposition of fines originating from the Camboriú River. Nutrients originating from the Camboriú River (mainly ammoniacal nitrogen) on the surface (in the south) and organic matter from the sediments (in the north) stimulate primary production and feeding of bryozoans, respectively. The accumulation in the north suggests that it is the effect of circulation in the bay, so that the nutrients that arrive mainly through the Camboriú River favor the increase in the biomass of primary producers in the water column throughout the mixing. Part of this biomass is transferred to the bottom where it favors the growth of bryozoans, and is concentrated in the northern region, where the *Arribadas* are most evident.

The supply of nutrients and organic matter from the Camboriú River stimulates primary producers both in the water column and the development of zooplankton and suspension feeders on the bottom, leading to the development of a well-developed and eutrophic bentho-pelagic coupling system in the bay. In this way, plankton from the bay can be used as an index of eutrophication. Although this process is natural, anthropogenic input from urban runoff and mainly from sewage discharge presents a high chance of exacerbating the biomass of stranded organisms on the beaches.

Due to the speed of biogeochemical processes involving nutrients, and planktonic and benthic organisms, it is believed that the bay plays an important role as a depositional area and in the cycling of organic matter. The harmonization between the local ecology and the Anthropocene use of the river banks and the river itself as a receiver of domestic effluents must be reviewed.

## CRediT authorship contribution statement

**Charrid Resgalla:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Bianca R.C. Tocci:** Writing – original draft, Methodology, Investigation, Formal analysis. **Márcio S. Tamanaha:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Jurandir Pereira Filho:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Mauro M. Andrade:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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## Declaration of competing interest

The authors declare that the manuscript entitled " Accumulation and stranding process of bryozoans and benthic microalgae on a beach in southern Brazil: Eutrophication and secondary succession case study" submitted to the Science of the Total Environment is part of a work in progress and the subject of a research project that was financed by the Santa Catarina State Research Support Foundation (FAPESC) to understand the process of accumulation of organisms on its central beach.

The present manuscript does not present any influence of its conclusions on the part of the aforementioned government, as it did not present any impediment in its dissemination or limitation for its publication.

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## Data availability

Data will be made available on request.

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