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ECOSYSTEMS

# Zooplankton variability and possible oceanographic anomalies from 1996 to 2009 on the south coast of Brazil

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**Abstract:** The analysis of 14 years of sampling data on the zooplankton community in southern Brazil showed a tendency toward increased density and reduced species richness. This behavior could be a response to a prolonged period of negative sea surface temperature (SST) anomalies in the Pacific Ocean and the ENSO phenomenon. The persistence of the La Niña phenomenon between 2001 and 2008 was associated with a higher incidence of stress from southwest winds and a greater reach of the front of the La Plata River plume, with possible responses being lower temperatures in the summer/autumn and lower salinities in the winter/spring in the study area. Under these conditions, one response in the zooplankton community was larger copepod domains. This group was responsible for specific changes in the community, with an increase in the population of *Acartia tonsa* while populations of species with more thermophilic characteristics showed a decrease. It cannot be disregarded, however, that possible interactions between different abiotic and biotic forces acting in the environment may have influenced the structure of the community. It remains unknown whether a new steady state has been established in the environment or whether there has been a return to initial conditions.

**Key words:** Decrease in regional salinity, front of the La Plata River plume, regional cooling, zooplanktonic alteration.

## INTRODUCTION

Long-term studies on zooplankton are considered highly relevant to assess the variability of the marine ecosystem in response to climate change that is in process or already established (Escribano et al. 2012). The response capacity of the community is mainly due to its composition, which consists of a number of predominantly short-lived taxa responding quickly to environmental changes. This is associated with the high sensitivity of the populations to variations in oceanographic conditions, involving changes in temperature, salinity and the quantity and quality of food, among several other factors.

Zooplankton responses to long-term changes can be seen through alterations in species composition and diversity, changes in biomass and abundance, size spectra and phenology (Richardson 2007). However, these parameters may differ in terms of sampling resolution, which reflects the scales of oceanographic and climatic processes (Mackas & Beaugrand 2010).

In general, long-term studies require investments and government interest, with the expectation that the data collected and accumulated can be used in future studies to identify and highlight responses to environmental changes that had not been predicted. In this regard, it can be noted that there is considerable research on zooplankton in temperate systems in the northern hemisphere but a scarcity of knowledge of the tropical and southern hemisphere systems (Richardson 2007).

In Brazil, there are few long-term studies available on zooplankton variability. Some examples are the work of Magris et al. (2011) on the northeast coast, Dias & Bonecker (2008) and Marcolin et al. (2015) on the southeast coast and Teixeira-Amaral et al. (2017) on the Lagoa dos Patos estuary in the extreme south of Brazil. Interestingly, these studies involved a maximum period of 5 years of sampling, which limits speculation about climate change or events on a larger scale. In addition, the disclosure of the results is dependent on publications that report climatic events during the study period, which, in turn, has induced a lack of analysis of time series of greater amplitude.

In this study, the biennial variations in the zooplankton community along the south coast of Brazil were analyzed considering 14 years of data. This was only possible after a period in which the conditions of the physical structure had been relatively well studied. Thus, the events observed during the sample period could be better explained or interpreted. The collection of data on the zooplankton community was initially stimulated by a coastal works project that involved dredging and landfill activities carried out in 1996 in the South Bay region on the margins of the island of Santa Catarina, located in the south of Brazil (Fig. 1). The initial objective of the sampling plan was to diagnose the potential impact of these activities, which

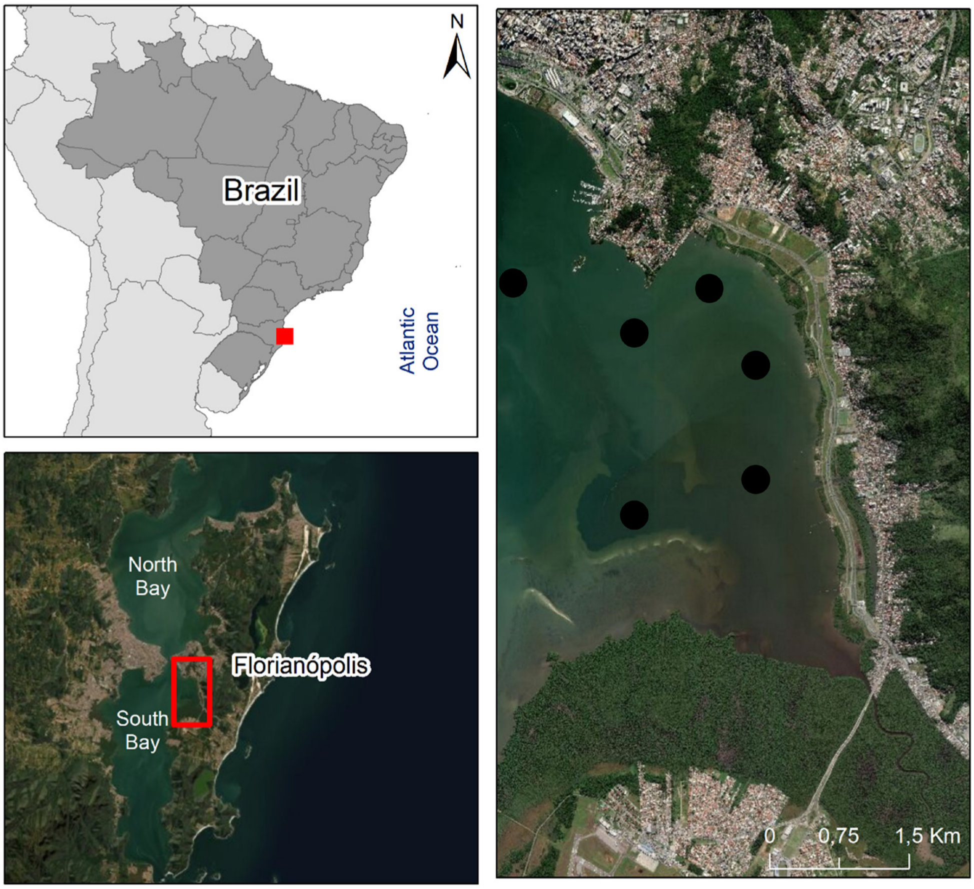


**Figure 1.** Location of the Pirajubaé Coast (sampling area and six sampling points), its location in the South Bay of Santa Catarina Island and the location of Santa Catarina Island on the Brazilian coast.

resulted in a 14-year period of sampling in the environment (from 1996 to 2009). The study area is a transitional coastal environment that comprises several estuarine channels. Its total surface area is 173 km$^2$, with a length of around 28 km and a maximum width of approximately 13 km. The average depth is around 3.30 m and the maximum depth in the central channel is 28 m.

