UNIVERSIDADE FEDERAL DO PARANÁ

BIANCA SALVADOR

VARIAÇÃO ZOOPLANCTÔNICA NO COMPLEXO ESTUARINO DE PARANAGUÁ – BRASIL DURANTE OS ANOS DE 2012 E 2013

PONTAL DO PARANÁ
2015

BIANCA SALVADOR

VARIAÇÃO ZOOPLANCTÔNICA NO COMPLEXO ESTUARINO DE PARANAGUÁ – BRASIL DURANTE OS ANOS DE 2012 E 2013

Dissertação apresentada como requisito parcial a obtenção do grau de Mestre em Sistemas Costeiros e Oceânicos. Programa de Pós-Graduação em Sistemas Costeiros e Oceânicos (PGSISCO), Centro de Estudos do Mar, Setor de Ciências da Terra, Universidade Federal do Paraná.

Orientador: Prof. Dr. José Guilherme Bersano Filho

PONTAL DO PARANÁ
2015

CATALOGAÇÃO NA FONTE:
UFPR / SiBi - Biblioteca do Centro de Estudos do Mar
Liliam Maria Orquiza - CRB-9/712

Salvador, Bianca
S182v Variação zooplanctônica no Complexo Estuarino de Paranaguá - Brasil durante os anos de 2012 e 2013. / Bianca Salvador. – Pontal do Paraná, 2015.
47 f.; 29 cm.

Orientador: Prof. Dr. José Guilherme Bersano Filho.

Dissertação (Mestrado) – Programa de Pós-Graduação em Sistemas Costeiros e Oceânicos, Centro de Estudos do Mar, Setor de Ciências da Terra, Universidade Federal do Paraná.

1. Baía de Paranaguá. 2. Zooplâncton. 3. Copepoda. 4. Estuário. 5. Condições ambientais. I. Título. II. Bersano Filho, José Guilherme. III. Universidade Federal do Paraná.

CDD 595.34

AGRADECIMENTOS

Agradeço ao professor Dr. José Guilherme F. Bersano pela orientação, ensinamentos e amizade ao longo desses anos. Obrigada pelas oportunidades de projetos e aventuras científicas e pelo apoio em todos os momentos desta jornada acadêmica.

Agradeço a Lorena Nascimento, companheira de laboratório, pela ajuda nas coletas e nos penosos processos de triagem e análise dos dados. Obrigada por ser sempre tão responsável e voluntariosa. Admiro seu profissionalismo.

A Camila Domit e aos membros da família LEC pela ajuda e participação nos anos de BioMar e sobretudo pela amizade e atenção. Adoro ser agregada desta família!

Aos professores Maurício Camargo, pelas instruções e essencial ajuda com as análises estatísticas, e Marcelo Dourado (Grupo de Física Marinha), pela disponibilização de imprescindíveis dados meteorológicos.

Ao SIMEPAR e ao INMET, também pelo fornecimento de dados meteorológicos fundamentais.

A CAPES e a PGSISCO, pela oportunidade e concessão da bolsa de mestrado, e a Fundação Grupo Boticário, pelo financiamento do projeto.

Agradeço ainda aos professores Carlos Borzone, Luiz F. Loureiro Fernandes e Jean Louis Valentin pela atenção e interesse em participar da banca de avaliação deste trabalho.

PGSISCO

CURSO DE PÓS-GRADUAÇÃO EM SISTEMAS COSTEIROS E OCEÂNICOS

Centro de Estudos do Mar - Setor Ciências da Terra - UFPR

Avn. Beira-mar, s/nº - Pontal do Sul – Pontal do Paraná – Paraná - Brasil

Tel. (41) 3511-8644 - Fax (41) 3511-8648 - www.cem.ufpr.br - E-mail: pgsisco@ufpr.br

Ata da sessão pública de Defesa de Dissertação para obtenção do grau de Mestra em Sistemas Costeiros e Oceânicos, área de concentração Biologia e Ecologia de Sistemas. Aos vinte e seis dias do mês de março de 2015, no anfiteatro do Centro de Estudos do Mar, às 14 horas, reuniu-se em sessão pública a Banca Examinadora da prova de Defesa de Dissertação da candidata ao Título de Mestra em Sistemas Costeiros e Oceânicos, **Bianca Salvador,** composta pelos seguintes membros: Dr. Carlos Alberto Borzone (UFPR/CEM), como presidente, Dr. Luiz Fernando Loureiro Fernandes (UFES) e Dr. Jean Louis Valentin (UFRJ), como examinadores. Após os esclarecimentos prestados pelo candidato às argüições feitas pelos membros da Banca, o Sr. Presidente suspendeu temporariamente a sessão a fim de que a Banca se reunisse em sessão secreta para deliberar sobre o resultado. Reaberta a sessão, o Sr. presidente deu conhecimento a candidata que, de conformidade com o Art. 67 da Resolução 65/09 CEPE, a dissertação foi **aprovada**, apenas condicionada à apresentação, no prazo de sessenta dias, da redação final com as alterações sugeridas.

Pontal do Paraná, 26 de março de 2015.

Dr. Carlos Alberto Borzone (UFPR/CEM)
Presidente

Dr. Luiz Fernando Loureiro Fernandes (UFES)
Membro Examinador

Dr. Jean Louis Valentin (UFRJ)
Membro Examinador

Dr. José Guilherme Bersano Filho
Orientador (afastado oficialmente)

Título da Dissertação: "Zooplankton variability in the subtropical estuarine system of Paranaguá bay - Brazil for the years of 2012 and 2013 "

RESUMO

A estrutura e dinâmica das populações biológicas em estuários, especialmente no que se refere à comunidade planctônica, é reflexo da elevada variabilidade espaçotemporal de habitats. Organismos zooplanctônicos respondem rapidamente a mudanças nos parâmetros abióticos e bióticos do sistema, sendo considerados potenciais bioindicadores de alterações ambientais. O Complexo Estuarino de Paranaguá (CEP) está entre os principais ecossistemas costeiros da região sul-sudeste do Brasil, abrigando áreas de planície costeira, manguezais, marismas e Mata Atlântica. Apesar de sua importância nos processos ecológicos, a atual dinâmica da comunidade zooplanctônica na região é pouco conhecida. Este trabalho tem como objetivo descrever a variabilidade zooplanctônica no CEP, com base em dados de composição e abundância obtidos durante os períodos de verão e inverno de 2012 e 2013, em relação a mudanças ambientais associadas à variação climática sazonal. Para tal, as coletas foram realizadas através de arrastos oblíquos com rede cilíndrico-cônica (0,5 m de boca e 200 µm de malha) ao longo de 37 pontos distribuídos no CEP, totalizando 148 amostras. Parâmetros ambientais, tais como temperatura da água e salinidade, foram coletados simultaneamente e dados atmosféricos foram obtidos a partir de estações meteorológicas da região. As variações de abundância e composição zooplanctônicas e suas relações com as condições hidrológicas foram avaliadas a partir de técnicas estatísticas de análise multivariada e os resultados indicaram diferenças significativas entre as comunidades. Foram detectados dois agrupamentos principais correspondentes às assembleias de verão e de inverno, separadas principalmente em função das diferenças de abundância. As maiores abundâncias foram encontradas nas campanhas de verão (períodos chuvosos), especialmente em 2012, quando a densidade média de organismos atingiu 16.378 ind.m^{-3}. As comunidades de inverno (períodos secos) apresentaram densidades relativamente baixas (médias de 4.054 em 2012 e 1.591 ind.m^{-3} em 2013). Contudo, variaram principalmente em termos diversidade, com os maiores valores observados para o Índice de Shannon. Durante os períodos de estudo foi registrado um total de 14 grupos taxonômicos no CEP, sendo a subclasse Copepoda a mais importante em termos de abundância e diversidade, representando 92% da abundância total com 22 espécies identificadas. As espécies mais abundantes e frequentes foram os copépodes *Acartia lilljeborgi* e *Oithona hebes*, seguidas por *Pseudodiaptomus acutus* e *Temora turbinata*, que apresentaram elevadas abundâncias e ocorrências mais pontuais. A composição zooplanctônica foi bastante homogênea durante campanhas amostrais, mas suas distribuições espaciais variaram de acordo com as condições hidrológicas predominantes em cada período. Os resultados indicaram fortes correlações entre a estrutura da comunidade e os parâmetros ambientais analisados, especialmente em função das variações climáticas sazonais. A distribuição das espécies foi possivelmente determinada por suas adaptações fisiológicas a condições específicas de salinidade. As variações de densidade, por outro lado, foram relacionadas à temperatura de água e as taxas de precipitação, particularmente responsáveis pelo incremento no fluxo de água doce e aporte de nutrientes no sistema durante períodos chuvosos.

Palavras chave: *Baía de Paranaguá; Zooplâncton; Copepoda; Estuário; Condições ambientais.*

SUMÁRIO

PREFÁCIO

A dissertação apresentada a seguir é composta por um capítulo único e foi elaborada em forma de artigo científico, conforme sugerido pelo Programa de Pós-Graduação em Sistemas Costeiros e Oceânicos da Universidade Federal do Paraná (PGSISCO – UFPR). O manuscrito foi redigido em língua inglesa e ainda será devidamente revisado por tradutor especializado. A formatação do documento foi baseada nas normas da revista inicialmente pretendida para submissão do artigo, a *Estuarine, Coastal and Shelf Science*, ISSN (0272-7714); Fator de Impacto (JCR, 2013) = 2,253; Qualis CAPES = Estrato A2 (Biodiversidade). O estudo tem como tema a comunidade zooplanctônica do Complexo Estuarino de Paranaguá e faz parte de um projeto mais amplo (Projeto BioMar – Monitoramento da biodiversidade e parâmetros oceanográficos no Complexo Estuarino de Paranaguá e zona costeira do Paraná, Brasil), realizado entre os anos de 2012 e 2014 e financiado pela Fundação Grupo Boticário de Proteção à Natureza.

Zooplankton variability in the subtropical estuarine system of Paranaguá bay - Brazil for the years 2012 and 2013

Bianca Salvador*, José Guilherme F. Bersano

Laboratório de Zooplâncton, Centro de Estudos do Mar, Universidade Federal do Paraná, Pontal do Paraná, Paraná, CEP 83255-971, Brasil

*Corresponding author: bsalvador.ufpr@gmail.com

Abstract

Spatial and temporal dynamics of zooplankton assemblages were studied in the Paranaguá Estuarine System (Southern Brazil) including data from summer (rainy) and winter (dry) periods of 2012 and 2013. Organisms were collected with a cylindrical-conical net (200 µm mesh) obliquely towed at 37 stations along the estuary. Environmental parameters were measured simultaneously. Variability in zooplankton abundance, composition and its relation to hydrological conditions were examined by multivariate techniques, as PCO and CAP. The results indicated significantly distinct assemblages, being abundance differences the major source of variability, predominantly over the temporal scale. Higher abundances were observed in summer communities, especially in 2012, when mean density reached 16378 ind.m^{-3}. Winter assemblages, on the other hand, presented relatively lower densities but higher species diversity due to major intrusion of coastal waters. A total of 14 taxonomic groups were registered, being Copepoda the most abundant and diverse (92% of total abundance and 22 species identified). The coastal copepods *Acartia lilljeborgi* (44%) and *Oithona hebes* (26%) were the most important species both on abundance and frequency, followed by *Pseudodiaptomus acutus* (estuarine species) and *Temora turbinata* (neritic species). The composition and dominance were basically homogenous during the study period, but its spatial distribution distinctly varied along the estuary. Results suggested strong influences of environmental parameters in the community structure, especially in response to seasonal climatic variations. It is suggested that the species spatial distribution was mainly determined by its preferences and tolerances to specific salinity conditions. On the other hand, its abundances were strongly related to higher water temperature and precipitations rates, which possibly increased the nutrient inputs and food supply in the system due to intense continental drainage.

Keywords: zooplankton; community variability; environmental changes; Paranaguá bay.

1 Introduction

Zooplankton populations play an important role in ocean food webs and ecological process transferring energy from primary producers to upper trophic levels, redistributing nutrients and regulating biogeochemical cycles (Richardson, 2008). These organisms respond rapidly and sensitively to many changes in the abiotic parameters (e.g. temperature, salinity, stratification) and biotic parameters (e.g. food supply and quality, competition, predation), comprising important biological indicators of environmental changes (Chiba and Saino, 2003; David et al., 2005; Marques et al., 2007). The community abundance and composition patterns are thus subject to strong variation, especially over spatial and seasonal scales (Winker et al., 2003).

In this context, estuarine ecosystems are of particular interest for studying zooplankton dynamics due to its instability and heterogeneity of hydrological parameters, which are directly affected by climatic variation (Viitasalo et al., 1995; Islam et al., 2006). The dynamics of estuarine ecosystems are mainly determined by the freshwater runoff and the exchange of water with the adjacent open sea (Flindt et al., 1999; Kimmerer, 2002). The instability of physical and chemical conditions may affect biological and ecological process, modifying physiological rates, such as respiration and osmoregulation, and life cycle parameters, as growth and reproduction (Laprise and Dodson, 1994; Gaudy et al., 2000; Hirst and Kiørboe, 2002). However, these effects depend on the taxonomic composition of the community and on the species physiological adaptations (Kiørboe and Nielsen, 1994).

