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Surf zone zooplankton communities: spatial patterns on rocky and sandy beaches of the Portuguese coast

Marta Alexandra Domingues Frazão

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Dissertação apresentada à Universidade de Coimbra para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Ecologia, realizada sob a orientação científica do Professor Doutor Miguel Ângelo Carmo Pardal (Universidade de Coimbra) e co-orientação da Doutora Sónia Cotrim Marques (Universidade de Coimbra).

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RESUMO

O ecossistema da *surf* zone tem vindo a ser progressivamente reconhecido como um dos mais importantes elos de ligação entre os ambientes costeiro e marinho. Estas áreas são caracterizadas por constantes variações hidrológicas e uma alta diversidade morfológica o que, associado aos organismos que as habitam e a sua adaptabilidade, as tornam únicas e dinâmicas e, por isso, extremamente relevantes para estudos científicos. Este estudo abordou a estrutura de um dos mais importantes níveis tróficos marinhos, o zooplâncton, ao longo da costa portuguesa. As amostras foram recolhidas em 4 transectos, durante o Verão de 2014, no Norte, Centro Norte, Centro Sul e Sul de Portugal. Para além da variabilidade espacial, este trabalho teve como objetivo a avaliação de diferenças na estrutura das comunidades de zooplâncton entre os dois mais importantes tipos de costa, rochosa e arenosa. Para esse efeito, cada transecto foi amostrado em duais praias: rochosa e arenosa.

Foram encontradas diferenças na estrutura das comunidades de zooplâncton ao longo de toda a costa portuguesa, o que está associado a um gradiente decrescente de temperatura ao longo da linha da costa, de Sul para Norte. Adicionalmente, foram também encontradas diferenças significativas na estrutura das comunidades presentes nas praias arenosas. Por outro lado, considerando as comunidades de zooplâncton das praias rochosas, não foi encontrado um padrão tão evidente. A costa rochosa a Sul não apresentou diferenças quando comparada com as restantes e, para o mesmo tipo de praia, entre as quatro, a região a norte diferenciou-se de forma mais evidente, particularmente quando comparada com a região Centro.

As comunidades de zooplâncton da *surf* zone são dominadas particularmente por copépodes, seguidos por cladóceros, bivalves e anfípodes. Todas as comunidades foram amplamente influenciadas pela temperatura, o pH, oxigénio dissolvido, ondulação e níveis de clorofila a.

A caracterização da *surf* zone portuguesa, em termos espaciais e morfológicos, abre assim portas a estudos experimentais nesta costa. Futuramente, trabalhos considerando, por exemplo, gradientes de temperatura e a respetiva resposta das comunidades de zooplâncton podem ser efetuados

ABSTRACT

The surf zone ecosystem has been gradually recognised has one of the most important links between coastal and marine environments through the years. Its morphological diversity and constant hydrological variations make this area and the organisms that inhabit there unique, dynamic and adaptable place for scientific studies. The present study addressed the community structure of the greatest marine food source, the zooplankton. Samples were collected along the Portuguese coast at four transects during the summer of 2014 (north, central north, central south and south). Apart from the spatial variability, this study also aimed to evaluate de differences in zooplankton community structure between the two main types of shores, rocky and sandy, in order to do so two sandy beaches and two rocky shores were sampled in each transect.

Differences in zooplankton community structure were found through the entire Portuguese coast which was associated with the decreasing gradient of temperature observed from the south to the north of the coastline. Furthermore differences in zooplankton community structures of sandy beaches along the coast were very significant. Contrasting with the results obtained for the sampled sandy beaches, the zooplankton communities of the rocky shores were not as evident through the extension of coastal zone sampled. South rocky shores showed no differences when compared to all the others and, for the same beach type, the north region was proved to be the most distinct among the four particularly when compared to the central regions. Local differences were found between beach types in the north, and the central regions, however in the south such pattern was not observed.

The zooplankton communities of the surf zone were dominated mainly by copepods, followed by cladocerans, bivalves and amphipods, and were strongly influenced by temperature, pH, dissolved oxygen, wave period and chlorophyll *a* levels.