Previous studies involving a shorter sampling period (1996 to 1998) indicated that the zooplankton community is diverse, abundant and with a clear quali-quantitative seasonality. The impacts caused by dredging and landfill activities ranged from physical factors, such as a reduction in the area, to food factors influencing the production of eggs and nauplii of the copepods *Acartia tonsa* and *Acartia lilljeborgi* (Resgalla Jr. 2001). Subsequently, Veado & Resgalla Jr. (2005), using samples collected between 1999 and 2002, observed an exchange of dominance in the environment between the two copepod species *A. tonsa* and *A. lilljeborgi*. This was explained by considering the morphodynamics of the environment, which was altered after dredging and landfill activities. In an analysis of samples obtained up to 2009, the behavior of the zooplankton showed a trend on a larger scale, suggesting the influence of water bodies external to the study area. This may be associated with climate change or the interannual cycles of the phenomenon El Niño – Southern Oscillation (ENSO). In this context, the objective of this study was to explain, by considering external phenomena, the changes observed in the zooplankton community over a 14-year period of sampling.

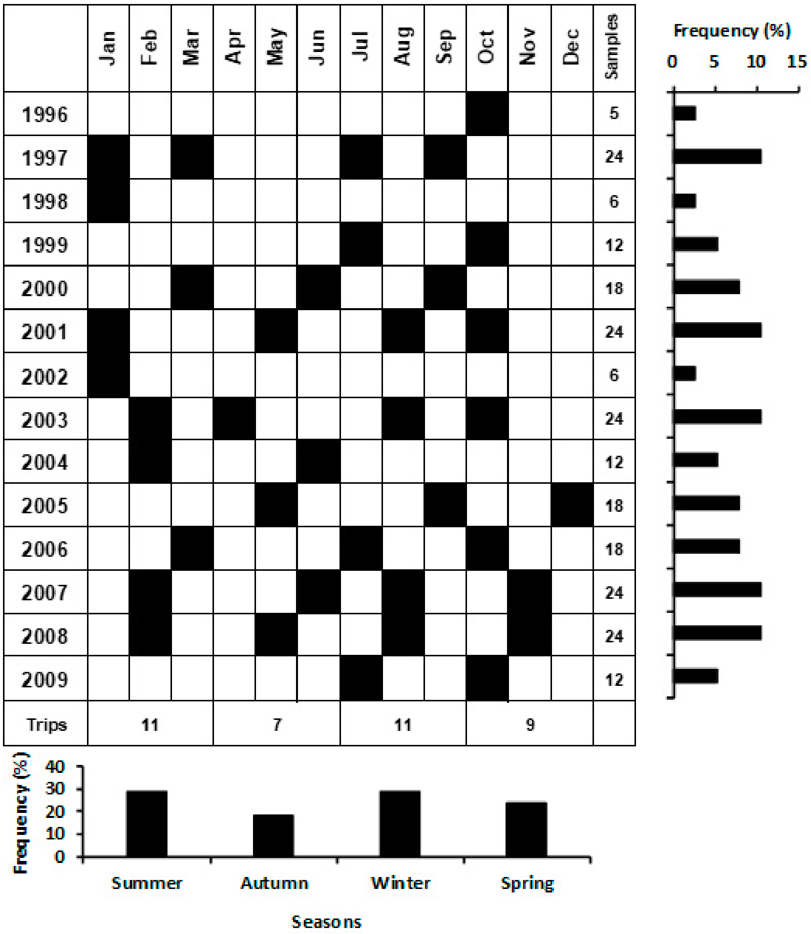
## MATERIALS AND METHODS

In this study, zooplankton samples obtained in 38 field trips and carried out from October 1996 to October 2009, with 227 analyzed samples (Fig. 2). Some sampling gaps were unavoidable due to several issues, mainly in relation to service contract renewals for the continuation of the impact assessment studies originally proposed. The original plan consisted of 6 sampling points distributed along the northeast region of the South Bay, a bay located between the continent and the island of Santa Catarina (27° 37’47.75”S and 48° 32’23.44” W). The sampled area corresponded to 7% (12 km$^2$) of the bay, with depths ranging from 1 to 5 m, and involved a diagnosis of the impacts associated with the dredging and landfill activities that took place in 1996-1997, which determined the sampling points in the region known as Costeira de Pirajubaé (Fig. 1).

Sampling campaigns to obtaining zooplankton samples were carried out with a 220 µm mesh net (type WP-2), 30 cm in diameter, and a flowmeter previously calibrated to measure the filtered water volume. Sampling was carried out obliquely, integrating the bottom to the surface. After collection, the samples were immediately fixed in a 4% formaldehyde solution. Temperature and salinity data were also obtained using an Oriba® multiparameter probe.

In the laboratory, qualitative and quantitative analyses of the smallest possible taxon were performed, using a stereoscope microscope, biological microscope and Bogorov-type chamber. The procedure recommended by Boltovskoy (1981) was applied, consisting of fractioning the samples for counting and identifying sub-samples of at least 10% of the total sample using piston-type sub-samples. For the classification of species, publications by Boltovskoy (1981, 1999) and Montú & Gloeden (1986) were used.

The results of the qualitative and quantitative analyses were expressed as the



|  | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Samples |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1996 |  |  |  |  |  |  |  |  |  | ■ |  |  | 5 |
| 1997 | ■ |  | ■ |  |  |  | ■ |  | ■ |  |  |  | 24 |
| 1998 | ■ |  |  |  |  |  |  |  |  |  |  |  | 6 |
| 1999 |  |  |  |  |  |  | ■ |  |  | ■ |  |  | 12 |
| 2000 |  |  | ■ |  |  | ■ |  |  | ■ |  |  |  | 18 |
| 2001 | ■ |  |  |  | ■ |  |  | ■ |  | ■ |  |  | 24 |
| 2002 | ■ |  |  |  |  |  |  |  |  |  |  |  | 6 |
| 2003 |  | ■ |  | ■ |  |  |  | ■ |  | ■ |  |  | 24 |
| 2004 |  | ■ |  |  |  | ■ |  |  |  |  |  |  | 12 |
| 2005 |  |  |  |  | ■ |  |  |  | ■ |  |  | ■ | 18 |
| 2006 |  |  | ■ |  |  |  | ■ |  |  | ■ |  |  | 18 |
| 2007 |  | ■ |  |  |  | ■ |  | ■ |  |  | ■ |  | 24 |
| 2008 |  | ■ |  |  | ■ |  |  | ■ |  |  | ■ |  | 24 |
| 2009 |  |  |  |  |  |  | ■ |  |  | ■ |  |  | 12 |
| Trips | 11 |  |  | 7 |  |  | 11 |  |  | 9 |  |  |  |

**Figure 2.** Months and years when samples of the zooplankton community were collected and the corresponding seasonal and annual frequencies.

number of organisms per cubic meter of water filtered through the net. The Margalef richness index was calculated according to Omori & Ikeda (1984), where:

$$D=\frac{S-1}{\ln(N)} \qquad (1)$$

where:

D = Richness
S = Number of taxonomic categories
N = Total number of organisms (org/m$^3$)

Zooplankton data from 1996 to 1998 were published by Resgalla Jr. (2001) following a small-scale impact assessment and between 1999 and 2002 data were published by Veado & Resgalla Jr. (2005) following a post-impact assessment. Data obtained from 2003 to 2009, which are unpublished, were also considered in this study, to give a total of 14 years of sampling.

