



# Surf zone zooplankton temporal dynamics and their environmental regulation in a southwestern Atlantic sandy beach (Pehuen Co, Argentina)

Carla A. Baleani<sup>a,\*</sup>, M. Clara Menéndez<sup>a</sup>, M. Cintia Piccolo<sup>a,b</sup>

<sup>a</sup> Instituto Argentino de Oceanografía, Consejo Nacional de Investigaciones Científicas y Técnicas (IADO-CONICET), Camino a la Carrindanga km 7.5, B8000FWB Bahía Blanca, Argentina

<sup>b</sup> Universidad Nacional del Sur (UNS), Departamento de Geografía y Turismo, 12 de octubre y San Juan, B8000FWB Bahía Blanca, Argentina

## ARTICLE INFO

### Keywords:

Zooplankton  
Surf zone  
Temporal dynamics  
Environmental variables  
Sandy beach

## ABSTRACT

Temporal dynamics of a zooplankton community were examined in the surf zone of Pehuen Co beach (PC), Argentina. The effect of environmental variables on the zooplankton composition and abundance was also investigated. Samples were obtained monthly between December 2016 and November 2017 from a fixed site during low tide. In all, 37 taxa were representative of the community. Meroplankton represented 59.45% of the total taxa, whereas holoplankton reached 40.54%. Five species were dominant: *Acartia tonsa* in summer months (2032 ind. m<sup>-3</sup> in March), *Paracalanus parvus* and *Ctenocalanus vanus* in winter (4055 ind. m<sup>-3</sup> and 264 ind. m<sup>-3</sup>, respectively, in July), and the sergestid *Peisos petrunkevitchi* (838.7 ind. m<sup>-3</sup> in September) and the mysids *Arthromysis magellanica* (284 ind. m<sup>-3</sup> in October) in spring. The highest total zooplankton abundances were registered in summer and winter, and the lowest ones were registered in autumn. The zooplankton community showed a strong seasonality, which can be mainly attributed to temporal changes in water temperature and to variations in suspended particulate matter (SPM), particulate organic matter (POM), and chlorophyll-*a* (Chl-*a*). Our results show that the zooplankton community structure was also affected by local variations in the velocity of the littoral current (VLC) and the wave height (WH). The present study shows that, besides seasonality, which seemed to be strong in this temperate region, other events affect zooplankton dynamics at a short-term time scale. Both VLC and WH are key factors that affect the zooplankton community structure in PC.

## 1. Introduction

The surf zone of sandy beaches is the transition area between the breaking zone of waves and the swash zone. It plays an essential role in the transport of materials and the exchange of organic matter and nutrients with adjacent habitats (McLachlan and Defeo, 2018). These productive ecosystems support a diverse coastal fauna (Schlacher et al., 2008; Dugan et al., 2015; Manning et al., 2013; McLachlan and Defeo, 2018) and are generally used by endemic species as well as by the transient taxa that arrive to take advantage of feeding conditions (McLachlan and Defeo, 2018). Despite the importance of the surf zone, current knowledge is mainly focused on variations in phytoplankton and benthic macrofauna there, with few studies focused on the zooplankton community (e.g., Dominguez-Granda et al., 2004; Odebrecht et al., 2010; Pinheiro et al., 2013; Odebrecht et al., 2014; Marin Jarrin et al., 2017).

Zooplankton communities play an essential role in the ecology of surf zones, serving as a connection with different trophic levels

(Oliveira-Santos et al., 2016). In addition, the fauna of the lowest beach may extend its distribution seawards into the turbulent surf zone, where zooplankton can be abundant (Defeo et al., 2009). DeLancey (1989) stated that zooplankton represents the main food item for larvae and juveniles of fishes visiting the surf zone. Given that zooplankton is a primary food supply for fishes but also for suspension feeding macrofauna, changes in this community would have a relevant impact on sandy beach ecosystems (Defeo et al., 2009). The zooplankton community is the least studied one in surf zones worldwide, mainly due to the difficulty in sampling because of the dynamic physical conditions (McLachlan and Defeo, 2018). Moreover, most previous studies focused on tropical and subtropical sandy beaches (Avila et al., 2009; Da Costa et al., 2011; Pinheiro et al., 2011, 2013; Aboul Ezz et al., 2014; Oliveira-Santos et al., 2016), whereas very few studies considered temperate systems (DeLancey, 1987; Stull et al., 2016; Menéndez et al., 2019).

It has been demonstrated that the effect of environmental variables on the spatio-temporal distribution of planktonic organisms in surf

\* Corresponding author.

E-mail address: [cbaleani@iado-conicet.gob.ar](mailto:cbaleani@iado-conicet.gob.ar) (C.A. Baleani).

<https://doi.org/10.1016/j.seares.2019.101833>

Received 12 June 2019; Received in revised form 28 November 2019; Accepted 16 December 2019

Available online 17 December 2019

1385-1101/ © 2019 Elsevier B.V. All rights reserved.

zones is substantial (Aboul Ezz et al., 2014; Stull et al., 2016; Menéndez et al., 2019). Constant temperatures and oligotrophic waters are factors influencing the zooplankton dynamics in subtropical sandy beaches such as Ajuruteua (Pinheiro et al., 2013) and Fortaleza (Oliveira-Santos et al., 2016) in northern Brazil. The effect of seasonality, principally in terms of changes in precipitation, and the associated changes in salinity have a substantial impact on local zooplankton dynamics in Ajuruteua beach (Da Costa et al., 2011). Thus, knowledge about the influence of environmental variables on surf zooplankton dynamics can contribute to an improved understanding of changes in the marine coastal function, potentially providing a useful tool for future samplings in similar coastal areas. Therefore, the specific aims of this study were: (i) to investigate the temporal dynamics of the composition and abundance of the surf zone zooplankton in a temperate sandy beach and (ii) to evaluate its association with environmental variables.

## 2. Material and methods

### 2.1. Study site

Pehuen Co beach (PC; 38°59'51" S; 61°33'16" W) is located in the southwest coast of Buenos Aires Province, Argentina, 80 km away from the innermost zone of the Bahía Blanca Estuary (BBE) (Fig. 1). It is a dissipative sandy beach, situated in an open bay with a straight E-W orientated shoreline. The area has a mesotidal regime with semidiurnal tides, with an amplitude range between 2.32 m and 3.35 m for neap and spring conditions, respectively (Servicio de Hidrografía Naval (SHN), 2009). In PC, the intertidal zone range varies between 120 m and 170 m from the base of the dune to the swash zone (Bustos, 2012).