Studies carried out in several estuaries worldwide have shown that temperature and salinity are the main factors influencing the distribution and abundance of zooplankton assemblages (Marques et al., 2006; Graham and Bollens, 2010). Spatial and temporal variation in these variables subsequently determines the segregation of species in estuaries according to its respective tolerances and preferences (Soetaert and Van Rijswick, 1993; Lawrence et al., 2004). Therefore, monitoring and understanding changes in the zooplankton community can provide essential information about the ecosystem functioning, contributing to the development of prediction models for natural and anthropic alterations in the environment, especially those induced by climatic variations (Costello et al., 2006; Tommasi et al., 2013).

The Paranaguá Estuarine System (PES), located in the southwestern Atlantic, presents seasonal variations generally characterized by annual cycles of rainy (summer) and dry (winter) periods (Lana et al., 2001). The freshwater inputs are thus significantly higher during the summer, increasing up to 170% of the annual mean value (Marone et al., 2005). The PES is among the largest estuaries in the Brazilian coast and includes a great diversity of environments such as coastal plain areas, mangroves, salt marshes and the Atlantic rainforest (Lana et al., 2001). Its economical relevance is mainly related to port activities since the Paranaguá harbor is an important handling site for grains and fertilizers in South America, what leads to potential anthropogenic impacts in these ecosystem (Martins et al., 2010; Mizerkowski et al., 2012).

The zooplankton community of the PES was primarily described by Montú and Cordeiro (1988), based on data fortnightly collected along five sampling stations from October 1980 to September 1981. Ten years later, Lopes et al. (1998) prioritized the spatial variation of the community analyzing data from 22 sampling stations distributed all over the bay for the winter of 1993 and summer of 1994. Currently, there is a huge lack of studies about the PES zooplankton community. In the present study, we describe the zooplankton variability during summer and winter of 2012 and 2013, identifying the dominant environmental factors responsible for the spatial and temporal distribution of species abundance and composition in the PES.

2 Materials and Methods

2.1 Study Area

The PES, located on northern coast of Paraná state (48º25' W, 25º 30' S), presents an area of 612 km² and water volume of approximately 14 x 10^9 m^3 (Lana et al., 2001). The system is connected to the sea by two main tidal channels (North and South inlets) and divided into two main sections: the East-West axis (EW), composed by Paranaguá and Antonina bays; and the North-South axis (NS), formed mainly by Laranjeiras and Pinheiros bays (Fig. 1; Kolm et al., 2002). The PES is classified as a partially mixed estuary (type *b*) and the water column may exhibit both homogeneous and stratified conditions, depending on tidal forces, wind speed and river discharge (Marone et al., 2007; Mizerkowski et al., 2012). The tidal regime is semi-diurnal with mean range of 2.2 m and water resident time of 3.5 days (Marone and Jamiyanaa, 1997). Local hydrodynamic processes are strongly driven by climatic factors (rain and wind regime) and the succession of rainy (spring and summer) and dry (autumn and winter) periods are responsible for contrasting circulation patterns generally observed in the system (Marone et al., 2005). The climate of the region is defined as subtropical wet with annual precipitation of more than 2,500 mm and mean river discharge of approximately 200 m^3s^{-1} (Lana et al., 2001).

2.2 Sample collection

Samplings were carried out at 37 stations in the PES during four surveys conducted in March and August of 2012 and in February and June of 2013 (Fig. 1 - A). Sampling surveys were defined as summer 2012 (S12), winter 2012 (W12), summer 2013 (S13) and winter 2013 (W13). Hydrological and biological data (n = 148) were collected in the same occasion. Vertical profiles of salinity and temperature were obtained with calibrated CTD's (JFE ALEC Compact-CTD in 2012 and CastAway-CTD in 2013; Fig. 1 - B). No CTD profiles were collected along the EW axes and Pinheiros bay during the first survey (summer of 2012). Temperature profiles were essentially homogenous throughout the water column and so were not shown and neither used in the data analysis. In addition, superficial water temperature (°C) and salinity were measured with a mercury thermometer and a refractometer. Water transparency (m) was estimated by a secchi disc.

Precipitation rates for two regions around the PES, Northern and Southern margins, were provided by the Brazilian Meteorological Nacional Institute (INMET – Paranaguá Meteorological Station) and by the Meteorological System of Paraná (SIMEPAR – Salto Morato Reserve Meteorological Station, Guaraqueçaba). Precipitation values used in the data analyzes correspond to cumulative rainfall of the fifteen days prior to each sampling survey.

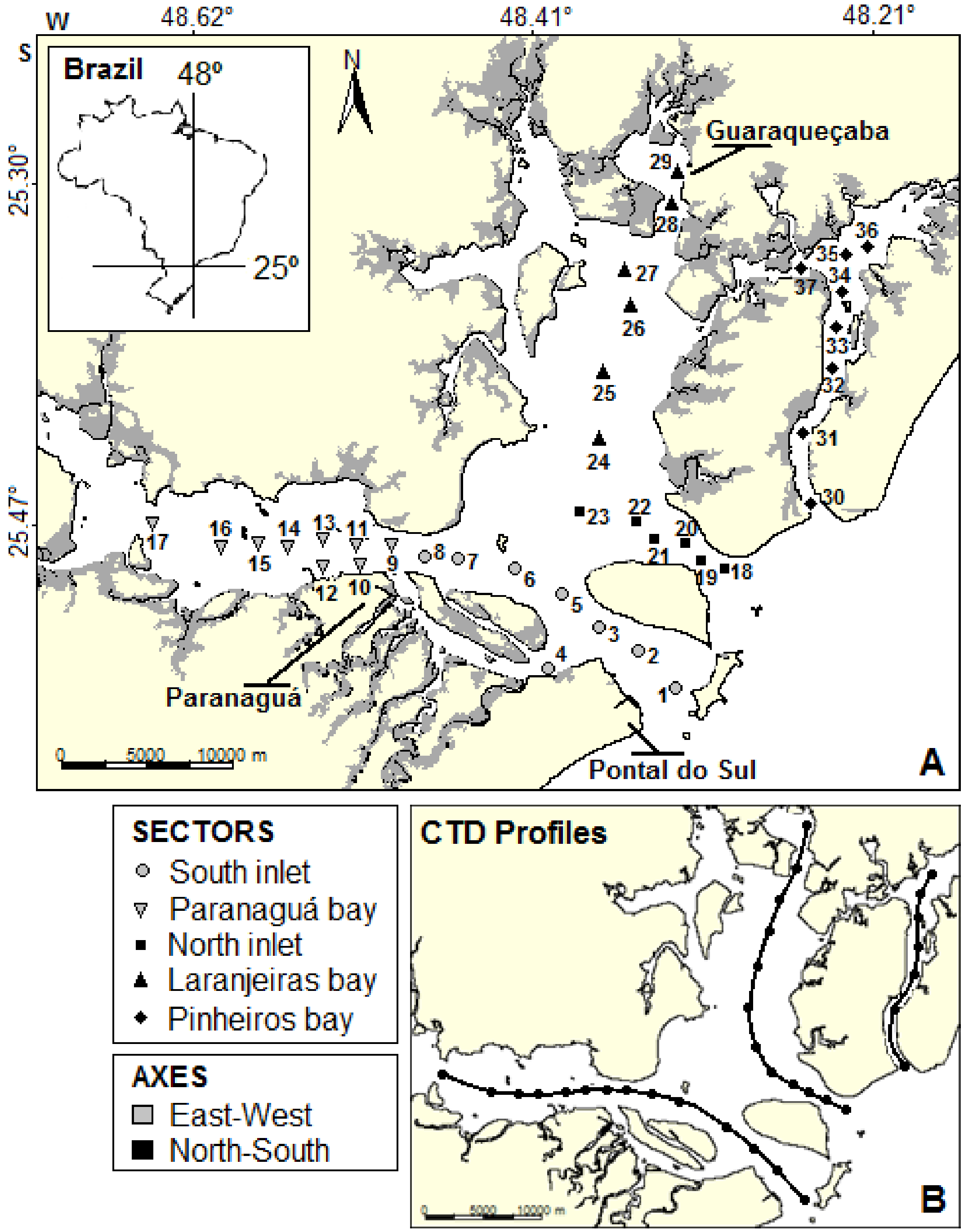

Figure 1: Map of the Paranaguá Estuarine System (Southern Brazil) and **(A)** distribution of sampling stations according to estuary sectors: South inlet (SI) and Paranaguá bay (PA) at the East-West axis; North inlet (NI), Laranjeiras (LA) and Pinheiros (PI) bays at the North-South axis. **(B)** Longitudinal transects of CTD profiling.

Wind data (speed and direction) measured at Pontal do Sul beach, located at PES's South inlet margin, were provided by the Physical Oceanography Group - Center of Marine Studies (Federal University of Paraná). Predominant wind direction and mean velocities were also estimated from daily resultants of the fifteen days prior to each survey. For the statistical analyses, wind data were decomposed into East-West and North-South components (*u* and *v*) and its averages were calculated: positive values indicate winds flowing toward the East and North, respectively.

Zooplankton samples were taken by oblique hauls (from bottom to surface) with a 2m long cylindrical-conical net (mesh: 200 µm; diameter: 0.5 m) equipped with flowmeter (Hydrobios in the S12 survey and General Oceanics in the remaining campaigns). The zooplankton collected was preserved in 4% buffered formaldehyde solution and its composition and abundance were analyzed in laboratory from aliquots taken with a plastic 10 mL subsampler spoon. A minimum of 300 organisms for each sample was transferred to Bogorov chambers and counted under a stereomicroscope (1.5x zoom). The identification was made to the lowest taxonomic level possible, according to specialized guides (Björnberg, 1981; Bersano and Boxshall, 1994; Boltovscoy, 1999). Zooplankton densities were expressed as number of individuals per m^{-3} and ecological indices were calculated (species richness and Shannon Diversity Index).

2.3 Data analysis

Data were examined by multivariate techniques using PRIMER-E software package (version 6.1.15) with PERMANOVA+ (version 1.0.3). As an arbitrary choice, only taxa that accounted for more than 1% of the total zooplankton abundance were selected for analysis and square root transformed. All procedures were performed using Bray-Curtis dissimilarity index, as suggested by Legendre and Legendre (1998). Spatial patterns in the zooplankton community were investigated by rating the sampling stations into 5 sectors according to physical and hydrographic characteristics and based on previous studies in the PES. These sectors were defined as South and North inlets (SI and NI), Paranaguá (PA), Laranjeiras (LA) and Pinheiros (PI) bays (Fig. 1 - A).

Spatial and temporal dynamics of the community were examined with a Principal Coordinate Analysis (PCO or metric MDS), an ordination procedure that can be based on any resemblance matrix and provide a direct projection of the points in the space defined by the actual dissimilarities (Anderson, 2008). A PERMANOVA was applied subsequently to test for significance of differences in the zooplankton community considering sampling periods and estuary sectors. This analysis is a non-parametric method based on a multivariate analogue to Fisher's F-ratio (pseudo-F) where *p*-values are obtained from permutations ($\alpha = 0.05$, N = 9999; Anderson, 2001). Pairwise comparisons based on a multivariate version of Student's t statistics were performed a posteriori among all pairs of levels when groups were significantly different (Anderson, 2008). A Permutation Dispersion Analysis (PERMDISP), analogous to the Levene test for homogeneity of variances, was also applied to test for any significant dispersion effects between spatial and temporal groups (Anderson, 2006).

Relationships between zooplankton dynamics and environmental parameters were investigated by Canonical Analysis of Principal Coordinates (CAP), a procedure that combines two multivariate techniques: PCO and canonical analysis (Anderson and Willis, 2003). The purpose of CAP is to find axes through the multivariate space that have the strongest correlation with some other set of variables, such as environmental data (Anderson, 2008). The analysis was performed retaining the number of PCO axes (*m*) which explained more than 60% of the total variation and where the residual error was at its minimum, as suggested by Anderson and Willis (2003). The abiotic parameters used in the CAP were: superficial water temperature and salinity; water transparency (Secchi depth); cumulative rainfall; zonal wind component (East-West); and salinity vertical stratification, represented by the salinity variation as a function of the water depth (∆Sal./z). The meridional wind component (North-South) was excluded from the analysis due to strong correlation with water temperature ($r^2 > 0.85$).

Species abundance data were also used to examine which taxa characterized the differences among zooplankton groups found by the CAP analysis. To this end, biological variables were standardized dividing individual abundances by the total of each sample in order to reduce the effect of abundances and make the data amounts comparable between sampling periods.

3 Results

3.1 Environmental parameters

Hydrological data obtained during the study showed spatial-temporal variation associated with local precipitation regime and seasonal cycle. Wind data was also consistent with the typical pattern observed in the region. Prevailing wind directions during summer surveys were from the east in 2012 and northeast in 2013, whereas winter surveys were mostly characterized by southeasterly (2012) and southerly winds

(2013; Fig 2 - A). Strongest winds were observed during S12 and W13 with averages speeds of 1.8 m/s (Table 1 - A). Cumulative rainfall for the fifteen days prior to each survey was higher during summer samplings, especially in 2013, reaching up to 159 mm in Paranaguá and 134 mm in Guaraqueçaba (Fig. 2 - B). The driest period were recorded in the W12, when the previous fortnight rainfall was practically 0 mm at both meteorological stations (Table 1 - B).

Table 1: (A) Prevailing wind directions (PD), frequencies of occurrence (FO%) and mean wind speeds (MS) measured in Pontal do Sul beach. **(B)** Cumulative precipitation (mm) registered in meteorological stations at Guaraqueçaba and Paranaguá. All values correspond to 15 days prior to each sampling survey.