For data analysis, abiotic and biotic information were grouped into two seasonal periods (summer/autumn and winter/spring) and into biennial periods, eliminating gaps in temporal information as well as spatial variability. Comparisons between the two seasonal periods for the same biennium were performed by Student *t*-test ($p<0.05$) while comparisons between bienniums were performed by ANOVA ($p<0.05$) according to Zar (2010).

Due to the lack of water temperature data for the years 2002-2003, the sea surface temperature (SST) data for the study area were obtained from the OceanColor Website of NASA (https://oceancolor.gsfc.nasa.gov/cgi/l3) and the readings were taken using the software SeaDAS (https://seadas.gsfc.nasa.gov/), also from NASA. The time series of the Oceanic and Trans-Oceanic Indices of El Niño that represent the sea surface temperature (SST) anomalies of the Pacific Ocean were obtained from the website of the National Center for Atmospheric Research (https://climatedataguide.ucar.edu/climate-data / nino-sst-indices-nino-12-3-34-4-oni-and-tni). The Oceanic Niño Index (ONI) is obtained from regions 3 and 4 (5°N-5°S, 120°-170°W) and is the index most commonly used to define El Niño and La Niña events. The Trans-Niño Index (TNI) gives the difference in normalized SST anomalies between regions 1, 2 (0°-10°S, 90°W-80°W) and 4 (5°N-5°S, 160°E-150°W). The TNI measures the gradient in SST anomalies between the central and eastern equatorial Pacific and has less variability compared to the ONI (Trenberth & Stepaniak 2001).

## RESULTS

The temperature variation appears to be partly associated with seasonal changes in the environment, with temperature maximums in summer/autumn (average 24.28 °C) and minimums in winter/spring (average 19.84 °C), while a clear seasonal pattern for the variation in salinity was not observed (average of 31.00 in summer/autumn and 31.35 in winter/spring).

Despite the seasonal variation, there was a trend towards lower salinity averages starting from winter/spring of 2004-2005 (F = 5.139, df = 44.35, p = 0.0004404) (average of 32.4 for 1996 to 2003 and average of 29.9 for 2004 to 2009) (Fig. 3b). In the case of temperature, the differences were more marked for the summer/autumn period with lower averages starting from 2000-2001 (F = 75.64, df = 31.62, p = 2.321E-17) (average of 27.14 for 1996 to 1999 and average of 23.14 for 2000 to 2009) (Fig. 3c).

In terms of global influence, for the same period, the anomaly of the El Niño Oceanic Index (ONI for Pacific 3-4 regions) highlighted positive anomalies for the years 1997-1998 and negative anomalies for 1998-1999 as well as for 2007-2008. In contrast, the El Niño Transoceanic Index (TNI for Pacific regions 1, 2 and 4), also used for studies on global changes, indicated, in addition to the positive anomalies in 1997-1998,

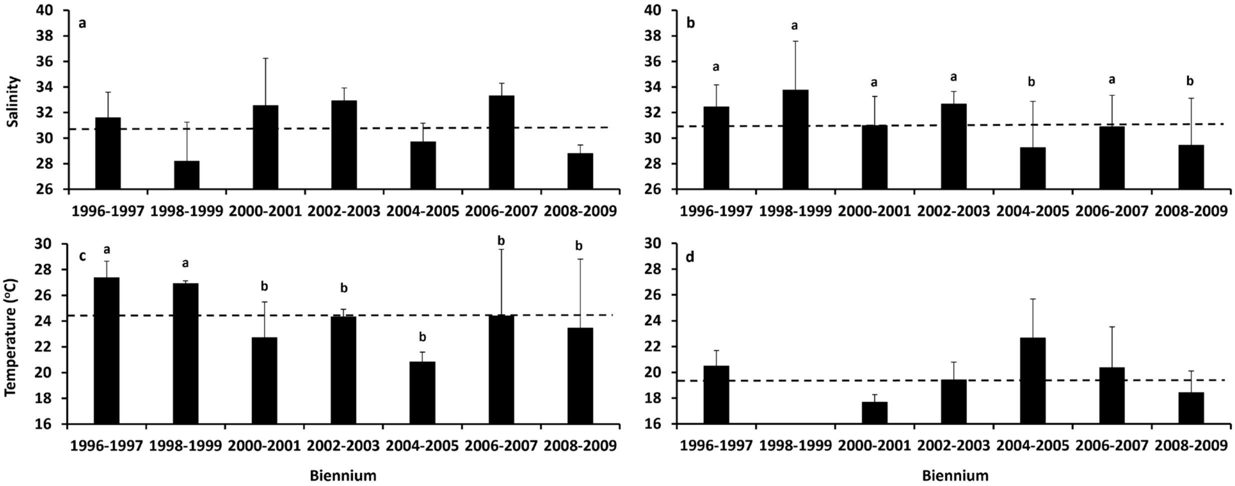


**Figure 3.** Biennium average values (bar) and standard deviation (solid line) for temperature (°C) and salinity: a and c for summer/autumn and b and d for winter/spring. The dotted line shows the overall average. The letters are the groups defined in ANOVA only for salinity in winter/spring and temperature in summer/autumn.

a long period of negative anomalies between 2001 and 2007 (Fig. 4).

In the case of the zooplankton, there was a tendency for the density values (number of organisms per $m^3$) to increase while the values for the Margalef species richness index showed a reduction in response to weighting the density values (Fig. 5). Seasonal variations (between summer/autumn and winter/spring) were more evident for the 2006-2007 and 2008-2009 biennia for density and 1996-1997 and 1998-1999 for species richness, according to the *t*-test results. The use of ANOVA to compare data for the biennia and for each season of the year indicated differences starting from 2006-2007 for density and from 2002-2003 for species richness (Table I and Figure 5).

The zooplankton community of the study area was characterized by 71 taxonomic categories distributed in 24 large groups (Table II). Of these, Copepoda, Chaetognatha (mainly *Sagitta friderici*), Decapoda (larvae), Appendicularias and Cladocera (mainly *Penilia avirostris*) were the most representative groups in terms of density and frequency of occurrence.