The BBE plume hugely influences PC coastal waters. This shallow and temperate estuary, located in the western limit of the study site, covers an area of nearly 2300 km<sup>2</sup> and consists of NW to SE tidal channels separated by extensive intertidal flats, low marshes, and islands (Piccolo and Perillo, 1990). The region has a temperate climate, with thermally well-differentiated winters and summers. Mean annual temperatures fluctuate between 9.9 °C (autumn - winter) and 27.1 °C (spring - summer), and the annual mean precipitation is 650 mm (Bustos et al., 2011). Prevailing winds come from the N, NW, and NE,

whereas the strongest ones come from the S, SE, and SW, mainly in summer and spring (Aliaga et al., 2017; National Meteorological Service, 1992).

### 2.2. Sample collection and analysis

This study combines biological and physicochemical monthly samplings performed between December 2016 and November 2017 in PC surf zone waters. Samples were collected during daylight hours at low tide at a fixed station (39°00'19.5 5" S; 61°32'53.50" W), located approximately 30 m from the shoreline, with depths ranging between 0.7 m and 1.2 m. Twelve samples were collected over the study period, one for each monthly sampling. Zooplankton samples were obtained using a hand-pulled conical cylindrical 300 µm net with a mouth diameter of 0.50 m. The sampling was hand-pulled parallel to the shoreline, walking along the inner surf zone countercurrently for approximately 200 m. A mechanical flowmeter recorded the total amount of water filtered, which ranged between 2.65 m<sup>3</sup> and 36.04 m<sup>3</sup> and averaged 9.74 m<sup>3</sup>. The samples were immediately fixed in a 4% formalin-seawater solution. The mesh size of the employed net certainly could not catch the copepod early life stages and smaller organisms. Thus, in this work, we mainly considered changes in the abundance of larger copepodites and adult copepods, which should be discussed with some prudence. Water temperature and salinity were registered *in situ* with a Horiba U-10® digital multisensor. The velocity and direction of the littoral current (VLC and DLC, respectively) were measured in the surf zone using a floating buoy. Thirty continuous current readings were taken at a fixed static point at 0.5 m above the sand bottom, according to Schneider (1981). Wave height (WH) was estimated visually considering the distance between the top of the sea surface and the crest (McLachlan et al., 2018). Wind velocity (WV) and direction were obtained from an automatic weather station located at 38°59'18.13"S, 61°18'43.83"W, on the coast. This station is equipped with sensors developed by the Instituto Argentino de Oceanografía (EMAC, <http://emac.iado-conicet.gob.ar/>). Water samples for determination of chlorophyll-*a* (Chl-*a*), suspended particulate matter (SPM), and particulate organic matter (POM) were also collected from surf waters.

In the laboratory, zooplankton and all the organisms were identified

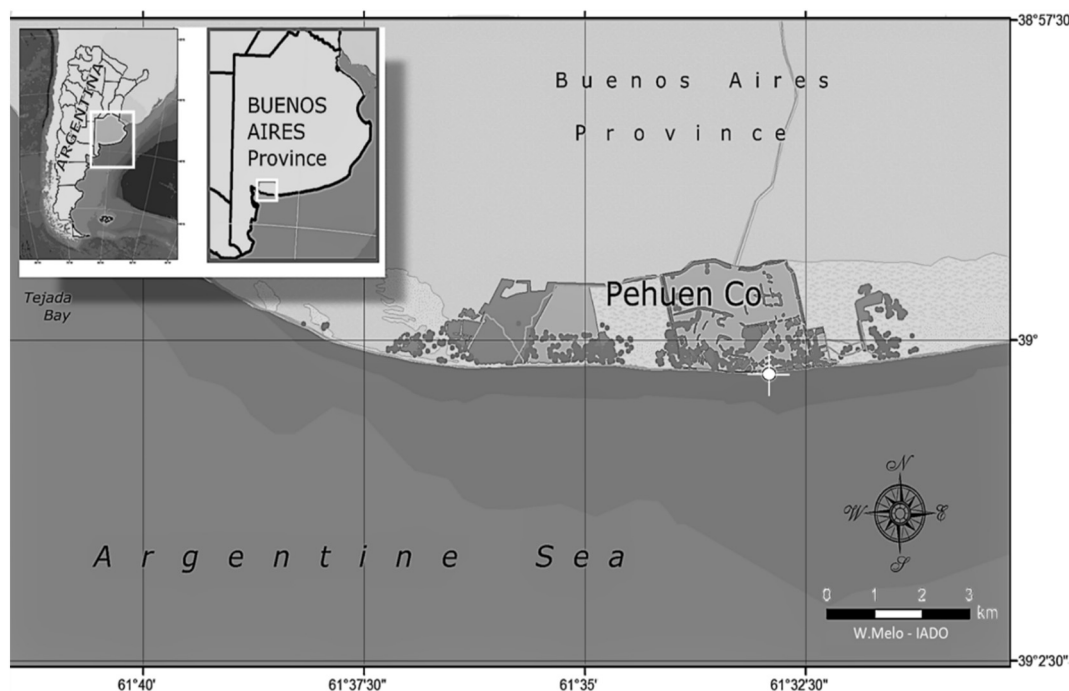


Fig. 1. Study area and fixed sampling site (white dot) at the surf zone of Pehuen Co sandy beach.

to the lowest taxonomic level under a stereoscopic microscope based on appropriate reference materials (e.g., Báez, 1997; Boltovskoy, 1999; Rodrigues and Vieira, 2012). According to Boltovskoy (1999), the final volumes were standardized for very high-abundant samples (more than fifty individuals per 5 ml) and then, they were subsampled (1/10). For those with fewer organisms, the entire sample was counted. Abundance was determined as the number of individuals per cubic meter of water filtered through the net ( $\text{ind. m}^{-3}$ ). Chl-*a* concentration was estimated according to the methods described in APHA-AWWA-WEF (1998), using a SLM-4800 fluorometer. Water samples were filtered and immediately stored at  $-80\text{ }^{\circ}\text{C}$ . Pigment extraction was done in 90% acetone, and SPM and POM were determined gravimetrically, filtering water on pre-combusted and weighed GF/F filters. The filters were then dried at  $60\text{ }^{\circ}\text{C}$  for 24 h and weighed for SPM estimation. Subsequently, they were combusted at  $500\text{ }^{\circ}\text{C}$  for 3 h and weighed for POM determination as to the difference between both weighted values.