A	**Wind (Pontal do Sul beach)**			**B**	**Precipitation (mm)**	
	PD	FO%	MS (m/s)		Guaraqueçaba	Paranaguá
Summer 2012	East	53	1.82		112.4	111.0
Winter 2012	Southeast	40	1.11		1.0	0.0
Summer 2013	Northeast	40	1.19		133.8	159.0
Winter 2013	South	40	1.83		35.6	50.0

As expected, water temperature presented temporal variation characterized by summer warming and winter cooling (Fig. 2 - C). Highest temperatures were observed during the S13 survey (29.3±0.1°C) and lowest values in W13 (20.6±0.1°C). In terms of spatial scale, water temperature varied slightly and did not differ considerably between the different estuary sectors. On the other hand, surface salinity presented pronounced variation over both spatial and temporal scale. Along the estuary, salinity decreased consistently from upstream to downstream stations, with a minimum of 14 in Laranjeiras bay and maximum of 34 in the estuary channels, especially in the outer stations (Fig 3 - A). Lowest values were recorded in the S13 survey (20±0.6), when the freshwater discharge into the system was increased by heavy rainfall (Fig. 2 - C). Furthermore, vertical profiles also showed marked salinity stratification during summer of 2013, especially in the mid sectors of PES (Paranaguá and Laranjeiras bays; Fig. 4).

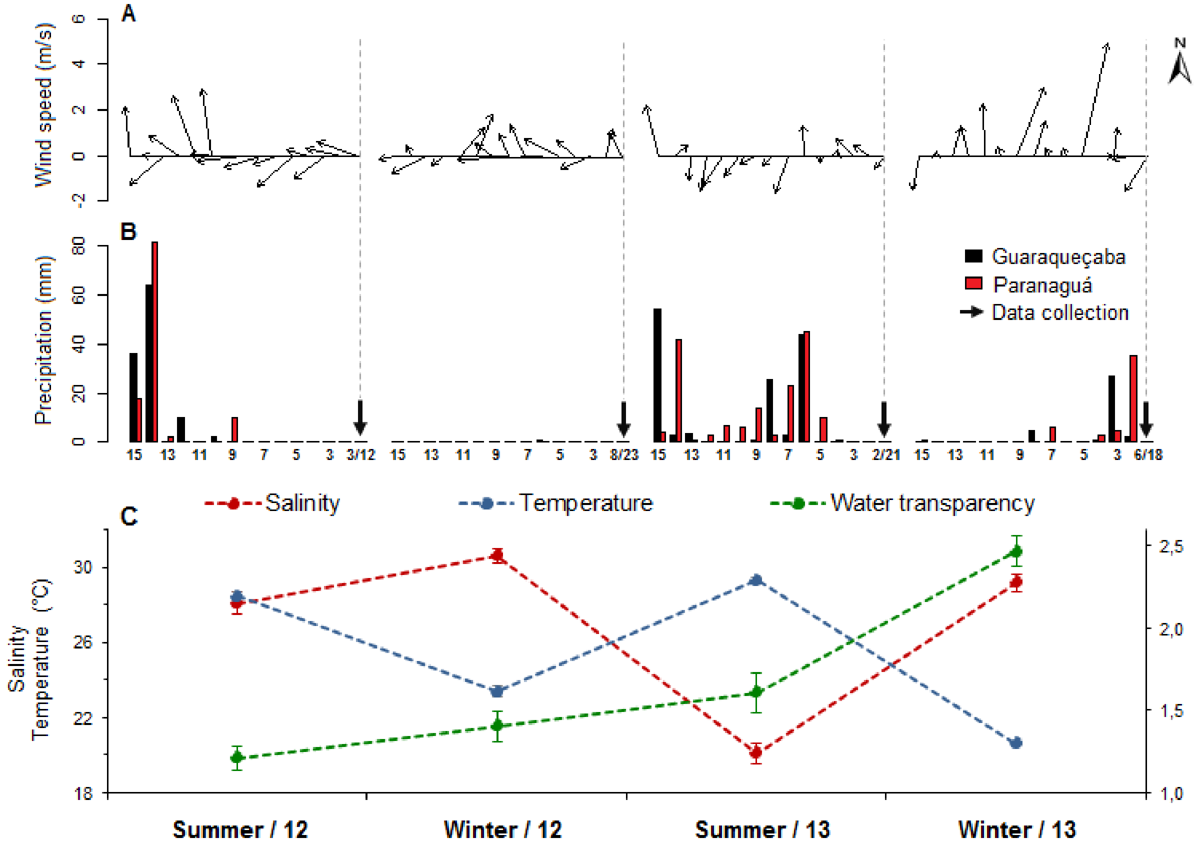

Figure 2: (A) Feather plots of daily mean wind speed and direction measured at Pontal do Sul beach. **(B)** Daily cumulative precipitation (mm) recorded in meteorological stations at Guaraqueçaba and Paranaguá. All values correspond to 15 days prior to each sampling survey. **(C)** Means of surface salinity, water temperature (°C) and Secchi depth (m) for each sampling period in the Paranaguá Estuarine System.

Meanwhile, winter surveys were characterized by higher surface salinities (31±0.4 in 2012 and 29±0.5 in 2013) and vertical profiles practically homogeneous as a result of low precipitation rates. Although the S12 survey was also carried out during the rainy period, surface salinities were also elevated (28±0.6) and vertical profiles of Laranjeiras bay and North inlet indicated very homogeneous salinity distributions (Fig. 4). This sampling survey was preceded by a long dry period with no precipitation recorded for eight days. Prevailing easterly winds possibly pushed coastal waters into the estuary reducing the effect of ebb currents and water turnover, leading to a relative well mixed water column.

Secchi depth and salinity presented a similar spatial pattern, increasing constantly towards the sea, except at the Pinheiros bay, where the transparency was basically uniform along the sampling stations (Fig. 3 - B). Secchi depth ranged from a minimum of 0.5 m in Laranjeiras bay and a maximum of 3.4 m in the inlets. Highest values of water transparency were recorded during W13 (2.5±0.1 m), while S12 presented the lowest secchi depths (1.2±0.1 m).

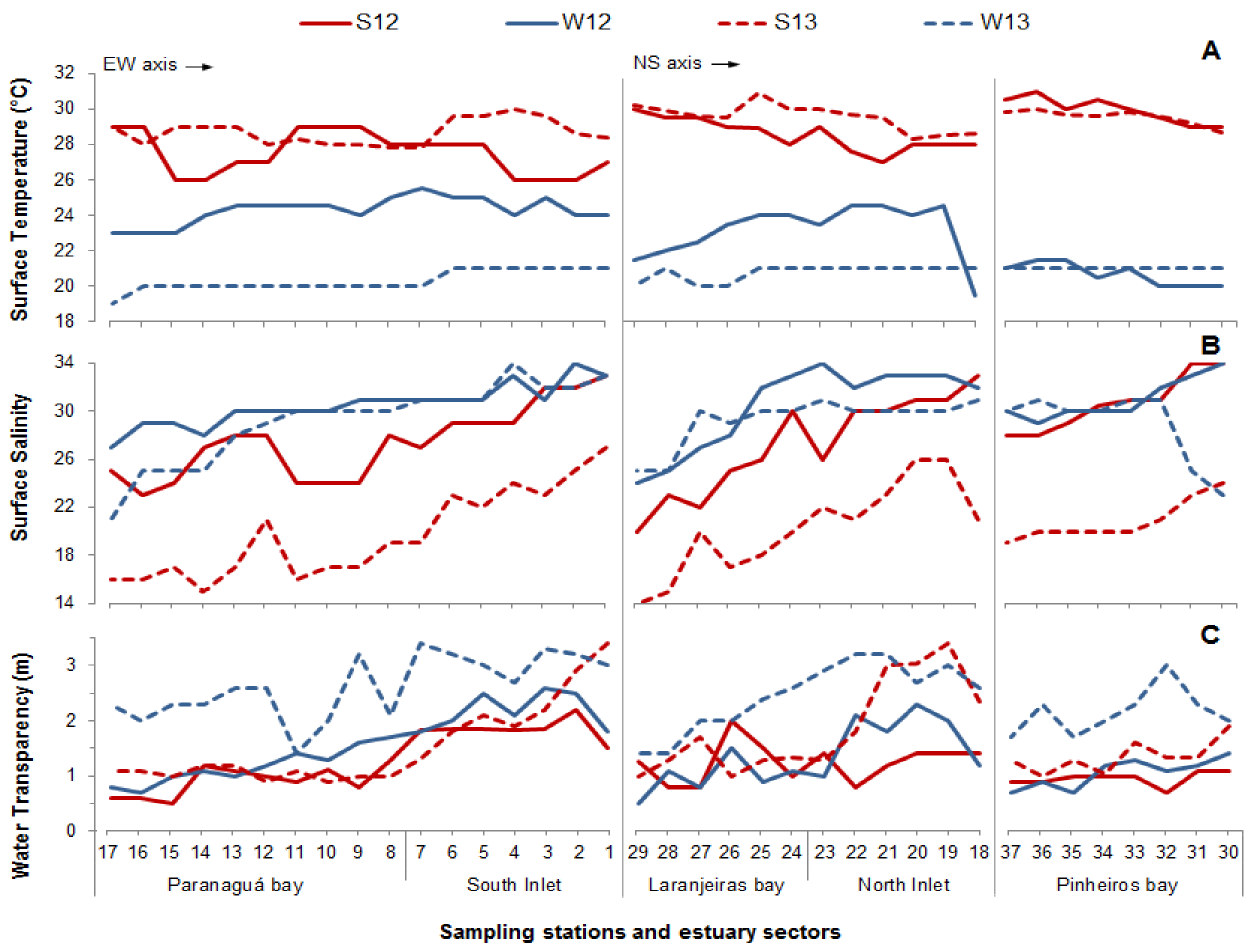

Figure 3: Spatial variation of **(A)** surface salinity, **(B)** surface temperature and **(C)** water transparency (m) for each sampling period in the Paranaguá Estuarine System.

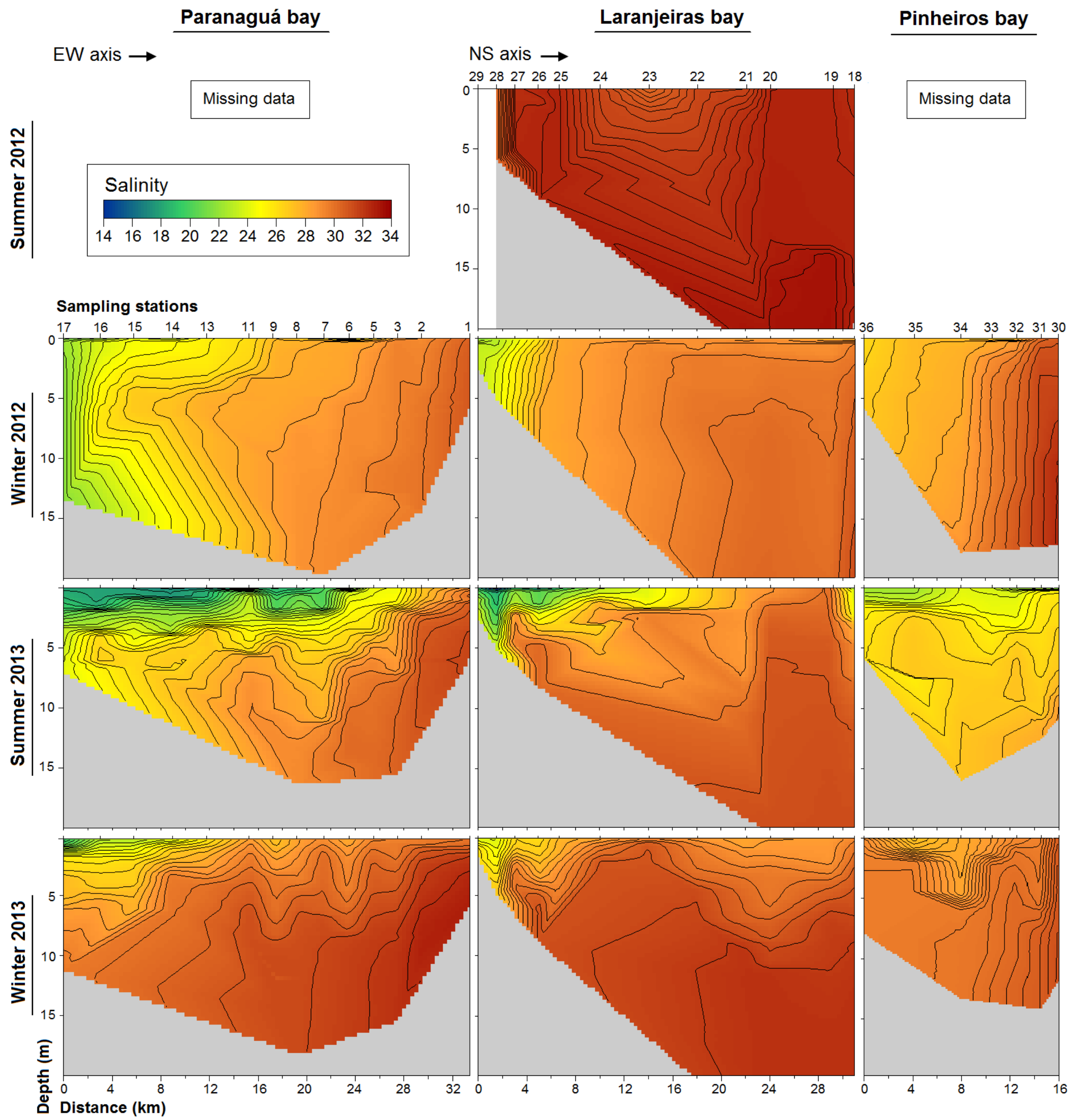

Figure 4: Interpolated vertical salinity profiles from CTD measurements on longitudinal transects through the EW axis (Paranaguá bay) and the NS axis (Laranjeiras and Pinheiros bays) for each sampling period in the Paranaguá Estuarine System (Fig. 1 – B). Gridding method: Triangular with linear interpolation. Salinity profiles from Paranaguá and Pinheiros bays during the S12 survey are not available.