The group that determined the general behavior of the zooplankton density variations in the study area was Copepoda. The same behavior of increasing density, although less evident, was observed for Chaetognatha and Appendicularias. Decapoda and Cladocera larvae did not show a clear pattern of density variation between the years of study (Fig. 6).

Among the copepod community, there were also different behaviors in the variation, with some species showing an increase in density, some showing a decrease and others showing no change. The evidence for the different behaviors of the species could only be observed from a frequency of minimum occurrence of 30% in the sampling, which limits an evaluation of the other species as well as the other groups of zooplankton. The copepod species that showed an increase in density over the sampling period were *Acartia tonsa, Temora turbinata, Corycaeus giesbrechti* and *Pseudodiaptomus richardi*. Those that showed a decrease were *Temora stylifera, Eucalanus pileatus, Paracalanus quasimodo* and *Parvocalanus crassirostris*. Species for which no clear pattern of increasing or decreasing behavior was observed were *Acartia lilljeborgi, Oithona oswaldocruzii, Euterpina acutifrons* and *Centropages velificatus*.

The behavioral patterns of the species previously classified were represented by the key species of each group in terms of average

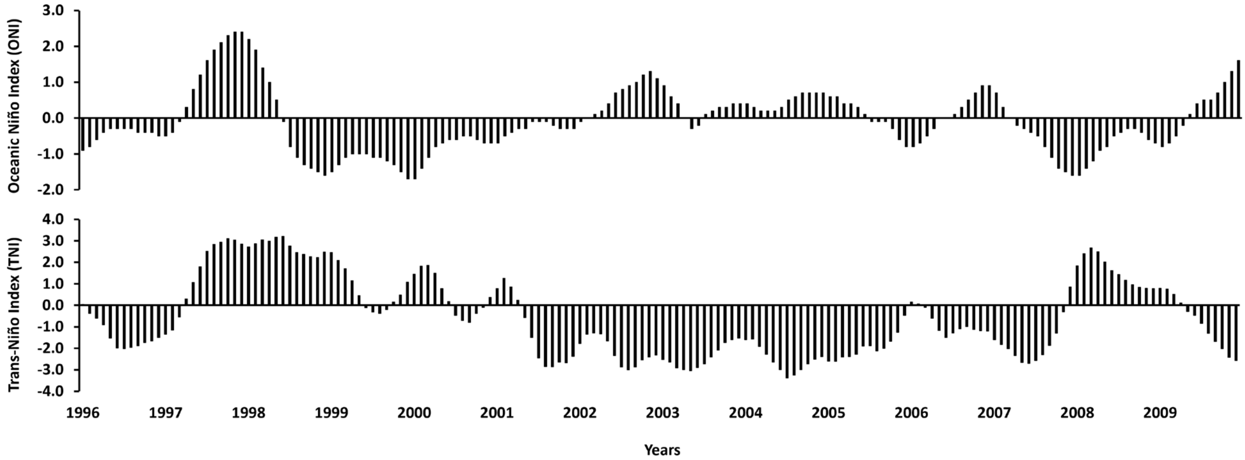


**Figure 4. Thermal anomaly indices (SST) for the Pacific regions: for regions 3-4 (ONI) and for regions 1,2 and 4 (TNI), in the period of 1996 to 2009. Data obtained from National Center for Atmospheric Research (USA).**

density by season (Fig. 7). A pattern is observed for all species represented, with their occurrence in all seasons of the year regardless of the behavior of increment, decay or constancy. In the case of an increase (*A. tonsa*) or decease (*P. quasimodo*) in density, the inflection points of the registered events were similar for the general density of the community, and between 2002-2003 and 2004-2005.

## DISCUSSION

In the compilation presented, there are several time gaps in the information on the zooplankton community as well as the physical-chemical parameters of the water; however, the observed trends may be relevant to assess the variability of an ecosystem compared to general event patterns. In addition, given the absence of information on temporal variations in the southern hemisphere and along the Brazilian coast, as previously highlighted (Richardson 2007, Escribano et al. 2012), there is a need to propose hypotheses regarding events that could be influencing coastal areas, with responses reflected on other scales and in different areas.

Besides the importance of temporal data on zooplankton, in terms of ecological, behavioral and productivity changes, the climate-ecosystem relationship is particularly well represented by the zooplankton community and this can be applied in climate change studies (Mackas & Beaugrand 2010). In particular, the cited authors note that, for the southern hemisphere, the wind pattern regimes determine seasonality, in contrast to the northern hemisphere where temperature is the main determining factor. These facts converge to offer possible explanations of the hypotheses raised in this study regarding the trend of decreasing temperature and salinity

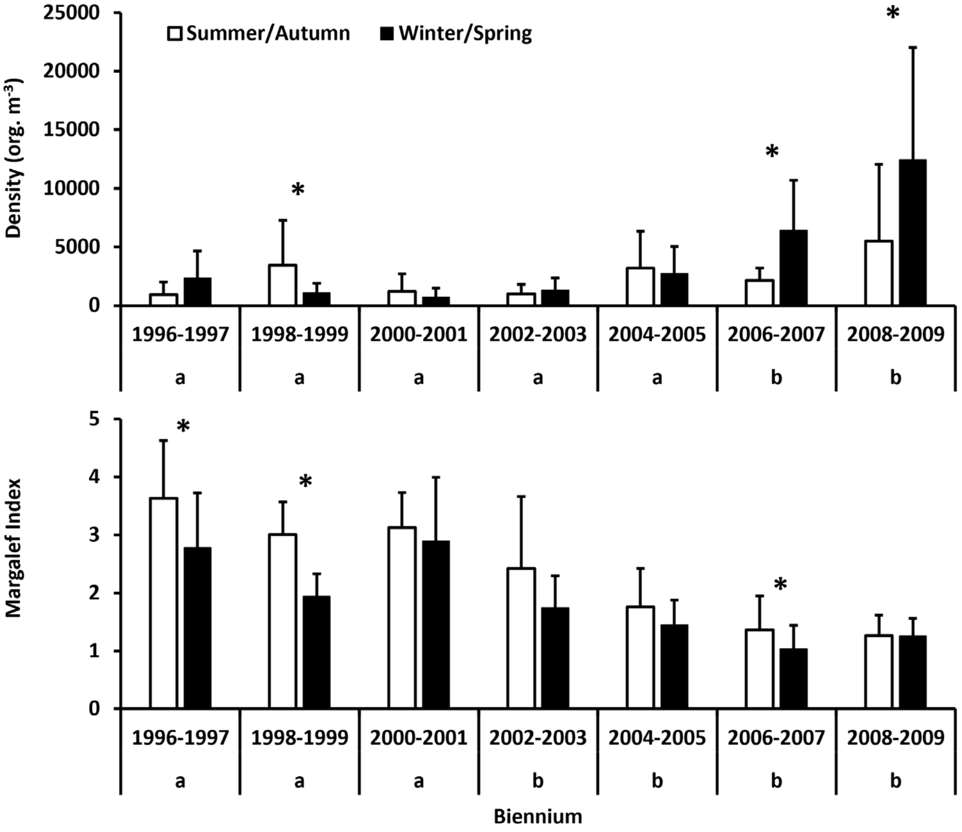


**Figure 5.** Mean values (bar) and standard deviations (line) for the biennium zooplankton density (org $m^{-3}$) and Margalef index (richness). *significant difference between the seasons for the same biennium (*t*-test) and the letters on the x axis are the groups defined in ANOVA between the biennia.

of the water in the study area in a total of 14 years of sampling.