This characterization of the Portuguese surf zone, both spatial and morphological, opens the doors for experimental science in this coast. Further studies considering, for example, temperature gradients and zooplankton responses can now be conducted.

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CHAPTER 1

- Introduction -

1. INTRODUCTION

THE COASTAL ZONE: THE SURF ZONE ECOSYSTEM

The worldwide coastal regions are unique areas. Their remarkable biological productivity, easy accessibility and beauty have made them attractive for humans since early times. This narrow geographic strip where land meets the sea provides the most diverse range of habitats for living organisms and offers a unique blend of habitats that can't be found elsewhere (Knox, 2000). Coastal marine ecosystems provide an array of goods and services: they host the world's primary marine ports, sustains high levels of primary production and biodiversity of fish, shellfish and seaweed, resources important for mankind and animal consumption. In addition, they are also a considerable source of fertilizers, pharmaceuticals and cosmetics and household materials (Burke et *al*. 2001). Marine habitats from the intertidal zone to the continental shelf are estimated to provide 43% of the global total ecosystem goods and services per year and are amongst the most economically and socio-economically vital on the planet (Harley et al. 2006).

The ecosystems of these marine habitats are organized in an endless interconnected subsystems whose functions cannot be duplicated. They are precisely balanced and are susceptible to a variety of threats including those induced by human activity. Despite its fragility, the coastal zone ecosystems are amazingly resilient and as a whole are a dynamic and regenerative force where natural mechanisms maintain an equilibrium between living beings and natural environment (Beatley et *al*. 2001).

A good knowledge and understanding of the physical and biological processes is required to forecast local impacts. Figure 1 shows the total extent of the coastal zone: inshore, foreshore and backshore. The inshore extends from the limits of wave backrush during the low tides to the water depth beyond which there is little movement of beach material. The backshore is the region that is normally above the limit of wave uprush during high tides, however it may occasionally be submerged by the sea during storms. Unlike the backshore region, the foreshore is every day covered and uncovered by the sea during high and low tides (Hedges, 2014). In this thesis we propose to study a very specific and dynamic portion of the coastal zone: the surf zone.

Surf zone (Figure 2) is defined as the moving water between the water-up-rush on the shore and the breaking point of the waves (Lock et al. 2011). It includes the swash zone which is the region alternately covered and uncovered by the tides and, unlike the coastal zone which changes its position and width