3.2 Zooplankton abundance and composition

Total zooplankton abundance varied considerably within the sampling periods and a seasonal tendency could be observed. Altogether, highest densities were recorded in S12 (mean of 16378 $ind.m^{-3}$), while winter campaigns presented means of 4054 and 1591 $ind.m^{-3}$ (2012 and 2013, respectively). Nevertheless, the maximum abundance peak was registered in the S13 survey, when a large concentration of organisms occurred in the inner stations of Paranaguá bay (Fig. 5). Although most of samples from S13 presented low densities, the mean density of the period reached 10598 $ind.m^{-3}$.

During the summer, great variability in spatial abundance was observed, especially in 2013, when total densities ranged from 617 to 57593 $ind.m^{-3}$. In general, large concentrations were recorded for the Paranaguá bay sector, particularly around the harbor facilities. On the other hand, zooplankton densities during winter campaigns presented spatial distribution practically homogeneous all over the estuary (Fig. 5).

Diversity indices varied distinctly during the study period. The species richness did not exhibit marked variation between sampling periods, but taxa numbers were generally higher among downstream stations of PES (Fig. 6 – A). Shannon Index also increased toward the sea and showed more pronounced variation over the temporal scale, particularly along the EW axis, with winter assemblages presenting higher diversities than summer ones (Fig. 6 – B). Samples from the NS axis did not show a clear pattern of variation in diversity values.

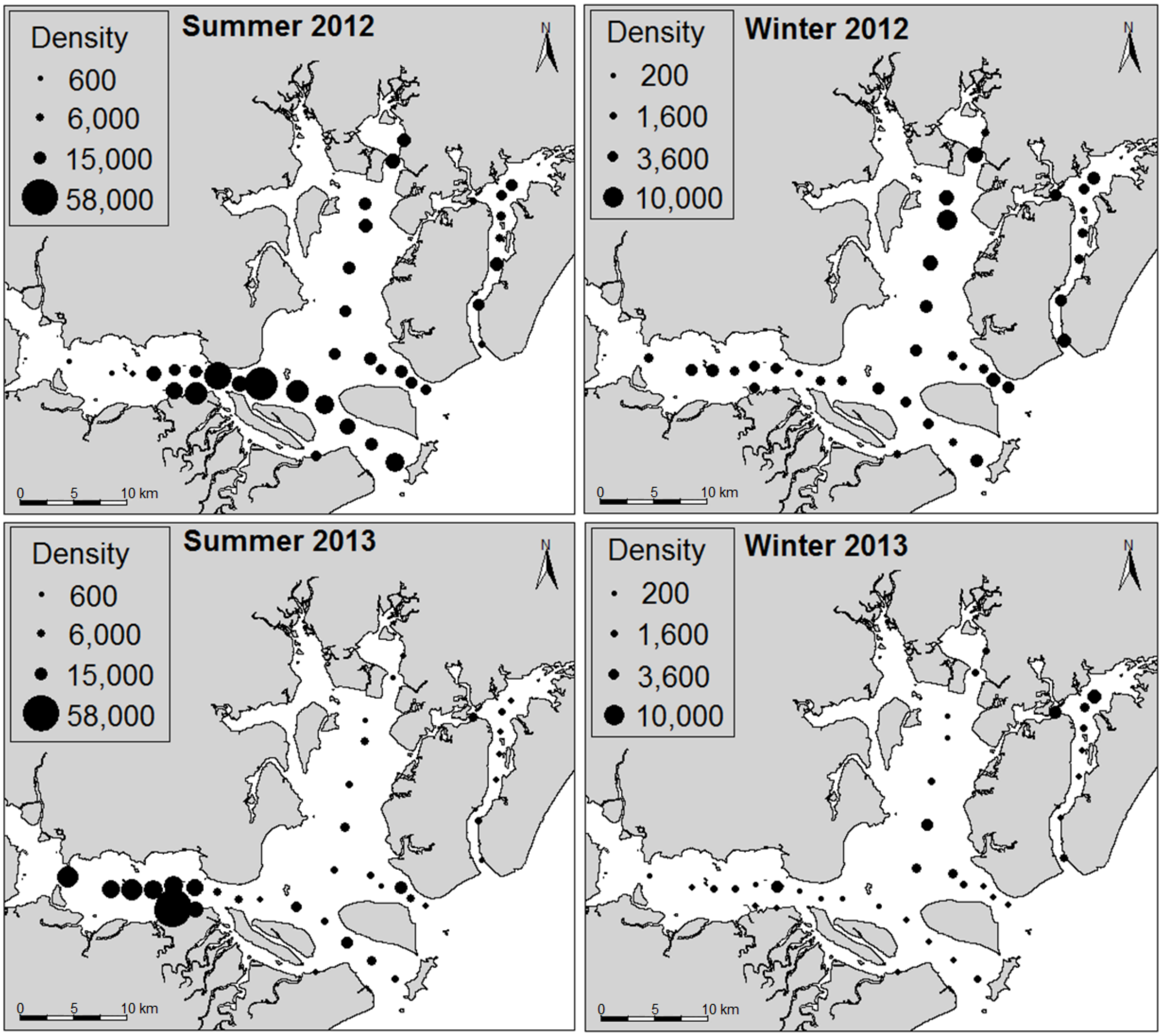

Figure 5: Spatial variation of total zooplankton densities (ind.m^{-3}) for each sampling period in the Paranaguá Estuarine System. Note different scales between summer and winter communities.

A total of 14 taxonomic groups were registered in the study area (Appendix A), being Copepoda strongly dominant in terms of abundance and diversity (92% of total abundance and 22 species identified). The remaining holoplanktonic organisms consisted mainly in Appendicularia and Chaetognatha species, contributing with 1.7 and 1.0% of total abundance, respectively (Table 2). Among meroplankton, most important groups were larvae of Decapoda, Mollusca and Cirripedia, representing together 3.3%

of total abundance. Other taxonomic groups registered were Hydromedusae, Polychaeta, Cladocera, Amphipoda, Mysida, Phoronida and Pisces.

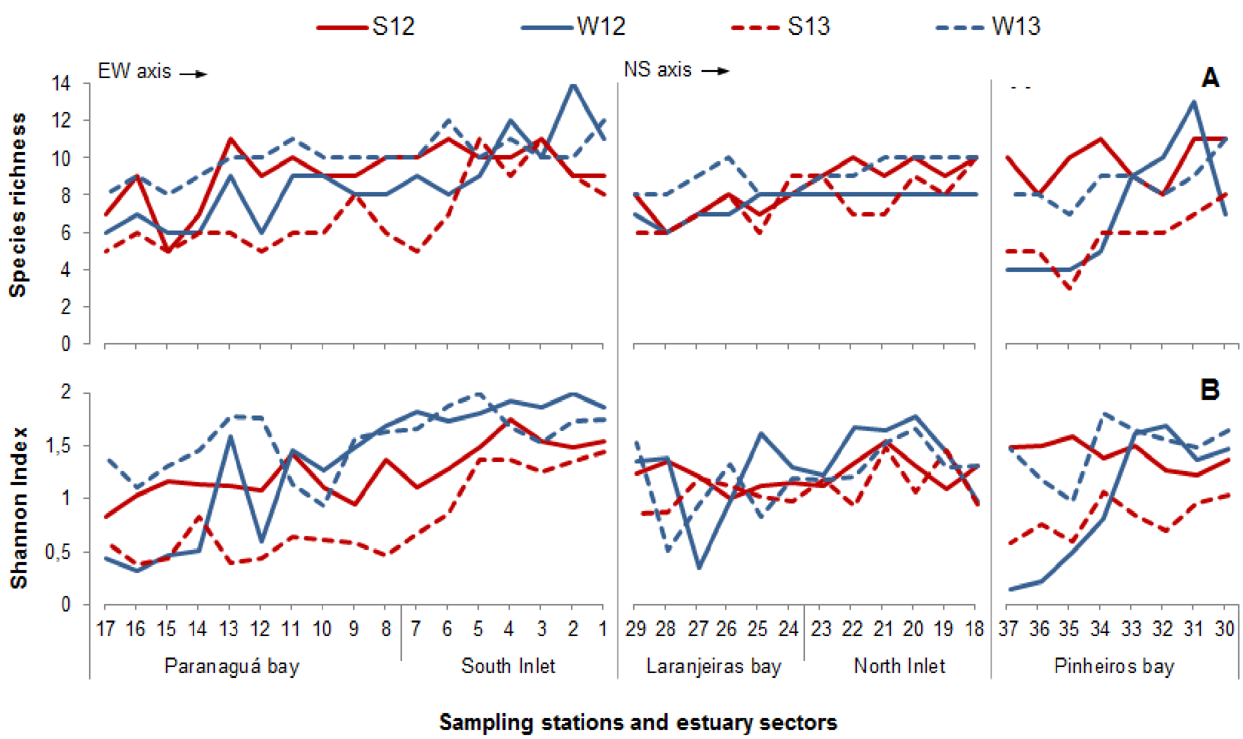

Figure 6: Spatial variation of **(A)** Species Richness and **(B)** Shannon Diversity Index for each sampling period in the Paranaguá Estuarine System.

Overall, dominant copepod species were the calanoid *Acartia lilljeborgi* (44%) and the cyclopoid *Oithona hebes* (26%), though its relative abundances have notably varied among sampling periods (Table 2). Considering the spatial-temporal variation, the estuarine copepod *Pseudodiaptomus acutus* and the marine species *Temora turbinata* were also important components of the community, contributing with 8 and 6% of total abundances, respectively. Other species that occurred regularly but in smaller numbers were *Paracalanus parvus* (3.1%) and *Labidocera fluviatilis* (1.7%). Large majority of copepods registered were estuarine and marine euryhaline, but some oceanic species sporadically occurred in the outermost stations of the estuary, such as *Ctenocalanus vanus*, *Centropages velificatus*, *Subeucalanus pileatus*, *Temora stylifera*, *Oncaea waldemari* and Corycaeus spp.

The zooplankton composition was essentially homogeneous during the study, but the species dominance and spatial distribution varied among periods (Fig. 7). Altogether, copepods composed 94% of the community in 2012 and 91% in 2013. The copepod *O. hebes* (42%) was dominant in most of the estuary during the S12 survey, being only superimposed by *A. lilljeborgi* (27%) in some sampling stations. On the other hand, the S13 was strongly dominated by the latter species (71%), especially along the EW axis, while the *O. hebes* only represented 9% of the community (Fig. 7). The third most important species in both summer campaigns was the copepod *P. acutus* (10% in 2012 and 6% in 2013), followed by *T. turbinata* in 2012 (6%) and *L. fluviatilis* in 2013 (3%). In general, summer communities presented higher species dominance, especially in 2013, when a single copepod (*A. lilljeborgi*) represented more than 60% of the community.

Table 2: Mean densities (MD±SE; ind.m^{-3}) and contribution of most important zooplankton taxa (> 1.0%) to the total zooplankton abundance (%) for each sampling period in the Paranaguá Estuarine System.

		2012				2013			
	Total	Summer		Winter		Summer		Winter	
Copepoda	%	MD±SE	%	MD±SE	%	MD±SE	%	MD±SE	%
Acartia lilljeborgi	44	4386 (839)	27	1851 (265)	46	7504 (1705)	71	535 (125)	34
Euterpina acutifrons	1	81 (20)	0	68 (12)	2	5 (2)	0	23 (4)	1
Labidocera fluviatilis	2	73 (13)	0	163 (21)	4	318 (73)	3	14 (3)	1
Oithona hebes	26	6883 (918)	42	372 (57)	9	939 (140)	9	175 (25)	11
Paracalanus parvus	3	531 (121)	3	294 (63)	7	88 (25)	1	90 (18)	6
Parvocalanus crassirostris	1	195 (49)	1	14 (7)	0	3 (2)	0	14 (2)	1
Pseudodiaptomus acutus	8	1707 (259)	10	196 (47)	5	667 (132)	6	95 (18)	6
Temora turbinata	6	913 (243)	6	522 (110)	13	42 (18)	0	449 (103)	28
Other									
Appendicularia	2	210 (32)	1	122 (15)	3	146 (27)	1	61 (10)	4
Chaetognatha	1	167 (26)	1	39 (8)	1	107 (32)	1	10 (3)	1
Cirripedia	1	75 (17)	0	97 (22)	2	167 (49)	2	36 (4)	2
Decapoda	1	164 (28)	1	76 (19)	2	142 (29)	1	6 (1)	0
Mollusca	1	157 (34)	1	66 (19)	2	89 (23)	1	26 (5)	2

During winter surveys, the species composition was more equitably in terms of distribution and dominance. The most abundant species were *A. lilljeborgi* (46% in 2012 and 34% in 2013), numerically dominant in the inner sectors of PES, and *T. turbinata* (13% in 2012 and 28% in 2013), occurring especially at the downstream stations in 2012 and all over the estuary in 2013 (Fig. 7). The copepod *O. hebes* was the third most important species during winter (9% in 2012 and 11% in 2013), followed by *P. parvus* in 2012 (7%) and *P. acutus* in 2013 (6%). In general, non-copepods organisms were slightly more abundant during the winter, representing 13% of the community in 2012 and 10% in 2013. Most important groups were Appendicularia (3.0% in 2012 and 3.8% in 2013) and Cirripedia larvae (approximately 2.5% in both years; Table 2).