### 2.3. Data analysis

Prior to the analysis, a Detrended Correspondence Analysis (DCA) was carried out in order to decide whether to use a linear or an unimodal ordination method. Following the guidelines described in Ramette (2007), we chose the linear method (PCA) because the first eigenvalue of the DCA was 0.52202 (less than three standard deviation units). The PCA was performed based on the Spearman's rank correlation matrix to examine the association between environmental variables and their seasonal variations. The Spearman's coefficient was chosen because of the different scale and variance of the variables. The following data were used for the analysis: water temperature, salinity, Chl-*a*, SPM, POM, VLC, DLC, WV, and WH. A correlation analysis was then performed to evaluate the relationship between the principal components that retained most of the total environmental variation and the abundance of important taxa (those species having an abundance that represented  $> 5\%$  of the total zooplankton abundance). The selected species were: *Acartia tonsa*, *Paracalanus parvus*, *Arthromysis magellanica*, *Peisos petrunkevitchi*, and *Ctenocalanus vanus*. The abundance data were standardized by dividing the species abundance value by the total abundance in the sample (Legendre and Gallagher, 2001; Ramette, 2007). All analyses were performed with R (R core team 2017) using the packages vegan (Oksanen et al., 2018), Corrplot (Wei, 2017), and Psych (Revelle, 2019). In addition, monthly VLC anomalies were calculated through the difference between the VLC mean and each monthly value.

## 3. Results

### 3.1. Environmental variables

During the study period, water temperature varied from  $10\text{ }^{\circ}\text{C}$  in August to  $25\text{ }^{\circ}\text{C}$  in February (Fig. 2A). Salinity showed a similar trend, with minimum values in August (31) and maximum ones in February (34) (Fig. 2A). Chl-*a* fluctuated between  $2.5\text{ }\mu\text{g L}^{-1}$  (February) and  $17\text{ }\mu\text{g L}^{-1}$  (November), being high in March ( $11.1\text{ }\mu\text{g L}^{-1}$ ), July ( $12\text{ }\mu\text{g L}^{-1}$ ), and September ( $12.3\text{ }\mu\text{g L}^{-1}$ ) (Fig. 2B). SPM and POM showed a clear seasonal pattern, with minimum concentrations in warmer months (SPM:  $45.3\text{ mg L}^{-1}$ , February; POM:  $1.8\text{ mg L}^{-1}$ , December) and maximum concentrations in colder months (SPM:  $444.9\text{ mg L}^{-1}$ , June; POM:  $69.1\text{ mg L}^{-1}$ , July) (Fig. 2C). The lowest VLC occurred in February ( $0.05\text{ m seg}^{-1}$ ) and the highest one in November ( $1.05\text{ m seg}^{-1}$ ). The maximum positive VLC anomaly was registered in November ( $0.72\text{ m s}^{-1}$ ) and the minimum negative one in February ( $-0.28\text{ m s}^{-1}$ ) (Fig. 2D). The DLC was mainly from an easterly direction (80% of the samplings), with only 20% of the measurements coming from the West (December and August). The lowest significant WH occurred in June and August (0.2 m) and the highest one in November (0.8 m). The prevailing wind directions were from the

SE-SSE (33.3%) and N-NNE (33.3%), whereas the remaining percentages corresponded to NW-NNW and SW-SSW (16.6% for both sectors). In summary, winds from an easterly direction dominated during most of the study period and averaged  $12.7\text{ km h}^{-1}$ . The minimum mean WV was registered in December ( $6.74\text{ km h}^{-1}$ ) and the maximum one in August ( $20.16\text{ km h}^{-1}$ ).

### 3.2. Zooplankton composition and abundance

The zooplankton community had 37 taxa. Meroplankton represented 59.45% out of the total taxa, whereas the remainder consisted of holoplankton (40.54%). Meroplankton was mostly represented by larvae of Cirripedia ( $10.8 \pm 36.4\text{ ind. m}^{-3}$ ), Spionidae ( $5.3 \pm 12.7\text{ ind. m}^{-3}$ ), and Grapsidae ( $4.4 \pm 11.2\text{ ind. m}^{-3}$ ). Crustaceans, mainly copepods, were the only elements of the holoplankton. The total zooplankton abundance showed a clear temporal pattern during the study period and varied between  $6.4\text{ ind. m}^{-3}$  in December and  $5417\text{ ind. m}^{-3}$  in July (Fig. 3A). Five species were dominant: the calanoid copepods, *A. tonsa* (Dana, 1849), *P. parvus* (Claus, 1863) and *C. vanus* (Giesbrecht, 1888), and the shrimps *P. petrunkevitchi* (Burkenroad, 1945) and *A. magellanica* (Cunningham, 1871) (Fig. 3B). The maximum abundances of *A. tonsa*, *P. parvus*, and *C. vanus* were  $2032\text{ ind. m}^{-3}$  (March),  $4055\text{ ind. m}^{-3}$  (July), and  $264.1\text{ ind. m}^{-3}$  (July), respectively. The highest densities of *A. tonsa* represented 42.53% out of the total zooplankton abundance, whereas for *P. parvus* they represented 39.38% out of the total abundance. The sergestid shrimp *P. petrunkevitchi* dominated only in September, with  $838.7\text{ ind. m}^{-3}$ . *A. magellanica* was the dominant taxa in October ( $284\text{ ind. m}^{-3}$ ), although high abundances were also found in August ( $479.1\text{ ind. m}^{-3}$ ). Other taxa occurred regularly but with low abundances: *Parasagitta friderici* (Ritter-Záhony, 1911) ( $1.3\text{--}80.4\text{ ind. m}^{-3}$ ) and *Calanoides carinatus* (Krøyer, 1849) ( $3.9\text{--}33.9\text{ ind. m}^{-3}$ ). *Euterpina acutifrons* (Dana, 1847) and *Monstrilla helgolandica* (Claus, 1863) were also observed in the samples, but their contribution to the total zooplankton was not relevant (e.g.  $< 1\%$ ).

### 3.3. Statistical analysis: relationship between physicochemical and biological variables

The first two components of the PCA explained 42.39% and 25.84% of the total variance (Fig. 4). The first axis (PC1) was negatively correlated with salinity and water temperature (contributions of 14.07% and 16.04% to PC1, respectively) and positively correlated with SPM, Chl-*a*, POM, and WV (contributions of 21.71%, 18.39%, 15.36%, and 10.33% to PC1, respectively) (Fig. 4). The second axis (PC2) was positively correlated with WH and VLC (contributions of 39.25% and 17.21% to PC2, respectively) (Fig. 4). The seasonal succession of environmental conditions was clearly apparent along PC1 (hereafter renamed seasonal component SC), with the highest temperature and salinity in summer, and the highest MOP, SPM, Chl-*a*, and WV occurring in spring. PC2 (hereafter renamed local component, LC) represented term variations in environmental conditions in VLC and WH.