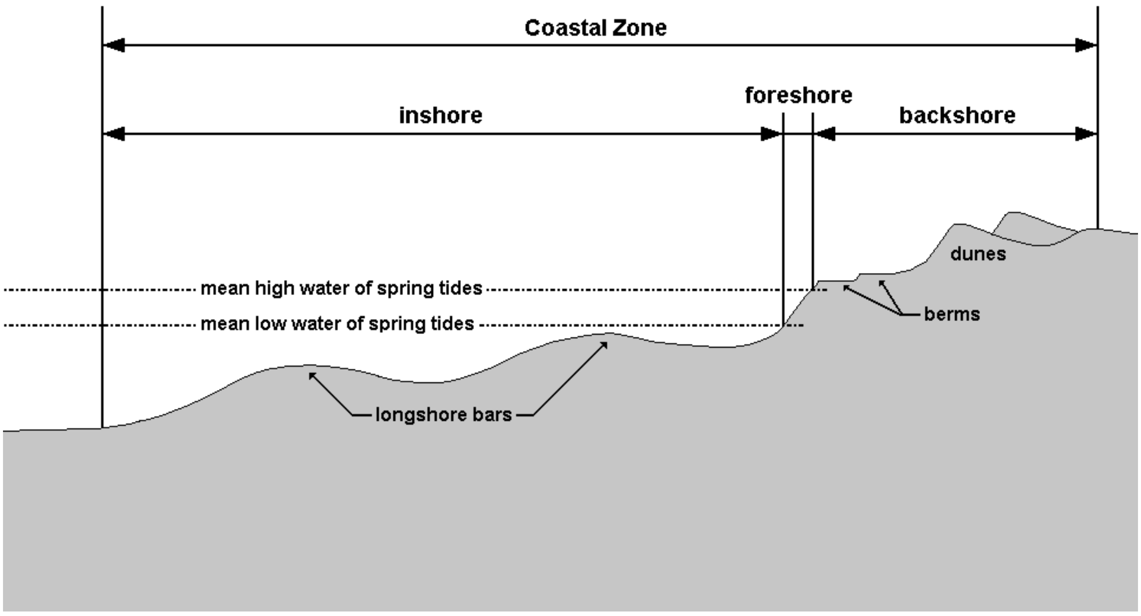

Figure 1- The extent of the coastal zone, including the inshore, foreshore and backshore regions (retrieved from Hercules Network).

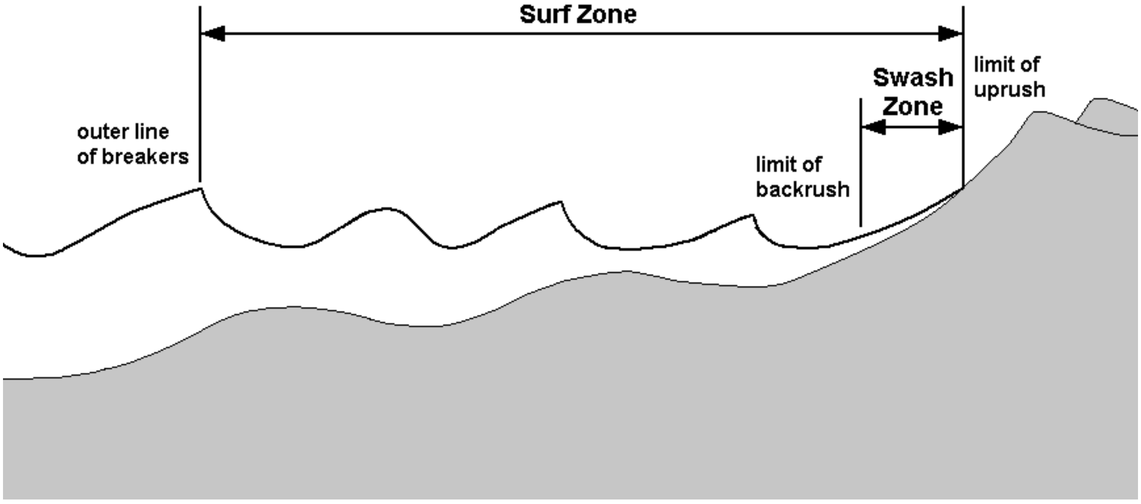

Figure 2- The surf zone. Meaning of the terms related to the wave breaking at the shore (retrieved from Hercules Network).

only gradually, the surf zone shifts with the tide and its width depends on wave conditions (Hedges, 2014). Much of the wave energy expended on the shore also affects the organisms and eventually serves to shape and alter the essential physical and biological character of the shoreline itself (Sumich & Morrissey, 2004).

For many years the surf zone habitats were characterized as structurally standardized environments and were thought to provide very little variability in terms of habitat diversity, cover or productivity (Granda et al. 2004). However, Clark et al. (1996) has suggested that certain physical variables such as degree of wave exposure, sediment particle size and turbidity have a strong influence on the relative abundance of certain species and may alter the composition and species richness of surf zone assemblages. The surf zone has a very high turbidity, oxygen levels and sunlight exposition which makes it a highly productive marine area for animal life. Therefore, many teleost and invertebrate species use the surf zone as a nursery area, their larvae feed on the hyperbenthic community and the characteristics of this zone provide refugee for smaller specimens until they are larger and less vulnerable to predators (Hajisamae et al. 2013). The specimens present in these areas are influenced by the lunar cycles (tides), salinity, temperature, food availability and depositional processes as well as the interactions among these factors (Costa et al. 2011).