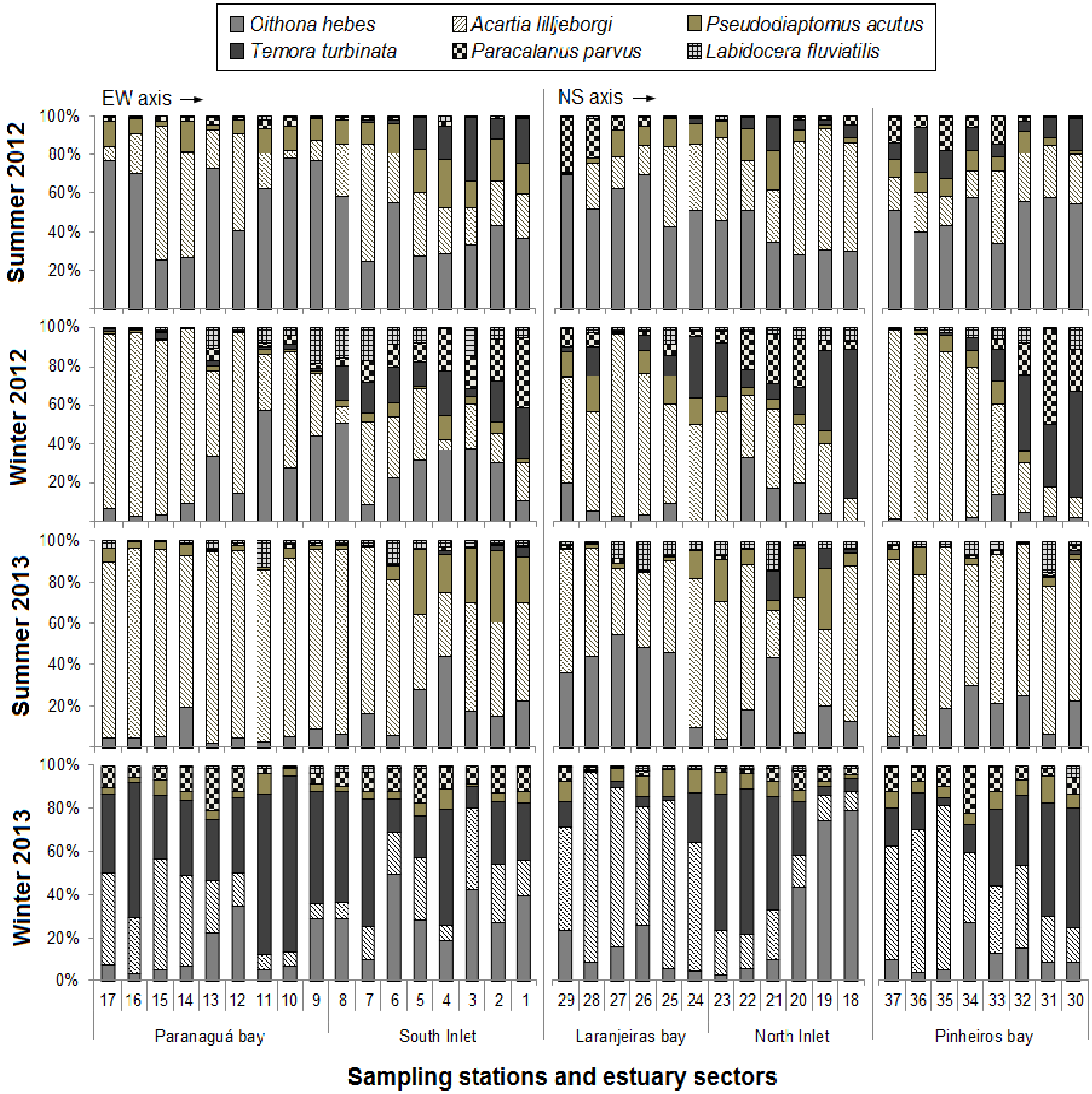

Figure 7: Spatial variation in composition of the most important copepods registered in the Paranaguá Estuarine System during the study period.

3.3 Community variability and environmental influences

In general, zooplankton community was seasonally distinguished in the PCO plot with two major groups separating summer from winter surveys (Fig. 8 - A). These major groups were also subdivided according to sampling periods (2012 and 2013), resulting in four assemblages based on abundance and species composition, even though some overlapping occurred among stations. The first two axes of the principal coordinate analysis captured 59% of the total variation in zooplankton assemblages. Differences in abundance explained the major variability by progressively decreasing along the first axis (PCO1 – 44.5%), especially over the temporal scale, separating S12 from W13 surveys (highest to lowest densities; Fig. 8 - C). Generally, the remaining variation (PCO2 – 14.4%) can be explained by differences in biodiversity, represented in the plot by Shannon Diversity Index, with highest values observed in the S12 and winter survey, especially among outer stations of PES (Fig. 8 – D). Spatial differences in abundance and species distribution between stations were also responsible for great variability within zooplankton assemblages.

Highest spatial variability were observed among W12 and S13 campaigns, being the former caused by differences in species diversity, as could be seen by the dispersion along the second axes; and the latter caused by differences in abundance, dispersing along the first axes. However, it was not possible to distinguish a clear pattern of variation among sampling stations or estuary sectors (Fig. 8 – B).

Despite moderate convergence of abundance and composition between groups, as showed by the PCO, differences were statically significant between all zooplankton assemblages (PERMANOVA: $p < 0.05$; Table 3 - A). However, differences within-group were highly significant between estuary sectors (PERMDISP: $p < 0.05$), indicating that the spatial variation was affected by dispersion among samples. On the other hand, as no dispersion effects were found between sampling periods (PERMDISP: $p > 0.05$), its indicated that temporal variation were actually induced by differences in abundance and species composition.

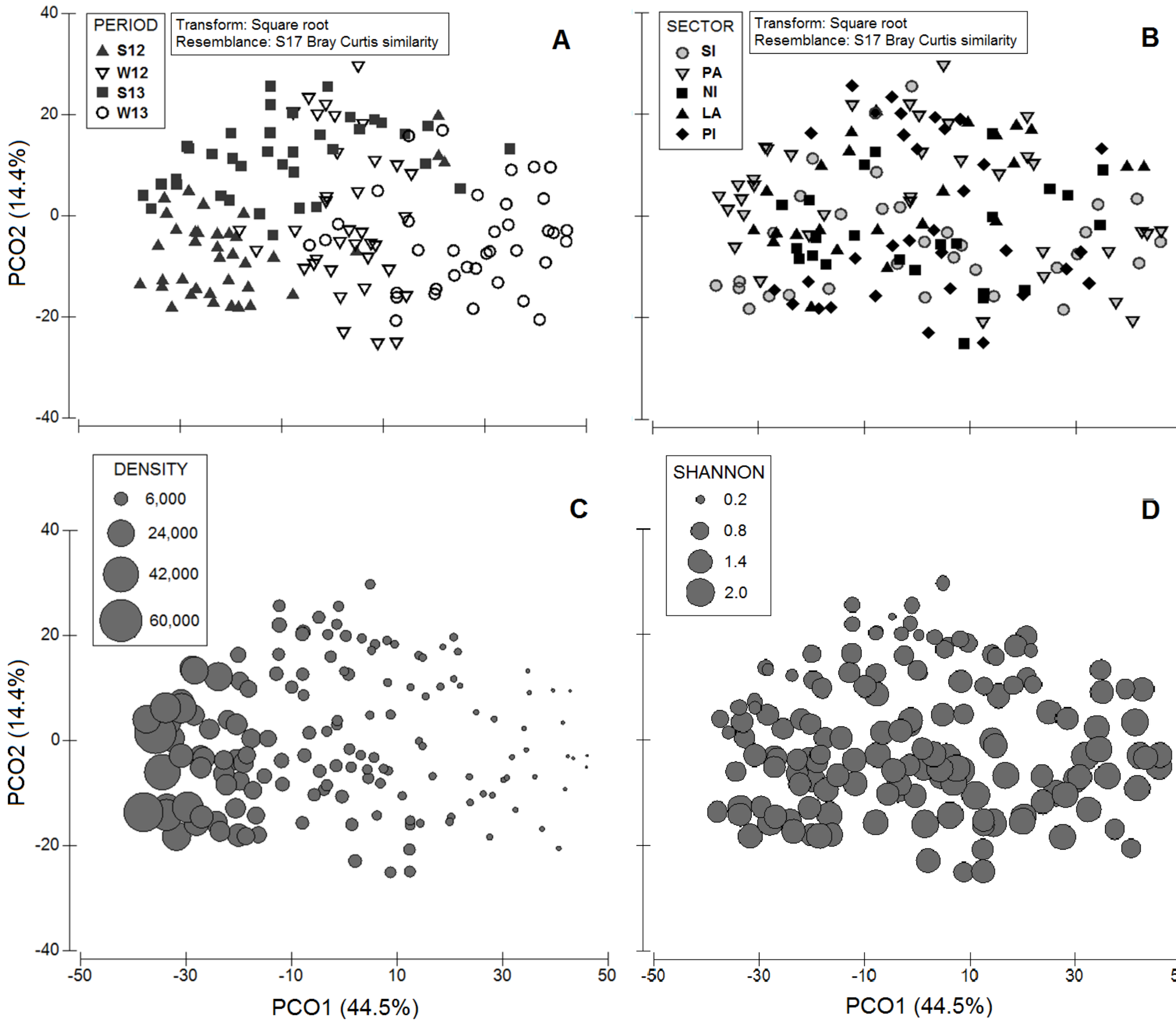

Figure 7: Principal Coordinate Analysis (PCO) of zooplankton abundance and composition in the Paranaguá Estuarine System according to **(A)** sampling periods and **(B)** estuary sectors. Superposition of **(C)** total densities (ind.m^{-3}) and **(D)** Shannon Diversity Index on the ordination plot as volume bubbles.

As PERMANOVA results also showed significant interactions between location and period (p < 0.05), pairwise comparisons among all levels of both factors were performed. Differences between sampling periods were statistically significant for all estuary sectors analyzed separately ($p < 0.05$), indicating that the community structure varied by sector depending on sampling period (Table 3 – B). In general, spatial patterns in zooplankton assemblages were not detected, but better distinction between sectors was observed within S12 and W12 surveys. Only the most spatially distant sectors, as Paranaguá and Pinheiros bays or South inlet and Laranjeiras bay, were significantly different at all sampling periods.

Table 3: (A) PERMANOVA and PERMDISP results (*p*-values from permutation tests) for differences in zooplankton assemblages between sampling periods and estuary sectors in the in the Paranaguá Estuarine System. **(B)** PERMANOVA results from pairwise comparisons among spatial levels of each survey. Significant differences ($p < 0.05$) in bold.

A	**PERMANOVA**			**PERMDISP**		
Groups	N	pseudo-*F*	*p*	N	*F*	*P*
Sampling periods	9919	38.06	**0,0001**	9999	2.13	0.128
Estuary sectors	9910	3.76	**0,0001**	9999	5.73	**0.001**
Periods * Sectors	9848	4.35	**0,0001**			

B	**2012**				**2013**			
	Summer		**Winter**		**Summer**		**Winter**	
Sectors	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*P*
SI – PA	2.10	**0.012**	3.12	**0.000**	3.05	**0.000**	1.13	0.259
SI – NI	1.91	**0.004**	1.59	**0.025**	0.77	0.695	1.40	0.125
SI – LA	2.28	**0.000**	3.28	**0.000**	1.73	**0.017**	2.08	**0.006**
SI – PI	2.82	**0.000**	2.03	**0.011**	1.86	**0.012**	2.73	**0.001**
PA – NI	1.51	0.086	2.44	**0.000**	3.17	**0.000**	1.34	0.154
PA – LA	1.37	0.139	2.42	**0.000**	3.19	**0.001**	1.81	**0.035**
PA – PI	1.86	**0.033**	1.75	**0.030**	3.94	**0.000**	2.22	**0.013**
NI – LA	2.21	**0.006**	1.77	**0.015**	1.39	0.097	1.37	0.157
NI – PI	1.92	**0.004**	1.08	0.310	1.32	0.125	1.39	0.129
LA - PI	2.22	**0.003**	1.50	0.085	0.92	0.502	1.78	**0.044**

The Canonical Analysis CAP revealed significant correlations between zooplankton assemblages and environmental parameters ($p < 0.05$; Fig. 9 - A). The first canonical axis presented the strongest relationship with the abiotic variables (73%, $p < 0.05$), especially water temperature. The second axis had a smaller correlation (39%) and was mainly associated with salinity variation.