The most abundant species, *A. tonsa*, was highly significant negative correlation with SC ( $r = -0.85$ ,  $p < .01$ ), and *P. parvus* showed a marginally significant positive correlation with SC ( $r = 0.53$ ,  $p < .1$ ). On the other hand, *P. parvus* showed a marginally significant negative correlation with LC ( $r = -0.55$ ,  $p < .01$ ), and *C. vanus* showed a significant negative correlation with LC ( $r = -0.59$ ,  $p < .05$ , Table 1).

## 4. Discussion

We observed strong seasonal variation in the zooplankton community structure in PC. Total zooplankton abundance was similar to that found by Morgan et al. (2016) for the surf zone of some sandy beaches in Monterey Bay, USA, but approximately an order of magnitude lower than those reported in similar studies in other temperate surf waters

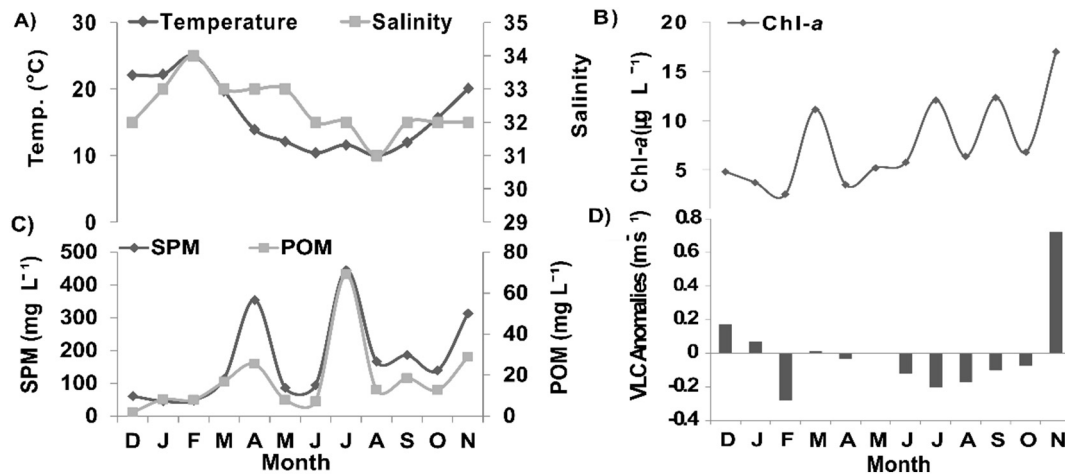


Fig. 2. Monthly values of physicochemical variables between December 2016 and November 2017 in surf zone waters of the study area. (A) Water temperature (°C) and Salinity, (B) Chl-a ( $\mu\text{g L}^{-1}$ ), (C) SPM ( $\text{mg L}^{-1}$ ) and POM ( $\text{mg L}^{-1}$ ), (D) Monthly littoral current anomalies ( $\text{m s}^{-1}$ ). Temp. = water temperature, Chl-a = chlorophyll-a, SPM = suspended particulate matter, POM = particulate organic matter, VLC = velocity of littoral current.

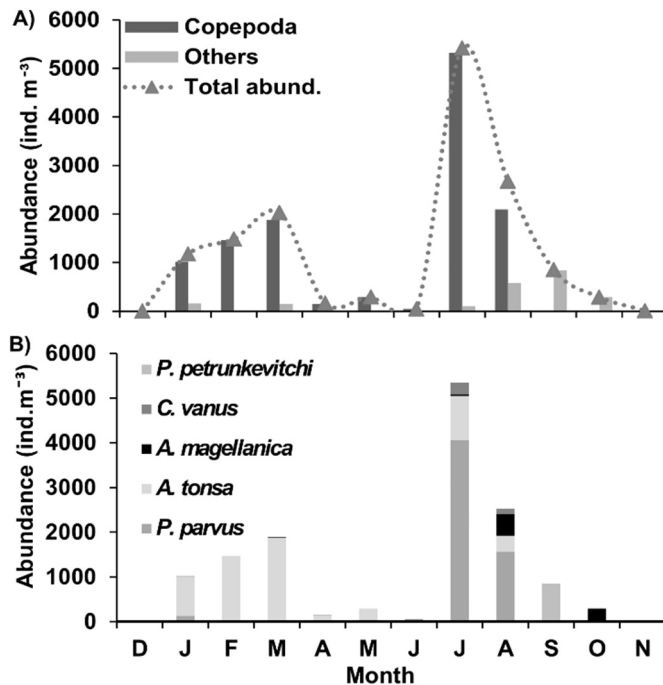


Fig. 3. Monthly abundances of total zooplankton, Copepoda, main planktonic species (*Paracalanus parvus*, *Acartia tonsa*, *Peisoides petrunkevitchi*, *Arthromysis magellanica*, and *Ctenocalanus vanus*) and other planktonic groups ( $\text{ind. m}^{-3}$ ) in the surf zone of PC. Total abund. = Total abundance. *P. parvus* = *Paracalanus parvus*, *A. tonsa* = *Acartia tonsa*, *P. petrunkevitchi* = *Peisoides petrunkevitchi*, *A. magellanica* = *Arthromysis magellanica*, *C. vanus* = *Ctenocalanus vanus*.