Phenomena that are contrary to the processes of global warming, that is, that indicate cooling instead of heating, are not rare. Cooling is usually associated with the influence of El Niño – Southern Oscillation (ENSO) and this reflects in wind patterns and oceanographic processes in the southern hemisphere (Falvey & Garreaud 2009, Rouault et al. 2010).

For the period of time covered in this study, when considering the Trans-Oceanic El Niño Index (TNI), persistent negative anomalies from 2001 are observed, suggesting that for successive years La Niña was present in the Pacific. According to Grimm (2004), the south of South America suffers from a lack of rain in La Niña years and there is a tendency toward more severe winters.

The southern coast of Brazil is influenced by the mixture of coastal water with the low salinity plume of water under the influence of the La Plata River, also characterized by high chlorophyll-a levels (Gonzalez-Silvera et al. 2006). The northern reach of this plume is not due to the river discharge but due to stress patterns of southwest winds, that can displace the plume over a distance of more than 1,300 km (Piola et al. 2005, 2008, Pimenta et al. 2005).

Based on historical data and simulations, different authors (Piola et al. 2005, 2008, Matano et al. 2014) (Fig. 8) have determined that the southwest wind patterns prevailed almost continuously from 2000 to 2007 (except for 2004 and 2005). According to Piola et al. (2005), the stress caused by southwest winds favors the displacement of coastal water influenced by the La Plata River to the south and southeast regions of Brazil, characterized by waters with low salinity and temperature. This process is probably governed by the displacement of the low pressure center of the Andes to the Atlantic Ocean, which occurs in La Niña years. However, the cited authors point out that these patterns also have interannual variability and are usually difficult to explain. What can be highlighted

**Table I. Significance level obtained in the *t*-tests carried out to compare the seasons for each biennium and ANOVA to compare the biennia according to the season considering the means of the density values and the Margalef index (richness). *p-value indicates significant difference (p<0.05).**

| ***t*-Test to compare seasons for each biennium** | | |
|---|---|---|
| **Summer/Autumn X Winter/Spring** | **Density** | **Richness** |
| 1996-1997 | 0.059 | 0.027* |
| 1998-1999 | 0.048* | 0.000* |
| 2000-2001 | 0.197 | 0.336 |
| 2002-2003 | 0.272 | 0.082 |
| 2004-2005 | 0.658 | 0.154 |
| 2006-2007 | 0.000* | 0.040* |
| 2008-2009 | 0.032* | 0.929 |

| ANOVA to compare biennia according to the season | | | | |
|---|---|---|---|---|
| | | F | df | p |
| Density | Summer/Autumn | 4.508 | 32.34 | 0.002* |
| | Winter/Spring | 12.75 | 45.2 | 2.3E-08* |
| Richness | Summer/Autumn | 32.69 | 34.52 | 7.49E-13* |
| | Winter/Spring | 19.04 | 43.03 | 1.12E-10* |

in these patterns is that the zooplankton seasonality of tropical and subtropical regions is generally associated with changes in average wind speed and direction, which in turn alter the circulation patterns of the area of interest (Mackas & Beaugrand 2010).

A concentration of events was observed between 2001 and 2007 with the presence of La Niña years associated with southwest wind stress and the tendency of decreasing salinity and water temperature in the study area. On the other hand, the lack of synchronization between events can be attributed to different factors, such as the need for a time lapse between the displacement of low pressure centers and the speed of displacement of the plume along the coast, water permeability in protected areas and even inertia processes after long-term events (Piola et al. 2008).

Despite environmental changes, probably affected by the greater influence of the Plata front in the study area since 2001, the entry and occurrence of species from southern Brazil representative of cold water, such as *Pleopis polyphemoides* (occurrence limited to winters from 1999 to 2001 according to Resgalla Jr. 2011), were not registered. This finding could be due to either the similarity of the fauna that occurs in coastal waters in southern Brazil or the evolution of the community depending on the distance from its origin (mouth of the La Plata River) and the area of study (1,200 km). The environmental changes were probably reflected in the physical-chemical characteristics of the water and possibly also in the nutrients (Braga et al. 2008), which favor or inhibit the development of certain species of the zooplankton community. This peripheral behavior of water bodies is stronger than that at the center of a normal range of organism distribution within a narrower range of temperature and salinity (Mackas & Beaugrand 2010). On the other hand, a differentiated behavior is observed when smaller scale oceanographic processes, such as the entry of ocean waters on the continental shelf (intrusion of ACAS - Central Water of the South Atlantic), determines the interannual variability of the zooplankton structure, as reported by Marcolin et al. (2015) for the southeastern region of Brazil.

Abrupt regime changes in ecosystems occur in response to subtle changes in climate or physical oceanographic forces, leading to a new steady state (Richardson 2007, Mackas & Beaugrand 2010). Taking that into account, the response of biological processes will also, theoretically, follow the chronology of the events. Changes in the zooplankton community were observed starting from 2002-2003 for richness and from 2006-2007 for organism densities. It is expected that changes in diversity would occur before quantitative changes, because, in principle, the occupation of a species, within its survival tolerance limits, would be expected before physiological responses, such as reproduction, interfered with its density. In addition, the seasonality of the zooplankton community also changed, being observed in the species richness until 1999, before possible environmental changes, and seasonality in the density of organisms started from 2006-2007, that is, after the La Niña events.

The dominance of certain species at the expense of others could occur in response to environmental changes, which would lead to a new balance in the system. Also, the results of competitive processes based on the overlap of niches play a role and all of these factors will be governed by the relatively rapid life cycle of most zooplanktonic organisms (Omori & Ikeda 1984, Mackas & Beaugrand 2010, Richardson 2007).