As expected, summer assemblages were positively correlated to water temperature (S13) and precipitation rates (S12), while winter communities were related to higher salinities and transparency values (Secchi depth). Salinity differences vertically separated summer assemblages from 2012 and 2013, and created a spatial gradient of variation among winter samples, especially in 2012, with values increasing toward the sea. Salinity stratification was inversely related to surface salinity but presented much smaller correlation ($r^2 < 0.4$), being associated with some samples from S13 and W12. On the other hand, zonal winds showed strong correlations with zooplankton assemblages, specifically due to its negative relation to the S12 survey, when easterly winds were dominant.

Correlations (Spearman rank) of zooplankton species/groups with the resulting CAP axes indicated which taxa most contributed to observed differences among groups and its relations to abiotic parameters (Fig. 9 - B). Species with the strongest correlations were *T. turbinata* (CAP1, $\rho = 0.73$), *A. lilljeborgi* (CAP2, $\rho = -0.67$) and *O. hebes* (CAP3, $\rho = -0.61$). The S12 survey was mainly distinguished by the coastal estuarine copepods *O. hebes* and *P. acutus*, while *A. lilljeborgi* was particularly important in S13 and some low salinities stations from W12. *Labidocera fluviatilis*, a typical estuarine copepod, was also negatively associated with salinity, but presented a small correlation with the CAP axes and wasn't related to any special group. Marine species *T. turbinata, E. acutifrons* and *P. parvus* characterized the winter assemblages, being strongly associated to higher salinities and water transparency, especially in the outer stations of PES. Among non-copepods, low correlations were detected. Either way, Chaetognatha, Decapoda and Polychaeta larvae showed greater affinity with summer assemblages, while Appendicularia and Cirripedia larvae were related to winter communities.

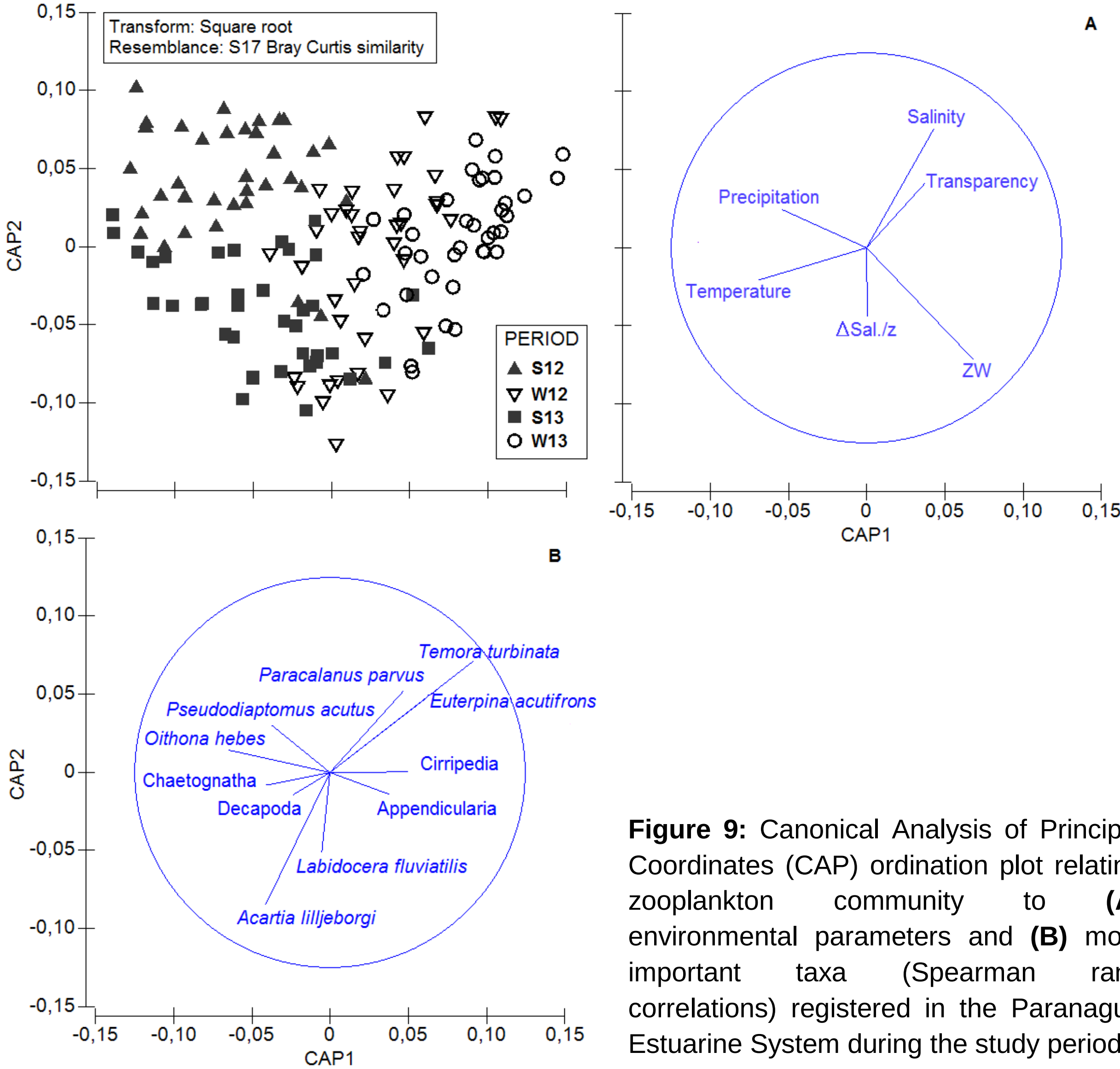

Figure 9: Canonical Analysis of Principal Coordinates (CAP) ordination plot relating zooplankton community to **(A)** environmental parameters and **(B)** most important taxa (Spearman rank correlations) registered in the Paranaguá Estuarine System during the study period.

4 Discussion

Environmental conditions strongly affected the zooplankton abundance and composition in the Paranaguá Estuarine System during the study periods. As observed in other estuaries worldwide, the spatial-temporal variation in zooplankton assemblages is determined by seasonal alterations in abiotic parameters due to changing prominence of coastal and riverine forces (Laprise and Dodson, 1994; Primo et al., 2009; Bollens et al., 2011; Breckenridge et al., 2015). In addition to the hydrological features, alterations in trophic status between rainy and dry periods may have affected the community structure as a response to changes in food quality and availability.

Differences in abundance were the main source of zooplankton variability, principally separating summer from winter communities. Along the estuary, these differences were also responsible for spatial variations, especially during summer surveys, when the abundance peaks were recorded. In relation to species composition, the community didn’t show great variation, being dominated by almost the same group of copepods during the study period. However, changes in relative importance of some species characterized a secondary source of variability in the PES, with greater diversities generally associated with higher salinities values.

Although zooplankton community showed typical seasonal characteristics, the community varied according to specific conditions of each sampling campaign. Differences in abundance were directly related to water temperature and precipitation rates, being the main factors associated with temporal fluctuations in the community. Maximum zooplankton densities were recorded during summer surveys, when heavy rainfall directly affects the environmental conditions in the area through large freshwater discharge into the PES (Marone et al., 2005). Numerous studies around the world have shown how estuarine populations may respond to increasing freshwater flow through several mechanisms (Kimmerer, 2002). Positive effects are related to trophic linkages, when nutrients enrichment stimulates the primary production providing abundant food supply to herbivore grazers, as copepods and other zooplankton organisms (Kimmel and Roman, 2004). However, intense freshwater flow can also negatively affect biological populations through advective transport and washout, dispersing the organisms before they demographically respond to the increased food supply within the estuary (Pace et al., 1992; Lawrence et al., 2004).

According to Mantovanelli et al. (2004), advective transport is the main process controlling the water circulation in Paranaguá bay under high-stratified conditions, especially observed in the rainy summer environments. Moreover, previous studies have shown the importance of continental drainage as main source of nutrients and organic matter in the Paranaguá bay (Machado et al., 1997; Mizerkowski et al., 2012). However, ecological process and zooplankton responses to this enrichment are still uncertain (Marone et al., 2005). Nevertheless, the results obtained here suggested that both mechanisms can occur in the study area, mainly because summer samplings varied considerably regarding to abundance distribution along the estuary.

The S13 survey was characterized by very heterogeneous conditions, especially evident by marked vertical and horizontal salinity stratification. Even though total mean densities were very similar, this period presented higher abundance variation than the S12 survey. Low densities registered in most of samples from S13 suggest the community could have suffered abundance losses due to strong effects of advective transport and organism dispersion (Pace et al., 1992). On the other hand, extremely high densities in the inner stations of Paranaguá bay may have been enable by the occurrence of a “Maximum Turbidity Zone” around the harbor area (Noernberg, 2001), acting as a physical barrier to advective transport and concentrating the organisms above the mixing zone (Roman et al., 2001).

Abundance peaks in S13 were directly related to high densities of the copepod *A. lilljeborgi*, a coastal neritic calanoid widely distributed in estuarine waters of Brazil (Lopes, 1994; Ara, 2001a; Sant’Anna and Björnberg, 2006). The species is known to tolerate a wide range of salinity variation, but various studies have shown its preference to higher salinities (Björnberg, 1981; Lopes, et al., 1998; Sterza and Fernandes, 2006). Even though the S13 survey was characterized by lower superficial salinities, the water column showed pronounced salinity stratification, explaining the species occurrence in the inner stations of Paranaguá bay.

The dominance of *A. lilljeborgi* during the study period was only overcome by the cyclopoid *O. hebes* in the S12 survey, when particular environmental settings possibly affected the community abundance and structure. Small body-length copepods such as *Oithona* are frequently associated with high temperatures and eutrophic conditions in estuarine ecosystems (Park and Marshall, 2000; Ara, 2004; Lam-Hoai et al., 2006). A general shift to small-sized cyclopoids with increasing eutrophication can be attributed to a change in the food quality, from large diatoms to small flagellates, the preferred prey of cyclopoids (Uye, 1994; Marcus, 2004; Chen et al., 2011). Moreover, Almeda et al. (2010) suggested that Oithonids lower metabolic needs, in comparison to calanoids, may explain their high abundance both in coastal eutrophic waters and in oligotrophic oceanic environments. Indeed, the S12 campaign presented a combination of climate and hydrological conditions that may have promoted a particularly thriving environment, resulting in generally high densities especially distributed along the EW axis. While the continental drainage contributed to the nutrients enrichment and food availability, constant and intense easterly winds may have increased the water residence time in the system, allowing the plankton community to successfully grow and develop within the estuary. Additionally, the well mixed conditions observed in the S12 may have increased the suspended particles concentration in the water column, acting as an alternative source of nutrients and organic matter to the ecosystem.

The occasional dominance shift from the ubiquitous *A. lilljeborgi* toward *O. hebes* in summer communities possibly represents a biological indicator of changing food resources and estuarine trophic state, as observed by Murrell and Lores (2004) in a subtropical estuary in Florida. The authors verified higher densities of *Oithona* sp. with increases in picophytoplankton during the summer, while the dominant species *Acartia tonsa* was possibly food-limited and decreased in abundance. Alterations in the zooplankton community may eventually affect higher trophic levels through bottom-up process, leading to major impacts on fish populations (Marcus, 2004). In this case, the replacement of a large calanoid such as *A. lilljeborgi* by the small-sized cyclopoid *O. hebes* may be unfavorable for some planktivorous fish, as observed in Tokyo bay by Uye (1994). Even with elevated zooplankton biomasses, higher-order consumers may decline due to changes in food quality and nutritional conditions following the taxonomic shifts in the zooplankton community (Kratina and Winder, 2015). These observations highlight the importance of more detailed studies about the plankton dynamics and ecological process in the PEC.

Other small-sized copepod observed in the S12 survey was the poecilostomatoid *O. waldemari*, being the first record of the species in the PEC. In general, Oncaeidae family is composed by marine pelagic microcopepods especially relevant in oceanic waters, being among the most numerically important copepods in Brazilian coast (Sartori and Lopes, 2000; Miyashita et al., 2009; Brandini et al., 2014). Some species were already registered in Brazilian estuaries and in the PES, such as *O. venusta* and *O. media*, but in very low frequency and abundance (Lopes et al., 1998). The absence of *O. waldemari* in previous studies may be related to the relatively recent species description (Bersano and Boxshall, 1994), in addition to its small size (< 0.6 mm body length), probably being undersampled by common use of nets with meshes > 200 µm. In this study, the species occurred in all sampling periods but was especially important in the S12 survey, when it was registered in more than 50% of the samples. This fact may be related to the particular environmental conditions observed in the period, which also favored the small-sized cyclopoid *O. hebes*.

The spatial variation in trophic conditions may also be responsible for differences in abundance within the estuary. Abundance fluctuations were more pronounced at the EW axes, where zooplankton densities reached maximum peaks in summer samples. This area, and especially the southern margin, concentrates the majority of human occupation and economical activities around the PES, such as port industries, fisheries and agriculture (Marone et al., 2005). The city and harbor of Paranaguá are responsible for a significant amount of anthropogenic nutrient inputs into the bay, which may trigger primary production, especially in the typically stratified conditions of the rainy season (Mizerkowski et al., 2012). In fact, the occurrence of high phytoplankton stocks in the middle sector of the bay was previously described by several studies (Knoppers et al., 1987; Brandini et al., 1988; Machado et al., 1997), and seen to be a typical feature of the estuary. Therefore, favorable food conditions should probably support seasonal peaks of zooplankton abundance in the area, although its distribution and permanence in the estuary may depend on circulation processes. On the other hand, usually lowest densities registered in the NS axis can be associated with the relative reduced inputs of nutrients and organic matter in comparison to the EW axis, since the area is not affected by anthropogenic activities (Lana et al., 2001; Martins et al., 2012).