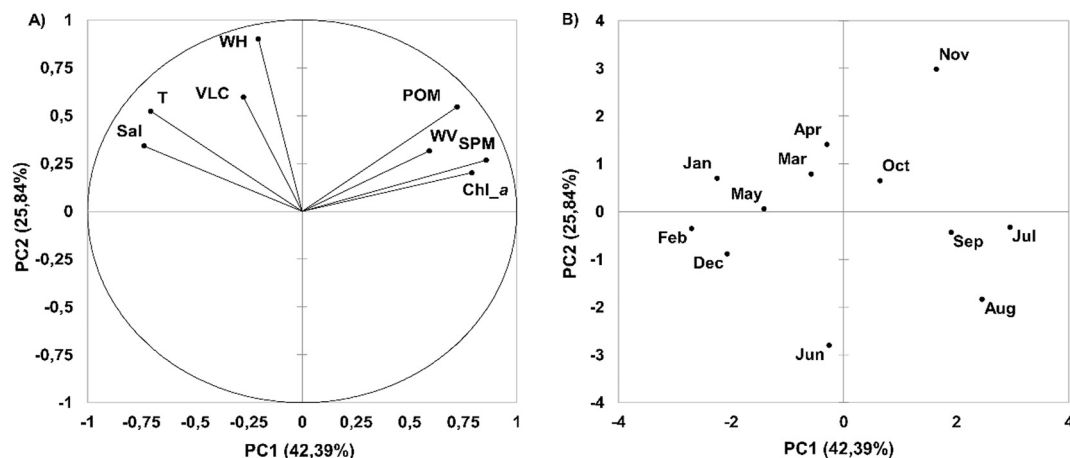
(Stull et al., 2016) and tropical areas (Da Costa et al., 2011; Pinheiro et al., 2013). The seasonal pattern in abundances of the dominant copepods was strongly associated with changes in water temperature and weakly associated with variations in SPM, POM, and Chl-a. The dominance of copepods had been reported in other surf zones (Da Costa et al., 2011; Pinheiro et al., 2011; Pinheiro et al., 2013; Menéndez et al., 2019).

The most abundant taxon was *A. tonsa*, which is generally restricted to summer months along Atlantic and European coasts (e.g., Primo et al., 2009; Chen and Hares, 2011; Menéndez et al., 2012a; Howson et al., 2017). High abundances of this species were found principally during late summer (March), but it was present throughout the year.

Additionally, high concentrations of Chl-a coincided with the highest abundances of *A. tonsa*. This species is commonly associated with eutrophic waters (Cardoso et al., 2004; Pardo et al., 2004), which have high concentrations of organic matter (Marques et al., 2007). It has a cosmopolitan distribution and is generally an important component of the zooplankton in subtropical and warm temperate latitudes in both the Atlantic and the Pacific coasts of America (e.g. Menéndez et al., 2012b; Muxagata et al., 2012; Aguilera et al., 2016; Rice et al., 2015) as well as in coastal waters and estuaries in Europe (Leandro et al., 2007; Marques et al., 2007). In the nearby BBE, *A. tonsa* occurs throughout the year with higher abundances in summer than in winter (Menéndez et al., 2012b).

In PC surf waters, the most important species during colder months was *P. parvus*. This species peaked in winter (July) but presented very low abundances during the rest of the year, similar to that found in studies on the Mediterranean Sea (Calbet et al., 2001). This coastal-neritic species, typical of outer estuaries and inner shelf zones, is one of the primary grazers in terms of biomass and production rate in these type of waters (Morgan et al., 2003; Islama et al., 2006; Sun et al., 2008; Moon et al., 2010; Lee et al., 2011). This copepod can ingest ciliates, dinoflagellates, and nanoflagellates in massive abundances, in addition to phytoplankton (Suzuki et al., 1999; Wu et al., 2010). Despite the apparent dominance of Copepoda in surf waters, we observed a change in this typical structure during September and October, when *P. petrunkevitchi* and *A. magellanica*, respectively, dominated the surf waters. These organisms are planktonic filter feeders, consuming primarily detritus, phytoplankton, and/or microzooplankton (Boschi, 2016; McLachlan and Defeo, 2018) in the areas where the coastal circulation concentrates such particulates in the surf zone (McLachlan and Defeo, 2018).

Both the environmental variables and the main dominant zooplanktonic species registered in this study showed a clear temporal dynamic. The high-medium water temperature was related to the dominance of *A. tonsa* whereas the low water temperature was correlated with high abundances of *P. parvus*. This trend is in accordance with other studies in similar temperate coastal areas (Calbet et al., 2001; Marques et al., 2007; Badylak and Phillips, 2008; Marques et al., 2009; Stull et al., 2016), in which it has been demonstrated that metabolic processes of zooplankton are related primarily to water temperature (Leandro et al., 2007; Marques et al., 2009). A weak seasonal trend was also observed for SPM, POM, Chl-a, and WV, suggesting that water temperature is a proxy driver of the seasonal variability of zooplankton together with SPM, POM, Chl-a, and WV. Low zooplankton abundances were associated with sampling days with high velocities



**Fig. 4.** Results of the Principal Component Analysis (PCA) of physicochemical data. A two-dimensional plot of principal components (PC1 and PC2) is represented in the correlation circle (A) and for the samples (B). Abbreviations: T° = temperature, Sal. = Salinity, SPM = suspended particulate matter concentration, POM = Particulate organic matter, Chl-a = Chlorophyll-a, WV = wind velocity, WH = Significant wave Height, VLC = Velocity of littoral current, Dec = December, Jan = January, Feb = February, Mar = March, Apr = April, Jun = June, Jul = July, Aug = August, Sep = September, Oct = October, Nov = November.

**Table 1**

*r*-values and *p*-values of the correlation test among the zooplankton abundances of the main planktonic species and SC and LC. *A. tonsa* = *Acartia tonsa*, *P. parvus* = *Paracalanus parvus*, *P. petrunkevitchi* = *Peisoides petrunkevitchi*, *A. magellanica* = *Arthromysis magellanica*, *C. vanus* = *Ctenocalanus vanus*, SC = seasonal component, LC = Local component.

	<i>r</i> -value ( <i>p</i> -value)	
	SC	LC
<i>A. tonsa</i>	-0.85 ( <i>p</i> < .01)	0.09 ( <i>p</i> = .79)
<i>P. parvus</i>	0.53 ( <i>p</i> < .1)	-0.55 ( <i>p</i> < .01)
<i>P. petrunkevitchi</i>	0.31 ( <i>p</i> = .32)	-0.09 ( <i>p</i> = .78)
<i>A. magellanica</i>	0.33 ( <i>p</i> = .3)	0.44 ( <i>p</i> = .15)
<i>C. vanus</i>	0.31 ( <i>p</i> = .33)	-0.59 ( <i>p</i> < .05)