Several studies have already been conducted regarding the surf zone: regarding invertebrate larvae (Rilov *et al*. 2008), invertebrate communities (Barry *et al*. 1995; Beasley *et al*. 2005) and fish assemblages (Nakane *et al*. 2013) which are the organisms most exploited by science in these habitats. The frequent abundance of invertebrate larvae, juvenile and adult fish as well as adult planktivors in surf zones strongly suggest the importance of zooplankton assemblages as trophic intermediates (Stull *et al*. 2015).

The Portuguese Atlantic coast

The Portuguese coast is situated in the Iberian Coastal large marine ecosystem. It has an extension of 1,194 km and is characterized by a temperate climate, very diverse in what concerns topographical features with estuaries and rias (McGinley, 2008) and strong seasonal upwelling during spring and summer which promotes the enrichment of the euphotic zone with nutrients influencing the pelagic system productivity (Cunha, 1993).

Bathed by the Atlantic Ocean, the Portuguese coast is divided in three main areas according to its exposure: exposed coast, moderately exposed and sheltered Atlantic coast (Bettencourt et *al*. 2003).

The Portuguese exposed western coast extends from the northern border with Spain to Cape Carvoeiro and can be divided in two main morphological parts (Bettencourt et *al*. 2003). The first one, extending south from the northern border with Spain until the Douro estuary, is manly rocky and shallow with cliffs alternating with small beaches. Southward from the mouth of Douro to Cape Carvoeiro sandy beaches are the main morphological structures, interrupted only by Cape Mondego (Bettencourt et *al*. 2003). The uppermost zone of these shores are dominated by lichens such as *Verrucaria maur*; sessile feeders like *Mytilus* sp. are the most common organisms at midlevels on the shores of exposed zones; finally the lower littoral is characterized by a considerable diversity of turf forming algae and canopy species such as *Saccorhiza polyschides* and *Chondracanthus acicularis* (Araujo et al. 2005).

The coast from Cape Carvoeiro to Ponta da Piedade is entitled has the moderately exposed Atlantic coast of Portugal. From Cape Carvoeiro to Cape Raso cliffs replace the beaches and from there to Cape Sines two irregular coastal sectors alternate with two sandy sectors. The remaining moderately exposed coast ends in Ponta da Piedade where cliffs, interrupted by small beautiful beaches, are the main morphological assemblies (Bettencourt et *al*. 2003).

The remaining coast, stretching until the Guadiana estuary, is the sheltered Atlantic coast. From Ponta da Piedade to Ria Formosa the morphology is very similar to the previous one, with small beaches surrounded by cliffs. Ria Formosa is coastal lagoon system with many barrier islands and extending to the southeast frontier with Spain, the coast line is manly composed of sandy beaches (Bettencourt et *al*. 2003).

Sandy Beaches and Rocky Shores

From a geological point of view there are two major types of shores: rocky and sandy beaches. The environmental features and biodiversity associated with such habitats are quite different that little overlap exists between the species populations that inhabiting them (Knox et *al*. 2003). Regardless of the biological dissimilarities and functions neither rocky shores nor sandy beaches appear to be complete ecosystems by themselves, given that the energy transfer in all ecosystems has two complementary pathways: a grazing food web and a detritus food web and within the coastal zone neither one of these shores is able to accomplish both (Sumich & Morrissey, 2004).

In rocky littoral communities the trophic relations exhibit well-developed and complicated food webs, but due to its erosional nature the accumulation of detritus and the existence of detritus-dependent animals is very scarce. Therefore, the community is mostly composed of grazing species such as molluscs (Carroll & Highsmith, 1996; Barry et al. 1995) and crustaceans (Pineda, 1994). The patterns of distribution and abundance on these shores, as well as trophic relations, are complex and sometimes change from season to season (Sumich & Morrissey, 2004).