The changes observed for the large groups Copepoda and Chaetognatha could be associated with prey-predator relationships. Interestingly,

**Table II.** **Taxons of zooplankton identified in the study area according to Resgalla Jr. (2001) (except ichthyoplankton) during the sample period (1996 to 2009).**

| **Groups/Species** | **Groups/Species** |
|---|---|
| | |
| Cnidaria | Cirripedia (larvae) |
| Polyps | Naupliu |
| Hidromedusae | Cypri |
| *Liriope tetraphylla* (Chamisso and Eysenhardt, 1821) | |
| | Stomatopoda (larvae) |
| Ctenophorae | |
| | **Mysidacea** |
| **Mollusca** | *Metamysidopsis elongata atlantica* (Bacescu, 1968) |
| Bivalvia (veliger) | *Promysis atlantica* Tattersall, 1923 |
| Gastropoda (veliger) | |
| *Creseis* sp. | Isopoda |
| | |
| Annelida | **Caprellidae** |
| Polychaeta (larvae) | |
| | Gammaridea |
| Cladocera | |
| *Penilia avirostris* Dana, 1852 | Hiperiidea |
| *Pseudoevadne spinifera* P.E. Müller, 1867 | |
| *Pseudevadne tergestina* (Claus, 1877) | **Ascidia (larvae)** |
| *Pleopis polyphemoides* (Leuckart,1859) | |
| *Pleoplis schmackeri* (Poppe, 1889) | **Euphausiacea** |
| | Caliptopsis |
| **Ostracoda** | |
| Benthonic | **Deacapoda** |
| | Protozoea |
| **Copepoda** | Mysis |
| *Acartia lilljeborgi* Giesbrecht, 1889 | Zoea |
| *Acartia* sp. | Megalopa |
| *Acartia tonsa* Dana, 1849 | Palinura (decapodito) |
| Calanidae | *Penaeus* sp. (decapodito) |
| *Calanopia americana* Dahl, 1894 | *Lucifer faxoni* Borradaile, 1915 |
| *Calocalanus* sp. | |
| *Centropages velificatus* (Oliveira, 1947) | Echinodermata |
| *Corycaeus* sp. | Pluteu |
| *Corycaeus giesbrechti* (F. Dahl, 1894) | |
| *Eucalanus pileatus* Giesbrecht, 1888 | Chaetognatha |
| *Euterpina acutifrons* (Brian, 1921) | *Sagitta* sp. |
| *Hemicyclops thalassius* Vervoort and Ramires, 1966 | *Sagitta enflata* Grassi, 1881 |
| *Macrosetella gracilis* (Dana, 1847) | *Sagitta hispida* Conant, 1895 |
| Monstrilloida | *Sagitta friderici* (=*tenuis*) (Ritter-Zahony, 1911) |
| *Oithona oswaldocruzi* Oliveira, 1947 | |
| *Oithona plumifera* Baird, 1843 | **Salpidae** |
| *Oithona* sp. | |
| *Oncaea venusta* Philippi, 1843 | **Doliolidae** |
| *Paracalanus nanus* (Sars, 1907) | |
| *Paracalanus quasimodo* Bowman, 1971 | Larvacea |
| *Paracalanus* sp. | *Oikopleura* sp. |
| *Parvocalanus crassirostris* (Dahl, 1894) | *Oikopleura dioica* (Fol, 1872) |
| Pontellidae | *Oikopleura parva* Lohmann, 1896 |
| *Pseudodiaptomus richardi* (Dahl, 1894) | |
| *Temora* sp. | **Ascidiacea (larvae)** |
| *Temora stylifera* (Dana, 1849) | |
| *Temora turbinata* (Dana, 1849) | Lophophorata (lavae) |

Fernández de Puelles & Molinero (2013) noted that disturbances in the zooplanktonic structure in the Mediterranean, due to climatic changes, usually favor chaetognaths and their prey in conditions of water cooling, since gelatinous forms predominate in warming conditions. In the case of appendicularians, an increase, as observed in 2007-2008, could be attributed to the maturation of the system, an increase in suspended particulate matter and the bacterial development of the system (Resgalla Jr. 2001). In the case of *Penilia avirostris*, the lack of a

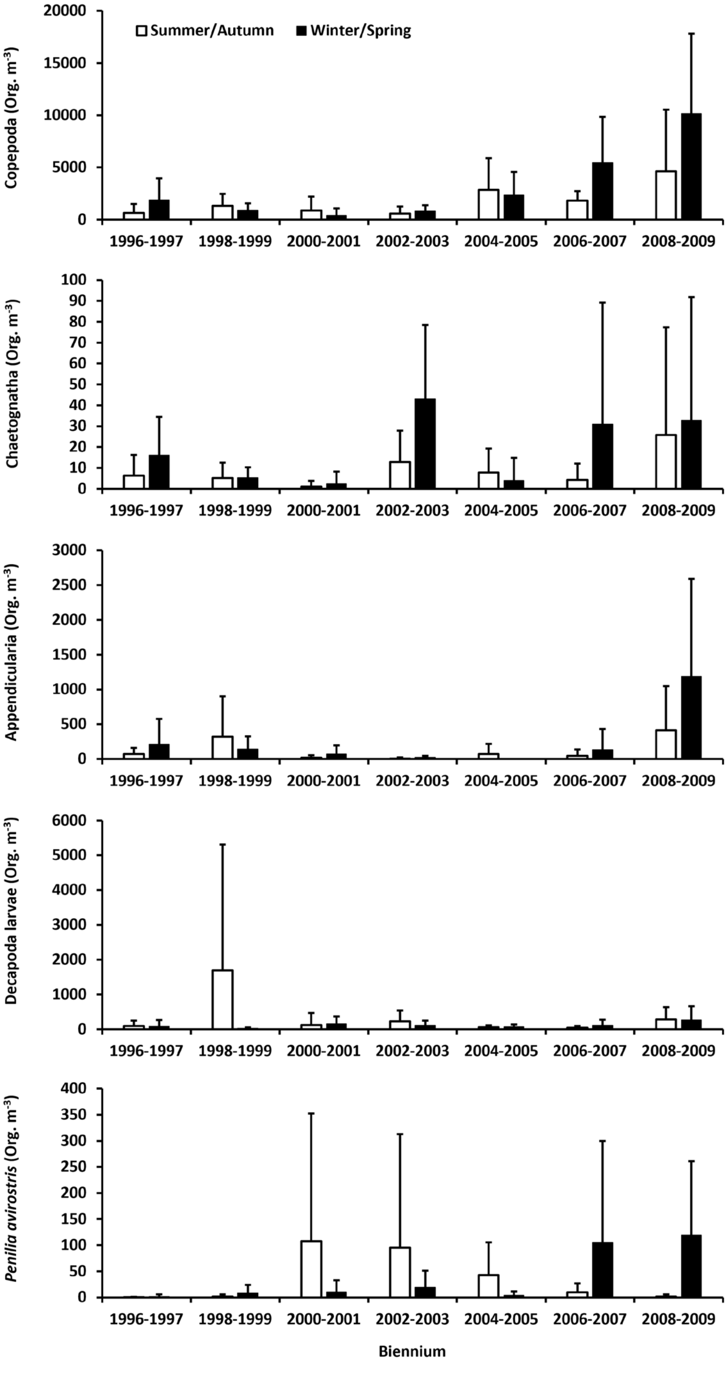


**Figure 6.** Mean values (bar) and standard deviations (line) for the biennium density of Copepoda, Chaetognatha, Appendicularia, Decapoda larvae and Cladocera (*Penilia avirostris*) from 1996 to 2009 for the study area.

clear pattern of its occurrence, including seasonal changes, with its presence in hot and cold months, even limits its classification as an indicator of Tropical Waters of the Brazil Current (Resgalla Jr. 2011).