and waves, suggesting that the surf zone hydrodynamics may be a fundamental mechanism that controls the short-term local-scale changes in zooplankton abundance, beyond the expected seasonal ones. Positive velocity anomalies ( $> 0.33 \text{ m s}^{-1}$ ) and significantly high waves were associated with the lowest zooplankton abundances, particularly in December and November and especially for *P. parvus* and *C. vanus*. This result was apparently in a strong correlation with LC. It has been hypothesized that planktonic organisms, especially those of larger size, may abandon the surf zone in very rough conditions (McLachlan and Defeo, 2018). However, there are no studies for medium-small sized organisms. Larger organisms such as postflexion larval fishes are usually concentrated in trough habitats within surf waters, which may be indicative of an active habitat selection for areas of reduced current velocity/wave action (Watt-Pringle and Strydom, 2003). In addition, Layman (2000) stated that the concentration of fishes in the runnels might reflect a direct response to the decreased physical wave energy, turbidity preferences, avoidance of predators, benefits of macrophyte/debris accumulation, and increased food availability (e.g. DeLancey, 1989; Gibson et al., 1998; Harvey, 1998). If a mechanism regulates the concentration/accumulation of zooplankton into the trough channels under such conditions, it will affect the availability of food for fishes in these coastal waters. Additionally, stronger planktonic organisms use effective mechanisms to avoid turbulent waters (Watt-Pringle and Strydom, 2003) whereas smaller ones find other kinds of strategies. Although there are no studies on this topic in surf areas, it has already been studied in other coastal areas (e.g., Castel and Veiga, 1990; Morgan et al., 1997; Dauvin et al., 1998). Active and passive mechanisms to upgrade retention are used by medium-sized zooplankton in

other coastal areas such as estuaries (Roman et al., 2001). Accordingly, this fact raises the possibility of occurrence of some habitat selection by copepods in PC surf waters, which allows them to avoid turbulence during rough conditions. In this coastal system, clearly physical conditions such as increased VLC and WH are the driving force at short-term local scale behind the use of another habitat.

In summary, the zooplankton community in PC surf zone showed a strong seasonality, mainly affected by changes in water temperature. Other variables such as SPM, POM, Chl-a, and winds also affect temporal variation to a lesser extent. In a short-term time scale, variations in significant WH and the associated VLC affect zooplankton abundances in surf waters, which evidences that hydrodynamic factors are very important in this energetic environment. Future works should consider measurements of currents and waves in the surf zone because their hydrodynamics can mask the effects of seasonality. To the authors' knowledge, there are not scientific works addressing the effect of these hydrodynamic variables on surf zone zooplankton. Therefore, this work can be considered as a new approach to understanding the temporal dynamics of the planktonic organisms in these turbulent waters. Future studies should also include a more intensive sampling program with different mesh sizes to perform an exhaustive analysis of the zooplankton community to generate a better understanding of this complex hydrodynamic ecosystem.

#### Financial support

This work was supported by the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, Argentina) through an internal doctoral scholarship-CONICET 2016-20120 (B. C. A., 2282016000116500).

#### Declaration of Competing Interest

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

#### Acknowledgments

Partial support for this research was provided by grants from the Agencia Nacional de Promoción Científica y Tecnológica (ANPCYT, PICT2012-0356) and Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, PIP 1122030100467CO). We also thank Dr. Walter

Melo for drawing the map of the study area and Dr. Martín Amodeo for his valuable contribution to the statistical analysis section of the manuscript.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seares.2019.101833>.