During the winter, when the water column is typically well mixed and low stratified (Mantovanelli et al., 2004), the trophic status of Paranaguá bay was previously evaluated as almost oligotrophic in response to lower freshwater inputs and light incidence (Knoppers et al., 1987; Marone et al., 2005). As expected, the zooplankton density in winter campaigns decreased to minimum levels due to lowest water temperatures and food supplies. With generally low densities along the estuary, winter communities varied mainly in species composition and diversity and this variation was strongly related to salinity values. In fact, the salinity gradient is known as key factor controlling the overall composition and species distribution in estuarine environments, with organisms segregating according to its salinity tolerance and physiological adaptations (Marques et al., 2008; Bollens et al., 2011). For all sampling periods, higher diversities were generally found in the inlets, where marine euryhaline and stenohaline species can occur depending on circulation conditions. In the EW axis, larger marine influence and more intense water circulation due to constant dredging and port activities enabled the penetration of these species further into the Paranaguá bay, as already observed by Miyashita et al. (2012). The reduced river flow during dry periods allows a major penetration of seawater, resulting in higher salinities along estuarine ecosystems (Primo et al., 2009). The consequent influx of marine species, along with resident estuarine organisms, resulted in higher zooplankton diversity in winter assemblages and particularly in stations situated near the estuary channels.

The most numerically important organism indicating the intrusion of seawater was the copepod *T. turbinata*, a typical species from tropical and subtropical coastal waters of North Hemisphere (Lopes et al., 1998). Studies in estuarine environments have shown the species preference to higher salinities, being specially concentrated around the inlets (Lopes et al., 1998; Ara, 2002; Sant'Anna and Björnberg, 2006). This copepod was first registered in Brazilian waters in the mid-1980s and is currently one of the most abundant species found in estuarine and neritic waters of Brazil (Ara, 2001b; Sterza and Fernandes, 2006; Araújo et al., 2008). In the PES, the only Temoridae species registered by the end of 1990s was *T. stylifera* (Montú and Cordeiro, 1988; Lopes et al., 1998), which is now being consistently replaced by the invasive copepod, one of the four most important species found in this study. *T. stylifera* was registered in very small number and frequency at outer samples of winter surveys, being considered a marine stenohaline copepod (Lopes et al., 1998) and suggesting the species is more abundant in the adjacent continental shelf. On the other hand, *T. turbinata*, considered a marine euryhaline by Lopes et al. (1998), was registered in the PES inlets at all sampling periods during this study. Moreover, the species was especially important in the winter surveys when it presented larger distribution and abundance over the estuary.

Among coastal and shelf copepods registered in the estuary, the sub-Antarctic calanoid *C. vanus* play an important role as biological indicator of upwelling effects in the southern Brazilian coast (Björnberg, 1981; Valentin, 1984). The species was registered during the W12 and S13 surveys in the outermost sampling stations, but its abundance and frequency were very low. The occurrence of *C. vanus* in southern

Brazilian waters is related to the frequent intrusion of cold and nutrient-rich South Atlantic Central Water in the summer due to the prominence of Northeasterly winds moving coastal waters away from the coast (Lopes et al., 1999; Sant'Anna and Björnberg, 2006; Brandini et al., 2014), as observed in the S13 campaign. On the other hand, constant S – SE winds in the winter could extend the influence of cold sub-Antartic waters transported northwards by the Malvinas Current (Soares and Möller, 2001; Ávila et al., 2009), possibly explaining the presence of *C. vanus* in the W12 samples. These observations provide complementary information about the hydrographic conditions and water circulation off Paranaguá Estuarine System, which are essential for a better understanding of ecological processes and biological productivity in the coastal area.

5 Conclusions

The zooplankton dynamics in the Paranaguá Estuarine System is strongly associated with environmental changes induced by seasonal atmospheric variations. In general, variations in zooplankton abundance and distribution exhibit seasonal characteristics, being especially determined by the succession of rainy and dry periods. Differences in abundance are the main source of variability in the community, being particularly evident over the temporal scale. During the rainy season (summer), the community reaches highest densities and presents great spatial variability due to organism concentrations in the Paranaguá bay area. Maximum abundance peaks recorded in this study were 51632 ind.m^{-3} in 2012 and 57593 ind.m^{-3} in 2013. On the other hand, winter communities are characterized by low densities all over the PES, with spatial variation mainly caused by composition changes due to salinity differences along the estuary. Mean densities registered here during the winter were 4054 ind.m^{-3} in 2012 and 1591 ind.m^{-3} in 2013.

Regarding the composition, the PES zooplankton is dominated by holoplanktonic organisms, being Copepoda the most abundant and diverse group. In terms of frequency and abundance, the most important species are the copepods *Acartia lilljeborgi*, *Oithona hebes*, *Pseudodiaptomus acutus* and *Temora turbinata.* The former three species occur regularly along the entire estuary, whereas the copepod *T. turbinata* is strongly related to higher salinities, constituting an indicator of euhaline waters. In general, the salinity gradient is the main factor affecting the community distribution and composition. The highest diversity is observed in the outer portions of the estuary, with influence of coastal waters, especially during dry winters when the marine influence is predominant.

Appendix

Appendix A: List of species registered at the Paranaguá Estuarine System during summer and winter of 2012 and 2013.

Filo Cnidaria

Hydromedusae

Filo Annelida

Polychaeta (larvae)

Filo Mollusca

Gastropoda (veliger)

Bivalvia (veliger)

Filo Arthropoda

Crustacea

Ordem Cladocera

Penilia avirostris (Dana, 1852)

Pseudevadne tergestina (Claus, 1877)

Cirripedia (nauplius)

Ostracoda

Copepoda

Ordem Calanoida

Acartia lilljeborgi (Giesbrecht, 1889)

Acartia tonsa (Dana, 1849)

Centropages velificatus (Oliveira, 1947)

Clausocalanus furcatus (Brady, 1883)

Ctenocalanus vanus (Giesbrecht, 1888)

Labidocera fluviatilis (Dahl, 1894)

Paracalanus parvus (Claus, 1863)

Parvocalanus crassirostris (Dahl, 1894)

Pseudodiaptomus acutus (Dahl, 1894)

Subeucalanus pileatus (Giesbrecht, 1888)

Temora stylifera (Dana, 1849)

Temora turbinata (Dana, 1849)

Ordem Cyclopoida

Oithona hebes (Giesbrecht, 1891)

Oithona plumifera (Baird, 1843)

Ordem Poecilostomatoida

Corycaeus speciosus (Dana, 1849)

Ditrichocorycaeus amazonicus (Dahl, 1894)

Oncaea media (Giesbrecht, 1891)

Oncaea waldemari (Bersano & Boxshall, 1994)

Onychocorycaeus giesbrechti (Dahl, 1894)

Ordem Harpacticoida

Euterpina acutifrons (Dana, 1852)

Microsetella norvergica (Boeck, 1865)

Microsetella rosea (Dana, 1847)

Malacostraca

Ordem Mysida

Ordem Amphipoda

Ordem Decapoda (larvae)

Filo Phoronida (larvae)

Filo Chaetognatha

Sagitta spp.

Filo Chordata

Appendicularia

Oikopleura spp.

Pisces (larvae)

References

ALMEDA, R.; AUGUSTIN, C.B.; ALCARAZ, M.; CALBET, A.; SAIZ, E. (2010). Feeding rates and gross growth efficiencies of larval development stages of Oithona davisae (Copepoda, Cyclopoida). **Journal of Experimental Marine Biology and Ecology**, v. 387, p. 24-35.

ANDERSON, M.J. (2001). A new method for non-parametric multivariate analysis os variance. **Austral Ecology**, v. 26, p. 32-46.

ANDERSON, M.J.; WILLIS, T.J. (2003). Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. **Ecology**, v. 82, n. 2, p. 511-525.

ANDERSON, M.J. (2006). Distance-Based Test for Homogeneity of Multivariate Dispersions. **Biometrics**, v. 62, p. 245-253.

ANDERSON, M.J.; GORLEY, R.N.; CLARKE, K.R. (2008). **PERMANOVA+ for PRIMER: Guide to software and statistical methods**. PRIMER-E, Plymouth, UK.

ARA, K. (2001a). Temporal variability and production of the planktonic copepods in the Cananéia Lagoon estuarine system, São Paulo, Brazil. II. *Acartia lilljeborgi*. **Plankton Biol. Ecol.**, v, 48, p. 35-45.

ARA, K. (2001b). Length-weight relationships and chemical content of the planktonic copepods in the Cananéia Lagoon Estuarine System, São Paulo, Brazil. **Plankton Biology & Ecology**, v. 48, n. 2, p. 121-127.

ARA, K. (2002). Temporal variability and production of *Temora turbinata* (Copepoda: Calanoida) in the Cananéia Lagoon Estuarine System, São Paulo, Brazil. **Scientia Marina,** v. 66, p. 399-406.

ARA, K. (2004). Temporal variability and production of the planktonic copepod community in the Cananéia Lagoon Estuarine System, São Paulo, Brazil. **Zoological Studies,** v. 43, n. 2, p. 179-186.

ARAÚJO, H.M.P.; NASCIMENTO-VIEIRA, D.A.; NEUMANN-LEITÃO, S.; SCHWAMBORN, R.; LUCAS, A.P.O.; ALVES, J.P.H. (2008). Zooplankton community dynamics in relation to the seasonal cycle and nutrient inputs in an urban tropical estuary in Brazil. **Braz. J. Biol.**, v. 68, n. 4, p. 751-762.

ÁVILA, T.R.; PEDROZO, C.S.; BERSANO, J.G.F. (2009). Variação temporal do zooplâncton da Praia de Tramandaí, Rio Grande do Sul, com ênfase em Copepoda. **Iheringia**, n. 99, p. 18-26.

BERSANO, J.G.F.; BOXSHALL, G.A. (1994). Planktonic copepods of the genus *Oncaea Philippi* (Poecilostomatoida: Oncaeidae) from the waters off southern Brazil. **Nauplius,**

v. 2, p. 29-41.

BJÖRNBERG, T.K.S. (1981). Copepoda. *In:* BOLTOVSKOY, D. (Ed.). **Atlas del Zooplancton del Atlantico Suboccidental y Métodos de Trabajo con el Zooplancton Marino**. Mar Del Plata: INIDEP, p. 587-679.

BOLLENS, S.M.; BRECKENRIDGE, J.K.; HOOFF, R.C.; CORDELL, J.R. (2011). Mesozooplankton of the lower San Francisco Estuary: spatio-temporal patterns, ENSO effects and the prevalence of non-indigenous species. **Journal of Plankton Research,** v. 33, n. 9, p. 1358-1377**.**

BOLTOVSKOY, D. (1999). ***South Atlantic Zooplankton***. Leiden: Backhuys Publishers, v.2, 1706 p.

BRANDINI, F.P.; THAMM, C.A.; VENTURA, I. (1988). Ecological studies in the Bay of Paranaguá III. Seasonal and spatial variations of nutrients and chlorophyll-*a*. **Nerítica**, v. 8, p. 55-72.

BRANDINI, F.P.; NOGUEIRA, M.; SIMIÃO, M.; CODINA, J.C.U.; NOERNBERG, M. (2014). Deep Chlorophyll maximum and plankton community response to oceanic bottom intrusions on the continental shelf in the South Brazilian Bight. **Continental shelf Research**, v. 89, p. 61-75.

BRECKENRIDGE, J.K.; BOLLENS, S.M.; ROLLWAGEN-BOLLENS, G.; ROEGNER, G.C. (2015). Plankton assemblage variability in a river-dominated temperate estuary during late Spring (high-flow) and late Summer (low-flow) periods. **Estuaries and Coasts**, v. 38, p. 93-103.

CHIBA, S.; SAINO, T. (2003). Variation in mesozooplankton community structure in the Japan/East Sea (1991-1999) with possible influence of ENSO scale climatic variability. **Progress in Oceanography,** v. 57, p. 317-339.

CHEN, M.; CHEN, B.; HARRISON, P.; LIU, H. (2011). Dynamics of mesozooplankton assemblages in subtropical coastal waters of Hong Kong: A comparative study between a eutrophic estuarine and a mesotrophic coastal site. **Continetal Shelf Research,** v. 31, p. 1075-1086.

COSTELLO, J.H.; SULLIVAN, B.K.; GIFFORD, D.J. (2006). A physical–biological interaction underlying variable phenological responses to climate change by coastal zooplankton. **Journal of Plankton Research**, v. 28, n. 11, p. 1099–1105.

DAVID, V.; SAUTOUR, B.; CHARDY, P.; LECONTE, M. (2005). Long-term changes of the zooplankton variability in a turbid environment: the Gironde estuary (France). **Estuarine, Coastal and Shelf Science**, v. 64, p. 171-184.

FLINDT, M.R.; PARDAL, M.A.; LILLEBØ, A.I.; MARTINS, I.; MARQUES, J.C. (1999). Nutrient cycling and plant dynamics in estuaries: a brief review. **Acta Oecol.**, v. 20, n. 4, p. 237–248.