Due to its ecological importance, attributed to its density and diversity, the copepod group is commonly the target of studies on environmental changes, including those attributed to climate change (Richardson 2007). In this study, the species in this group may respond to environmental changes of decreasing temperature and salinity, favoring the development of species with greater adaptive capacity. According to Resgalla Jr. (2001, 2011) and Veado & Resgalla Jr. (2005), the typical species of the environment under study were found to be the copepods *Acartia lilljeborgi, A. tonsa, Oithona oswaldocruzii, Temora turbinata, Temora stylifera, Paracalanus quasimodo, Parvocalanus crassirostris* and *Euterpia acutifrons*. Of these, the species that showed changes over the 14 years of sampling were *A. tonsa, T. turbinata, Paracalanus*

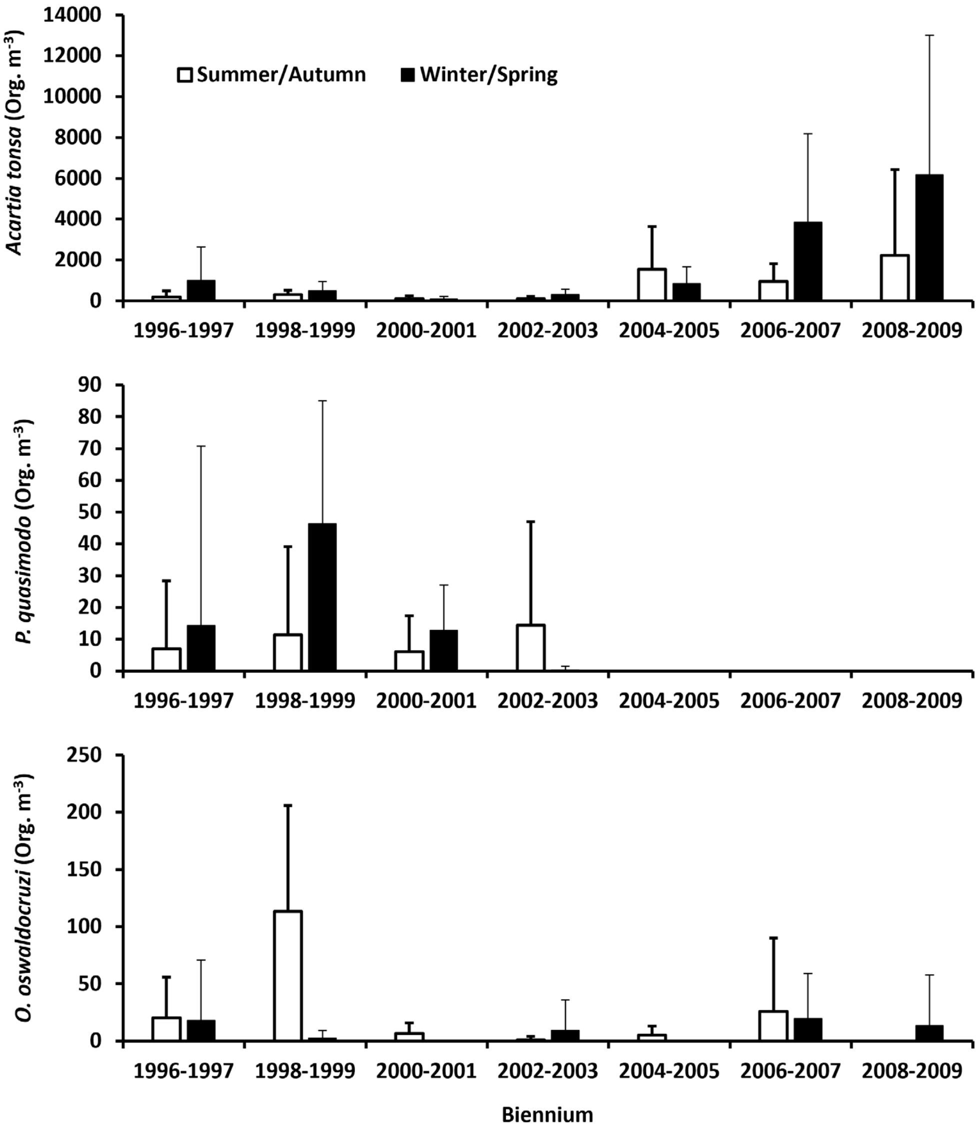


**Figure 7. Mean values (bar) and standard deviations (line) for the biennium density of *Acartia tonsa, Paracalanus quasimodo* and *Oithona oswaldocruzi*.**

*quasimodo* and *Parvocalanus crassirostris*, that is, there was a change in 50% of the most frequent and abundant species, confirming a reduction in species richness depending on the physicochemical changes in the waters.

*Acartia tonsa* is a common estuarine marine species on the Brazilian coast, occurring from north to south, indicating eurythermic characteristics, but its absence in certain environments along the coast suggests that lower salinity or brackish waters would be the ideal condition for its development (Cronin et al. 1962, Cervetto et al. 1999). In addition, *A. tonsa* is a species adapted to high concentrations of food (Reeve & Walter 1977, Paffenhöfer & Stearns 1988), which also suggests changes in the primary production of the environment as well as in the load of suspended particulate matter. *Acartia lilljeborgi* is a typically coastal copepod, occurring in waters with higher salinity and temperature (Bjornberg 1981). Although this species also occurs in the extreme south of Brazil (Lagoa dos Patos estuary) (Resgalla Jr. 2011), its distribution is limited to waters with higher temperatures (Ara 2001). The co-occurrence of these species, despite the existence of overlapping niches, remains unexplained (Sterza & Loureiro Fernandes 2006), but it can be assumed that the higher density of *A. tonsa* indicates competitive advantages.