The depositional features and the dominance of detritus food webs in sandy beaches make these the perfect ecologic complement to rocky shores. Large plants find the shifting nature of soft sediments difficult to cope with and very few exist there, even so the few plants that have managed to adapt support even fewer grazers. The detritus feeders of sandy shores are sustained by small amounts of organic material washed off adjacent rocky shores, the surrounding land or drifted in from kelp beds farther offshore (Sumich & Morrissey, 2004). These beaches occur where waves are sufficiently gentle to allow sand accumulation but still strong enough to wash the finer silts and clays away. Furthermore, the major exchanges of organic materials and nutrients are with the sea and the pathway for such exchanges is no other than the surf zone (McLachlan & Brown, 2006).

To the casual observer, sandy beaches may seem devoid of animal life, macroscopic algae and obvious epifauna are scarce and the most abundant organisms are amphipods, polychaetes, isopods and sand crabs (Brown & McLachlan, 2006). Due to the difficulties experienced in working in high-energy surf zones the fauna of these shores has received less attention than zooplankton and fish assemblages in other coastal systems. In Brazil, Beasley *et al*. (2005) turned to the exploration of molluscan diversity and abundance of the Ajuruteua peninsula, they registered a big diversity of bivalves followed closely by gastropods, and seasonal variations in density were also detected and linked to the effect of rainfalls in salinity and to desiccation during the dry season.

Unlike sandy beaches, rocky shores are plentiful of biodiversity occupying different ecological niches. Fauna and flora tend to have large dimensions when compared to sandy beaches, and are highly coloured. Contrasting with sandy beaches, rocky shores have been frequently studied and most of the taxa are well characterised. Pineda (1994) explored barnacle settlement rate in a California rocky shore (USA) and Rilov *et al*. (2008) tested the surf zone of rocky shores of Oregon and New Zealand for invertebrate larvae recruitment.

In Portugal the surf zone is very little studied. Bessa *et al*. (2013) addressed a pressing matter concerning the macrofaunal assemblages and the consequences of anthropogenic impacts on sandy beaches communities, and has found crustaceans (amphipods and isopods) to be the most abundant organisms on Leirosa beach (Portugal). Furthermore Bessa *et al*. (2013) identified the sandhopper (*Talitrus saltaror*) as an effective and reliable ecological indicator of the function of these ecosystems. In 1998 Lock and Mees have studied the hyperbenthic fauna of Ria Formosa, a tidal lagoon, and the adjacent sandy beaches. Even though the salinity of the lagoon didn't differ from the open sea the hyperbenthic fauna was quite different. At both locations, species diversity, biomass and density were higher in the tidal lagoon than in the sandy beach. This can be easily explained by differences on hydrodynamic characteristics, being sandy beaches more exposed to currents and wave energy than the beaches inside the lagoon.

The rocky shores of Portugal have been analysed for distribution patterns of intertidal communities (Boaventura *et al*. 2002). Boaventura *et al*. visited three main locals (north, centre and south) and a total of 27 locations along the Portuguese coast were sampled. The distribution patterns found on the sub-litoral fringe showed clear differences between northern shores, distinct for their large brown algae abundance, and shores located in the central and southern regions that were essentially dominated by red algae species.

Nevertheless, little attention has been given to the zooplankton communities occurring on the surf zone of the Portuguese coast.

Zooplankton: The surf zone Community

The world ocean fauna is dominated in terms of abundance and biomass by the drifting organisms collectively referred as plankton. These organisms are exceptional and occur in all marine waters, throughout all depths, and – for many species – across widespread biogeographical distributions (CMarZ, 2004).

The term “plankton” comprises all organisms drifting in the water column whose abilities of locomotion are insufficient to withstand currents (Harris et al., 2000). Zooplankton (planktonic animals) are taxonomically and structurally diverse and so perform a large variety of ecosystem functions such as consumers, predators and preys (MZC2, 2001). By controlling phytoplankton (photosynthesizing microscopic organisms) production and shaping pelagic ecosystems planktonic animals play a key role in the ocean well-function. Furthermore, because they are the main food source for larval and juvenile fish, the population dynamics, reproductive cycles, growth and survival rates are all important factors influencing recruitment of fish stocks and other macrofauna (Harris et al., 2000).