## References

- Aboul Ezz, S.M., Heneash, M.M.H., Gharib, M.S., 2014. Variability of spatial and temporal distribution of zooplankton communities at Matrouh beaches, South-Eastern Mediterranean Sea, Egypt. *Egypt. J. Aquat. Res.* 40, 283–290.
- Aguilera, V.M., Vargas, C.A.V., Lardies, M.A., Poupin, M.J., 2016. Adaptive variability to low-pH river discharges in *Acartia tonsa* and stress responses to high pCO<sub>2</sub> conditions. *Mar. Ecol.* 37, 215–226.
- Aliaga, V.S., Ferrelli, F., Piccolo, M.C., 2017. Regionalization of climate over the Argentine Pampas. *Int. J. Climatol.* 37, 1237–1247.
- APHA-AWWA-WEF, 1998. Standard Methods for the Examination of Water and Wastewater, 20th edition. American Public Health Association, Washington, DC.
- Avila, T.R., Pedrozo, C.S., Bersano, J.G.F., 2009. Variação temporal do zooplankton da Praia de Tramandaí, Rio Grande do Sul, com ênfase em Copepoda. *Iheringia, Ser. Zool.* 99, 18–26.
- Badylak, S., Philips, E.J., 2008. Spatial and temporal distributions of zooplankton in Tampa Bay, Florida, including observations during a HAB event. *J. Plankton Res.* 30, 449–465.
- Báez, P., 1997. Key to the families of decapod crustacean larvae collected off northern Chile during an El Niño event. *Investig. Mar.* 25, 167–176.
- Boltovskoy, D., 1999. South Atlantic Zooplankton, 1st edition. Backhuys Publishers, Leiden.
- Boschi, E.E., 2016. Los crustáceos de interés pesquero y otras especies relevantes en los ecosistemas marinos. Mar del Plata: Instituto Nacional de Investigación y Desarrollo Pesquero INIDEP. In: Boschi, E.E. (Ed.), *El Mar Argentino y sus Recursos Pesqueros*, tomo 6. Mar del Plata, pp. 271.
- Bustos, M.L., 2012. Estudio integrado ambiental del balneario Pehuen Co. PhD thesis. Universidad Nacional del Sur, Departamento de Geografía y Turismo, Bahía Blanca, Argentina.
- Bustos, M.L., Piccolo, M.C., Perillo, G.M.E., 2011. Efectos geomorfológicos de fuertes vientos sobre playas. El caso de la playa de Pehuen Co, Argentina. *Cuad. Investig. Geográfica* 37, 121–142.
- Calbet, A., Garrido, S., Saiz, E., Alcaraz, M., Duarte, C.M., 2001. Annual zooplankton succession in coastal NW Mediterranean waters: the importance of the smaller size fractions. *J. Plankton Res.* 23, 319–331.
- Cardoso, G.C., Garcia, R., de Souza, A.L., Pereira, O.G., CMS, de A., Pires, A.J.V., Bernardino, F.S., 2004. Performance of Simental steers fed sorghum silage, sugar cane and straw rice treated or not with anhydrous ammonia. *Rev. Bras. Zootec.* 33, 2132–2139.
- Castel, J., Veiga, J., 1990. Distribution and retention of the copepod *Eurytemora affinis hirundoides* in a turbid estuary. *Mar. Biol.* 107 (1), 119–128.
- Chen, G., Hares, M., 2011. Cryptic diversity and comparative phylogeography of the estuarine copepod *Acartia tonsa* on the US Atlantic coast. *Mol. Ecol.* 20, 2425–2441.
- Da Costa, K.G., Pinheiro, P.R.S., Melo, C.A.R., de, O.S.O.M., Pereira, L.C.C., Da Costa, R.M., 2011. Effects of seasonality on zooplankton community dynamics in the macrotidal coastal zone of the Amazon region. *J. Coast. Res.* 64, 364–368.
- Dauvin, J.C., Thiébaud, E., Wang, Z., 1998. Short-term changes in the mesozooplanktonic community in the seine ROFI (region of freshwater influence) (eastern English Channel). *J. Plankton Res.* 20 (6), 1145–1167.
- Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., Scapini, F., 2009. Threats to Sandy Beach Ecosystems: A Review. 81. pp. 1–12.
- DeLancey, L.B., 1987. The summer zooplankton of the surf zone at Folly Beach, South Carolina. *J. Coast. Res.* 3, 211–217.
- DeLancey, L.B., 1989. Trophic relationship in the surf zone during the summer at Folly Beach, South Carolina. *J. Coast. Res.* 5, 477–488.
- Dominguez-Granda, L., Fockede, N., De mey, M., Beyst, B., Cornejo M del, P., Calderón, J., Vincx, M., 2004. Spatial patterns of the surf zone hyperbenthic fauna of Valdivia Bay (Ecuador). *Hydrobiologia* 529, 205–224.
- Dugan, J.E., Hubbard, D.M., Nielsen, K.J., Altstatt, J., Bursek, J., 2015. Baseline Characterization of Sandy Beach Ecosystems along the South Coast of California. (Final Report), CM 2015. pp. 113.
- Gibson, R.N., Pihl, L., Burrows, M.T., Modin, J., Wennhage, H., Nickell, L.A., 1998. Diel movements of juvenile plaice *Pleuronectes platessa* in relation to predators, competitors, food availability and abiotic factors on a microtidal nursery ground. *Mar. Ecol. Prog. Ser.* 165, 145–159.
- Harvey, C.J., 1998. Use of sandy beach habitat by *Fundulus majalis*, a surf-zone fish. *Mar. Ecol. Prog. Ser.* 164, 307–310.
- Howson, U.A., Buchanan, G.A., Nickels, J.A., 2017. Zooplankton community dynamics in a Western Mid-Atlantic Lagoonal estuary. *J. Coast. Res.* 78, 141–168.
- Islama, M.S., Uedab, H., Tanakaa, M., 2006. Spatial and seasonal variations in copepod communities related to turbidity maximum along the Chikugo estuarine gradient in the upper Ariake Bay, Japan. *Estuar. Coast. Shelf Sci.* 68, 113–126.
- Layman, C.A., 2000. Fish assemblage structure of the shallow ocean surf-zone on the eastern shore of Virginia Barrier islands. *Estuar. Coast. Shelf Sci.* 51, 201–213.
- Leandro, S.M., Morgado, F., Pereira, F., Queiroga, H., 2007. Temporal changes of abundance, biomass and production of copepod community in a shallow temperate estuary (ria de Aveiro, Portugal). *Estuar. Coast. Shelf Sci.* 74, 215–222.
- Lee, C.R., Kang, H.K., Choi, K.H., 2011. Latitudinal distribution of mesozooplankton community in the northwestern Pacific Ocean. *Ocean. Polar. Res.* 33, 337–347.
- Legendre, P., Gallagher, E.D., 2001. Ecologically meaningful transformations for ordination of species data. *Oecologia* 129, 271–280.
- NMS (National Meteorological Service), 1992. Estadísticas Climatológicas 1981-1990. Secretaría de Aeronáutica de la Nación, Buenos Aires, Argentina.
- Manning, L.M., Peterson, C.H., Fegley, S.R., 2013. Degradation of surf-fish foraging habitat driven by persistent sedimentological modifications caused by beach nourishment. *Bull. Mar. Sci.* 89, 83–106.
- Marin Jarrin, J.R., Vanaverbeke, J., Fockede, N., del, M., Cornejo, P., de Grunauer, R., Dominguez-Granda, L., 2017. Surf zone fauna of Ecuadorian sandy beaches: spatial and temporal patterns. *J. Sea Res.* 120, 41–49.
- Marques, S.C., Azeiteiro, U.M., Martinho, F., Pardal, M.A., 2007. Climate variability and planktonic communities: the effect of an extreme event (severe drought) in a southern European estuary. *Estuar. Coast. Shelf Sci.* 73, 725–734.
- Marques, S.M., Azeiteiro, U.M., Martinho, F., Viegas, I., Pardal, M.A., 2009. Evaluation of estuarine mesozooplankton dynamics at a fine temporal scale: the role of seasonal, lunar and diel cycles. *J. Plankton Res.* 31, 1249–1263.
- McLachlan, A., Defeo, O., 2018. The Ecology of Sandy Shores, 3rd edition. Elsevier Academic Press, London, United Kingdom.
- McLachlan, A., Defeo, O., Short, A.D., 2018. Characterising sandy beaches into major types and states: implications for ecologists and managers. *Estuar. Coast. Shelf Sci.* 215, 152–160. <https://doi.org/10.1016/j.ecss.2018.09.027>.
- Menéndez, M.C., Dutto, M.S., Piccolo, M.C., Hoffmeyer, M.S., 2012a. The role of the seasonal and semi-diurnal tidal cycle on mesozooplankton variability in a shallow mixed estuary (Bahía Blanca, Argentina). *ICES J. Mar. Sci.* 69 (1), 389–398.
- Menéndez, M.C., Piccolo, M.C., Hoffmeyer, M.S., 2012b. Short-term variability on mesozooplankton community in a shallow mixed estuary (Bahía Blanca, Argentina): influence of tidal cycles and local winds. *Estuar. Coast. Shelf Sci.* 112, 11–22.
- Menéndez, M.C., Baleani, C.A., Amodeo, M., Acha, E., Piccolo, M.C., 2019. Assessment of surf zone zooplankton dynamics in a southwestern Atlantic sandy beach: seasonal cycle and tidal height influence. *Estuar. Coast. Shelf Sci.* 227, 106–307.
- Moon, S., Oh, H., Soh, H., 2010. Seasonal variation of zooplankton communities in the southern coastal waters of Korea. *Ocean. Polar. Res.* 32, 411–426.
- Morgan, C.A., Cordell, J.R., Simenstad, C.A., 1997. Sink or swim? Copepod population maintenance in the Columbia River estuarine turbidity-maxima region. *Mar. Biol.* 129 (2), 309–317.
- Morgan, C.A., Peterson, W.T., Emmett, R.L., 2003. Onshore-offshore variations in copepod community structure off the Oregon coast during the summer upwelling season. *Mar. Ecol. Prog. Ser.* 249, 223–236.
- Morgan, S.G., Shanks, A.L., Fujimura, A.G., Reniers, A.J.H.M., MacMahan, J., Griesemer, C.D., Jarvis, M., Brown, J., 2016. Surfzone hydrodynamics as a key determinant of spatial variation in rocky intertidal communities. *Proc. R. Soc. B* 283 s.
- Muxagata, E., Amaral, W.J.A., Barbosa, C.N., 2012. *Acartia tonsa* production in the Patos lagoon estuary, Brazil. *ICES J. Mar. Sci.* 69, 475–482.
- Odebrecht, C., Bergesch, M., Rörig, L.R., Abreu, P.C., 2010. Phytoplankton interannual variability at Cassino Beach, southern Brazil (1992–2007), with emphasis on the surf zone diatom *Asterionellopsis glacialis*. *Estuar. Coasts* 33, 570–583.
- Odebrecht, C., Preez, D.R., Abreu, P.C., Campbell, E.E., 2014. Surf zone diatoms: a review of the drivers, patterns and role in sandy beaches food chains. *Estuarine, Coastal and Shelf Science* 150 (A), 24–35.
- Oksanen, J., Guillaume Blanchet, F., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., Minchin, P.R., O'Hara, R.V., Simpson, G.L., Solymos, P., Henry, P., Stevens, H., Szoecs, E., Wagner, H., 2018. In: *Vegan: community ecology package*. In: R Package Version 2.4–6. <https://CRAN.R-project.org/package=vegan>.
- Oliveira-Santos, N.M., Martins-García, T., de Oliveira-Soares, M., 2016. Micro- and mesozooplankton communities in the surf zone of a tropical sandy beach (equatorial southwestern Atlantic). *Lat. Am. J. Aquat. Res.* 44, 247–255.
- Pardal, M.A., Cardoso, P.G., Sousa, J.P., Marques, J.C., Raffaelli, D., 2004. Assessing environmental quality: a novel approach. *Mar. Ecol. Prog. Ser.* 267, 1–8.
- Piccolo, M.C., Perillo, G.M.E., 1990. Physical characteristics of the Bahía Blanca estuary (Argentina). *Estuar. Coast. Shelf Sci.* 31, 303–317.
- Pinheiro, S.C.C., Leite, N.R., da Costa, V.B., da Costa, K.G., Pereira, L.C.C., da Costa, R.M., 2011. Spatial-temporal influence of hydrological variables on the diversity and abundance of copepods on an equatorial macrotidal beach in the Brazilian Amazon region. *J. Coast. Res.* 64, 425–429.
- Pinheiro, S.C.C., Magalhães, A., da Costa, V.B., Pereira, L.C.C., da Costa, R.M., 2013. Temporal variation of zooplankton on a tropical Amazonian beach. *J. Coast. Res.* 2, 1838–1843.
- Primo, A.L., Azeiteiro, U.M., Marques, M.F., Pardal, M.A., 2009. Changes in zooplankton diversity and distribution pattern under varying precipitation regimes in a southern temperate estuary. *Estuar. Coast. Shelf Sci.* 82, 341–347.
- R Core Team, 2017. *R: A Language and Environment for Statistical Computing*. <https://www.R-project.org/>.
- Ramette, A., 2007. Multivariate analyses in microbial ecology: multivariate analyses in microbial ecology. *FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Ecol.* 62, 142–160.
- Revelle, W., 2019. Using R and the psych package to find  $\omega$ . In: R Package Version 3.4.4. Department of Psychology Northwestern University.
- Rice, E., Dam, H.G., Stewart, G.M., 2015. Impact of climate change on estuarine zooplankton: surface water warming in Long Island sound is associated with changes in copepod size and community structure. *Estuar. Coasts* 38, 13–23.
- Rodrigues, F.L., Vieira, J.P., 2012. Surf zone abundance and diversity at two sandy