GAUDY, R.; CERVETTO, G.; PAGANO, M. (2000). Comparison of the metabolism of Acartia clausi and A. tonsa: influence of temperature and salinity. **Journal of Experimental Marine Biology and Ecology**, v. 247, p. 51-65.

GRAHAM, E.S.; BOLLENS, S.M. (2010). Macrozooplankton community dynamics in relation to environmental variables in Willapa Bay, Washington, USA. **Estuaries Coasts**, v. 33, p. 182–194.

HIRST, A.G.; KIØRBOE, T. (2002). Mortality of marine planktonic copepods: Global rates and patterns. **Mar. Ecol. Prog. Ser.**, v. 230, p. 195–209.

ISLAM, M.D.; UEDA, H.; TANAKA, M. (2006). Spatial and seasonal variations in copepod communities related to turbidity maximum along the Chikugo estuarine gradient in the upper Ariake Bay, Japan. **Estuarine Coastal and Shelf Science**, v. 68, p. 113–126.

KIMMEL, D.G.; ROMAN, M.R. (2004). Long-term trends in mesozooplankton abundance in Chesapeake Bay, USA: influence of freshwater input. **Mar. Ecol. Prog. Ser.**, v. 267, p. 71–83.

KIMMERER, W.J. (2002). Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? **Marine Ecology Progress Series**, v. 243, p. 39-55.

KIØRBOE, T.; NIELSEN, T.G. (1994). Regulation of zooplankton biomass and production in a temperate, coastal ecosystem. 1. Copepods. **Limnology and Oceanography**, v. 39, p. 493-507.

KNOPPERS, B.A.; BRANDINI, F.P.; THAMM, C.A. (1987). Ecological studies in the Bay of Paranaguá. II Some physical and chemical characteristics. Curitiba: **Nerítica**, v. 2, n. 1, p. 1-36.

KRATINA, P.; WINDER, M. (2015). Biotic invasions can alter nutritional composition of zooplankton communities. **Oikos**, doi: 10.1111/oik.02240.

LAM-HOAI, T.; GUIRAL, D.; ROUGIER, C. (2006). Seasonal change of community structure and size spectra of zooplankton in the Kaw River estuary (French Guiana). **Estuarine, Coastal and Shelf Science**, v. 68, p. 47-61.

LANA, P.C.; MARONE, E.; LOPES, R.M.; MACHADO, E.C. (2001). The subtropical estuarine complex of Paranaguá Bay, Brazil. In: SEELIGER, U.; LACERDA, L.D.; KJERFVE, B. (Eds.), **Coastal Marine Ecosystems of Latin America**. Basel: Springer Verlag, p. 131-145.

LAPRISE, R.; DODSON, J.J. (1994). Environmental variability as a factor controlling spatial patterns in distribution and species diversity of zooplankton in the St. Lawrence estuary. **Marine Ecology Progress Series**, v. 107, p. 67-81.

LAWRENCE, D.; VALIELA, I.; TOMASKY, G. (2004). Estuarine calanoid copepod abundance in relation to season, salinity, and land-derived nitrogen loading, Waquoit Bay, MA. **Estuarine, Coastal and Shelf Science**, v. 61, p. 547–557.

LEGENDRE, P.; LEGENDRE, L. (1998). **Numerical ecology**. Second English edition. Amsterdam: Elsevier.

LOPES, R.M. (1994). Zooplankton distribution in the Guaraú River Estuary (Southeastern Brazil). **Estuarine, Coastal and Shelf Science**, v. 39, n. 3, p. 287-302.

LOPES, R.M.; VALE, R.; BRANDINI, F.P. (1998). Composição, abundância e distribuição espacial do zooplâncton no complexo estuarino de Paranaguá durante o inverno de 1993 e o verão de 1994. **Revista Brasileira de Oceanografia**, v. 46, n. 2, p. 195-211.

LOPES, R.M.; BRANDINI, F.P.; GAETA, S.A. (1999). Distribution patterns of epipelagic copepods off Rio de Janeiro (SE Brazil) in summer 1991/1992 and winter 1992. **Hydrobiologia**, v. 411, p. 161–174.

MACHADO, E.C.; DANIEL, C.B.; BRANDINI, N.; QUEIROZ, R.L.V. (1997). Temporal and spatial dynamics of nutrientes and particulate suspended matter in Paranaguá Bay, PR, Brazil. **Nerítica**, Curitiba, v. 11, p. 17-33.

MANTOVANELLI, A.; MARONE, E.; SILVA, E.T.; LAUTERT, L.F.; KLINGENFUSS, M.S.; PRATA, V.P.; NOERNBERG, M.A.; KNOPPERS, B.A.; ANGULO, R.J. (2004). Combined tidal velocity and duration asymmetries as a determinant of water transport and residual in Paranaguá Bay estuary. **Estuarine, Coastal and Shelf Science**, v. 59, p. 523-537.

MARONE, E.; JAMIYANAA, D. (1997). Tidal characteristics and a numerical model for the M_2 tide at the estuarine complex of the Bay of Paranaguá, Paraná, Brazil. **Nerítica**, Curitiba, v. 11, p. 95-107.

MARONE, E.; MACHADO, E.C.; LOPES, R.M.; SILVA, E.T. (2005). Land-ocean fluxes in the Paranaguá estuarine system Southern Brazil. **Braz. J. Oceanogr.**, v. 53(3/4), p.169–181.

MARONE, E.; NOERNBERG, M.; LAUTERT, L.F.; SANTOS, I.; FILL, H.D.; BUBA, H.; MARENDA, A. (2007). Medições de Correntes e Curva Vazão-Maré na baía de Paranaguá, PR. **Boletim Paranaense de Geociências**, n. 60-61, p. 55-64.

MARQUES, S.C.; AZEITEIRO, U.M.; MARQUES, J.C.; NETO, J.M.; PARDAL, M.A. (2006). Zooplankton and ichthyoplankton communities in a temperate estuarie: spatial and temporal patterns. **Journal of Plankton Research**, v.28, n. 3, p. 297-312.

MARQUES, S.C.; PARDAL, M.A; PEREIRA, M.J.; GONÇALVES, F.; MARQUES, J.C.; AZEITEIRO, U.M. (2007). Zooplankton distribution and dynamics in a temperate shallow estuary. **Hydrobiologia,** v. 587, p. 213-223.

MARQUES, S.C.; AZEITEIRO, U.M.; LEANDRO, S. M.; QUEIROGA, H.; PRIMO, A.L.; MARTINHO, F.; VIEGAS, I.; PARDAL, M.A. (2008). Predicting zooplankton response to environmental changes in a temperate estuarine system. **Mar. Biol.**, v. 55, p. 531–541.

MARTINS, C.C.; BRAUN, J.A.F.; SEYFFERT, B.H.; MACHADO, E.C.; FILLMANN, G. (2010). Anthropogenic organic matter inputs indicated by sedimentary fecal steroids in a large South American tropical estuary (Paranaguá estuarine system, Brazil). **Marine Pollution Bulletin**, v. 60, p. 2137-2143.

MARTINS, C.C.; BÍCEGO, M.C.; FIGUEIRA, R.C.L.; ANGELLI, J.L.F.; COMBI, T.; GALLICE, W.C.; MANSUR, A.V.; NARDES, E.; ROCHA, M.L.; WISNIESKI, E.; CESCHIM, L.M.M.; RIBEIRO, A.P. (2012). Multi-molecular markers and metals as tracers of organic matter inputs and contamination status from an Environmental Protection Area in the SW Atlantic (Laranjeiras Bay, Brazil). **Science of the Total Environment**, v. 417-428, p. 158-168.

MIZERKOWSKI, B.D.; HESSE, K.J.; LADWIG, N.; MACHADO, E.C.; ROSA, R.; ARAUJO, T.; KOCH, D. (2012). Sources, loads and dispersion of dissolved inorganic nutrients in Paranaguá Bay. **Ocean Dynamics**, v. 62, p.1409–1424.

MIYASHITA, L.K.; MELO JUNIOR, M.; LOPES, R.M. (2009). Estuarine and oceanic influences on copepod abundance and production of a subtropical coastal area. **Journal of Plankton Research,** v. 31, p. 815-826.

MIYASHITA, L.K.; BRANDINI, F.P.; MARTINELLI-FILHO, J.E.; FERNANDES, L.F.; LOPES, R.M. (2012). Comparison of zooplankton community structure between impacted and non-impacted áreas of Paranaguá Bay Estuarine Complex, south Brazil. **Journal of Natural History,** v. 46, p. 1557-1571.

MONTÚ, M.; CORDEIRO, T.A. (1998). Zooplâncton del complejo estuarial de la Bahía de Paranaguá.I: Composición, dinámica de las especies, ritmos reproductivos y acción de los factores ambientales sobre la comunidad**. Nerítica**, Pontal do Sul, v. 3, n. 1, p. 61-83.

MURREL, M.C.; LORES, E.M. (2004). Phytoplankton and Zooplankton seasonal dynamics in a subtropical estuary: importance of cyanobacteria. **Journal of Plankton Research**, v. 26, n. 3, p. 371-382.

MARCUS, N. (2004). Na overview of the Impacts of Eutrophication and Chemical Pollutants on Copepods of the Coastal Zone. **Zoological Studies**, v. 42, n. 2, p. 211-217.

NEUMANN-LEITÃO, S. (1994/1995). Resenha literária sobre zooplâncton estuarino no Brasil. **Trabhs. Oceanogr**., Universidade Federal Pernambuco, v. 23, p. 25-53.

NOERNBERG, M.A. (2001). Processos **Morfodinâmicos no Complexo Estuarino de Paranaguá – Paraná – Brasil: Um Estudo a Partir de Dados in situ e LANDSAT – TM**. Curitiba. Tese (Doutorado), Pós-Graduação em Geologia, Universidade Federal do Paraná.

PACE, M.L.; FINDLAY, S.E.G.; LINTS, D. (1992). Zooplankton in advective environments: the Hudson River community and a comparative analysis. **Can. J. Fish. Aquat. Sci.**, v. 49, p. 1060-1069.

PARK, G.S.; MARSHALL, H.G. (2000). Estuarine relationships between zooplankton community structure and trophic gradients. **Journal of Plankton Research**, v. 22, p. 121-136

PRIMO, A.L.; AZEITEIRO, U.M.; MARQUES, S.C.; MARTINHO, F.; PARDAL, M.A. (2009). Changes in zooplankton diversity and distribution pattern under varying precipitation regimes in a southern temperate estuary. **Estuarine, Coastal and Shelf Science**, v. 82, p. 341-347.

RICHARDSON, A.J. (2008). In hot water: zooplankton and climate change. **ICES Journal of Marine Science**, v. 65, n. 279–295.

ROCHA, C.E.F. (1986). Copepods of the genus *Oithona* Baird, 1843 from mangrove areas of Central and South America. **Hydrobiologia**, v. 135, p. 95-107.

ROMAN, M.R.; HOLLIDAY, D.V.; SANFORD, L.P. (2001). Temporal and spatial patterns of zooplankton in the Chesapeake Bay turbidity maximum. **Marine Ecology Progress Series**, v. 213, p. 215-227.

SANT'ANNA, E.M.; BJÖRNBERG, T.K.S. (2006). Seasonal dynamics of mesozooplankton in Brazilian coastal waters. **Hydrobiologia**, v. 563, p. 253-268.

SARTORI, L.P.; LOPES, R.M. (2000). Seasonal variability of pelagic copepod assemblages on the inner continental shelf off Paraná, Brazil. **Nauplius**, v. 8, p. 79–88.

SOARES, I.; MÖLLER, O. (2001). Low-frequency currents and water spatial distribution on the southern Brazilian shelf. **Continental shelf Research**, v. 21, p. 1785-1814.

SOETAERT, K.; VAN RIJSWIJK, P. (1993). Spatial and temporal patterns of the zooplankton in the Westerschelde estuary. **Marine Ecology Progress Series**, v. 97, p. 47-59.

STERZA J.M.; FERNANDES, L.L. (2006). Zooplankton community of the Vitória Bay Estuarine System (southeastern Brazil). Characterization during a three-year study. **Brazilian Journal of Oceanography**, v. 54, n. 2/3, p. 95-105.

TOMMASI, D.; HUNT, B.P.V.; PAKHOMOV, E.A.; MACKAS, D.L. (2013). Mesozooplankton community seasonal succession and its drivers: Insights from a British Columbia, Canada, fjord. **Journal of Marine Systems**, v. 115-116, p. 10-32.

UYE, S.I. (1994). Replacement of large copepods by small ones with eutrophication of embayments: cause and consequence. **Hydrobiologia**, v. 292/293, p. 513-519.

VALENTIN, J.L. (1984). Spatial structure of the zooplankton community in the Cabo-Frio region (Brazil) influenced by coastal upwelling. **Hydrobiologia**, v. 113, p. 183-199.

VIITASALO, M.; VUORINEN, I.; SAESMAA, S. (1995). Mesozooplankton dynamics in the northern Baltic Sea: implications of variations in hydrography and climate. **Journal of Plankton Research**, v. 17, n. 10, p. 1857-1878.

WINKLER, G.; DODSON, J.J.; BERTRAND, N.; THIVIERGE, D.; VINVENT, W.F. (2003). Trophic coupling across the St. Lawrence River estuarine transition zone. **Marine Ecology Progress Series,** v. 251, p. 59-73.