The competitive relationship between *Temora turbinata* (considered invasive according

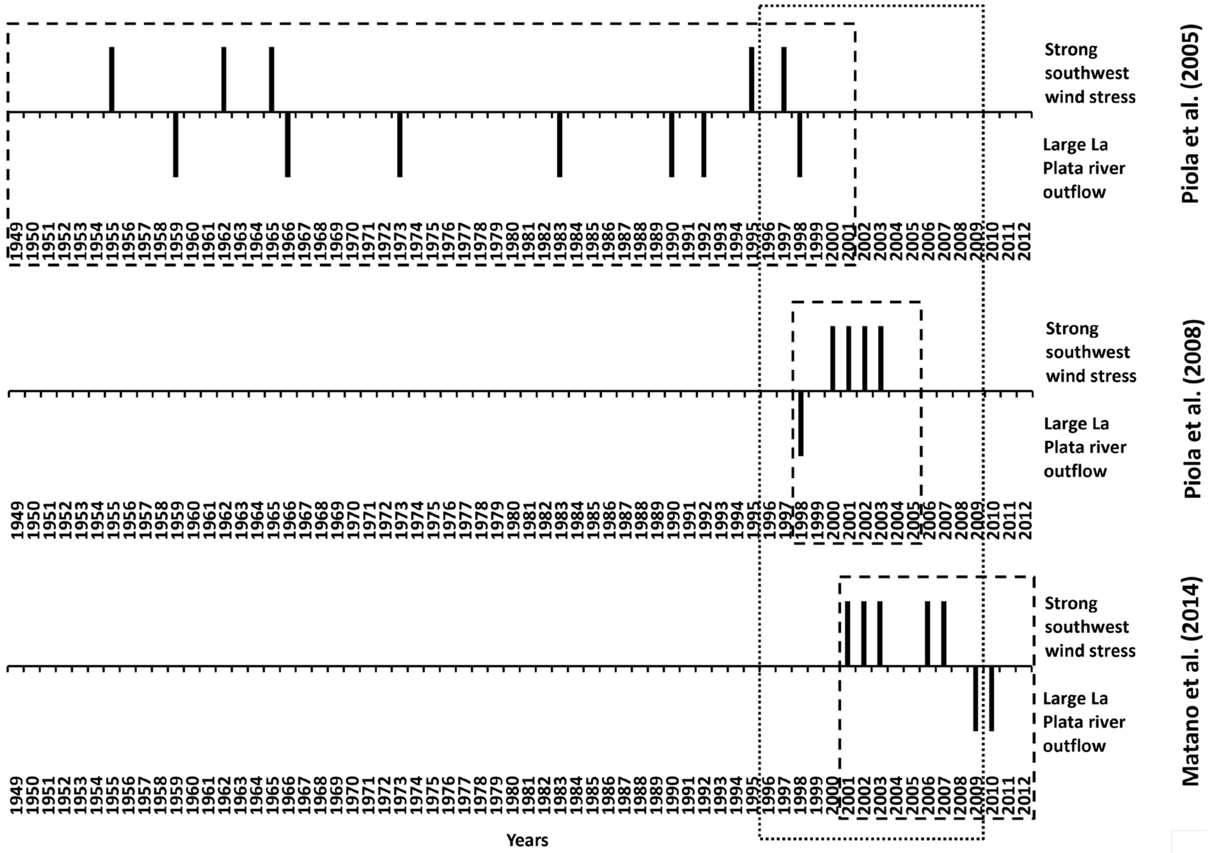


**Figure 8.** Record of years of occurrence of strong southwest wind stress and high discharge from the La Plata River reported by different authors. The dashed rectangles represent the period of study presented by the cited author, and the larger dotted rectangle represents the period considered in this study.

to Araújo & Montú 1993) and *Temora stylifera* (native) has been previously highlighted by Ara (2002) and Lopes (2004). These authors point out that *T. turbinata* has more eurythermal and euryhaline characteristics, besides being an effective competitor in relation to *T. stylifera*. The study by Magris et al. (2011), carried out in an estuary on the southeastern coast of Brazil, highlighted the increasing importance of *T. turbinata* in the brackish water domain, showing greater competitive power in relation to *A. lilljeborgi*, which occurs in waters with the same physicochemical conditions.

Likewise, species typical of warmer waters, such as *Eucalanus pileatus, Paracalanus quasimodo* and *Parvocalanus crassirostris* (Dias & Bonecker 2008, Resgalla Jr. 2011), would be harmed by physical-chemical changes in the water that favor other species, such as *Corycaeus giesbrechti* and *Pseudodiaptomus richardi*. In addition, several studies have highlighted the strong influence of salinity on the distribution and occurrence of several species occurring on the coast of Brazil, such as *P. quasimodo* (Sterza & Loureiro Fernandes 2006, Lopes et al. 1998, Magalhães et al. 2009) and *P. richardi* (Lopes et al. 1998). North of the study area, in the Cananéia estuary, which has similar fauna, the zooplankton community showed faunal behavior determined by salinity, with species selection mainly in low salinity conditions (Ara 2004). To the south, in the Lagoa dos Patos estuary, the influence of El Niño in the years 2009 to 2013 led to higher rainfall levels and changes in salinity, which affected the distribution of *A. tonsa*, *T. turbinata*, and two species of *Paracalanus* in the estuary (Teixeira-Amaral et al. 2017).

Once the new physical-chemical conditions of the environment have been established to favor adapted species, biotic processes, mainly involving competition for overlapping niches, probably aggravated by an altered phytoplankton community (L. Rörig, Florianópolis, personal communication), would determine the observed patterns in the zooplankton community. However, biotic factors are more difficult to measure and verify, and these relationships are generally addressed in the theoretical field, requiring studies under controlled conditions for a better diagnosis of the relationships between the species involved.

It cannot be disregarded, however, that possible interactions between different forces occurring in the environment may have influenced the structure of the zooplankton community. Thus, it is difficult to identify specific causes and processes that led to this succession of events and the diagnosed developments. In addition, there is a need for further sampling to be conducted in the study area, in order to diagnose the current situation of the environment, both in terms of physical-chemical and biotic characteristics. An assessment of the current conditions together with the situation between 1996 and 2009 could indicate whether a new steady state has emerged or there has been a return to the initial conditions.

## CONCLUSIONS

In this study, a trend was observed, with a reduction in species richness starting in 2002-2003 and an increase in the density of zooplanktonic organisms in 2006-2007. In the period of 2001 to 2007, there were anomalous conditions with regard to the Pacific SST. This period featured successive events of the La Niña phenomenon, which could explain the strong stress from southwest winds in southern South America, favoring a greater northern reach of the plume of the La Plata River between 2000 and 2007. With the subsequent physical and chemical changes in the waters, the selection of species from the copepod group seems to have occurred, which came to dominate the environment, determining a new community structure. However, it was not possible to establish whether this new structure was maintained, leading to a new steady state, or if the initial conditions returned in the period after the influence of ENSO.

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