- beaches separated by long rocky jetties. *J. Mar. Biol. Assoc. U. K.* 93, 867–875.
- Roman, M.R., Holliday, D.V., Sanford, L.P., 2001. Temporal and spatial pattern of zooplankton in the Chesapeake Bay turbidity maximum. *Mar. Ecol. Prog. Ser.* 213, 215–227.
- Schlacher, T.A., Schoeman, D.S., Dugan, J., Lastra, M., Jones, A., Scapini, F., McLachlan, A., 2008. Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. *Mar. Ecol.* 29, 70–90.
- Schneider, C., 1981. The Littoral environment observation (LEO) data collection program. In: Coastal Engineering Research Center. Coastal Engineering Technical AID NO, pp. 81–85.
- Servicio de Hidrografía Naval (SHN), 2009. Tablas de Marea. Departamento de Artes Gráficas del Servicio de Hidrografía Naval. Publicación H-610, Buenos Aires, pp. 140–144.
- Stull, K.J., Cahoon, L.B., Lankford, T.E., 2016. Zooplankton abundance in the surf zones of nourished and unnourished beaches in Southeastern North Carolina, USA. *J. Coast. Res.* 32, 70–77.
- Sun, X.H., Sun, S., Li, C.L., Zhang, G.T., 2008. Seasonal and spatial variation in abundance and egg production of *Paracalanus parvus* (Copepoda: Calanoida) in/out Jiaozhou Bay, China. *Estuar. Coast. Shelf Sci.* 79, 637–643.
- Suzuki, K., Nakamura, Y., Hiromi, J., 1999. Feeding by the small calanoid copepod *Paracalanus* sp. on heterotrophic dinoflagellates and ciliates. *Mar. Ecol. Prog. Ser.* 17, 99–103.
- Watt-Pringle, P., Strydom, N.A., 2003. Habitat use larval fishes in a temperate South African surf zone. *Estuar. Coast. Shelf Sci.* 58, 765–774.
- Wei, T., 2017. Visualization of a correlation matrix. Package 'corrplot'. In: R Package Version 3. 4. 4, . <https://github.com/taiyun/corrplot>.
- Wu, C.J., Chiang, K.P., Liu, H., 2010. Diel feeding pattern and prey selection of mesozooplankton on microplankton community. *J. Exp. Mar. Biol. Ecol.* 390, 134–142.