Few studies describe the zooplankton surf zone communities and address their trophic importance. Pinheiro *et al*. (2011) examined the seasonal differences in species composition and abundance of copepods off Ajuruteua beach (Amazon, Brazil) and proved the relation between copepod abundance and precipitation levels. In India, Sahu *et al.* (2012) studied the zooplankton abundance and composition at Gopalpur port, finding that this assemblages were dominated by copepods and also included chaetognaths and decapod larvae. Granda *et al.* observed the hyperbenthic fauna of Valdivia bay (Ecuador) and found mysid to be the dominant group followed by calanoid copepods chaetognaths and fish eggs. Lock *et al.* (2011) also explored the hyperbenthic community of the surf zone, he learnt that the sandy beaches of Belgium are dominated by mysida and that amphipoda is the most diverse group found on this shore line. DeLancey (1987) revealed the zooplankton community of the surf zone of a North Carolina beach (United States) and discovered the importance of zooplankton in food webs of anchovy (*Ancho* sp.) and silverslides (*Menidia* sp.). Despite all this, there is only a scarce source of descriptions of the surf zone zooplankton with considerable variation among studies in regard to taxonomic focus, sampling method and geology.

Additionally to zooplankton, some surf zone inhabitants live specifically in the lowest levels of the water column, close to the bottom, and are called hyperbenthos. These organisms are in close association with the seabed, can structure zooplankton communities by predation and are an important part of the diet of demersal fish (Hamerlynck & Mees, 1991). The hyperbenthos assemblages are composed by species living permanently in the lower layers of the water column (eg., mysids and copepods), species with a manly endobenthic lifestyle but making short outings from the sea bed for feeding, mating and dispersion (eg., amphipods, isopods, cumaceans and some polychaets) and early life stages of epibenthic species (eg., larvae and juveniles of several decapod and fish species) (Granda et al. 2004). However, due to the wave breaking process, the sediment rush-up, tides and the constant change in the surf zone, the hyperbenthic and the zooplanktonic communities are tied together and are hardly distinguished.

Given the highly dynamics of the community structure of the surf zone, a better understand of its trophodynamics requires further ecological studies of the communities assemblages

Objectives

In western Portugal the surf zone community has been described but the zooplankton community has been overlooked. Therefore, due to the importance of zooplankton communities in the marine environment, the aims of this study are:

1. To identify the zooplankton assemblages occurring in the surf zone of the western coast of Portugal;
2. To describe the environmental parameters influencing the community structure;
3. To compare the zooplankton communities of rocky shores and sandy beaches throughout the coast of Portugal.

CHAPTER 2

– Materials and Methods –

2. MATERIALS AND METHODS

Study area

This study was conducted along the continental Portuguese Coast within latitudes 41º 5’ N to 37º4’ N (Table I, Fig. 1), from 15 of July thought 19 of September 2014. The Portuguese coast is affected by a mesotidal regime, with semi-diurnal tides and frequent upwelling of cold water occurs in the summer (Boaventura et al, 2002), which is associated with the enhancement of pelagic system productivity (Cury et al, 2000). While on the west coast sea surface temperature can reach more than 20º in summer, on the south coast they generally are slightly higher (approximately 1 – 1.5º) due to the influence of warmer currents from the Mediterranean Sea (Boaventura et al, 2002).

Field Sampling and laboratory procedures

Sampling was performed in 4 different geographic areas along the Portuguese coast. In each area a four beach system, comprising two sandy beaches and two rocky shores (see Table I; Fig. 1), were sampled in two different occasions.

At each beach, three samples were collected during daylight and at low tide, ensuring consistency across all datasets used.

Zooplankton samples were collected with a gasoline-motor driven pump (Motobomba Honda WMP 20X) delivering approximately 0.5 m^3 min^{-1}. The samples were filtered through a 200 µm mesh net and preserved in a 4%

buffered formaldehyde solution immediately after collection. To characterize the environmental condition in each site, water temperature (ºc), salinity, pH and dissolved oxygen (DO, mg l^{-1}) were measured using a WTW Multi 3410 IDS. Water samples were collected and filtered for determination in laboratory of chlorophyll *a* (Chl *a*), suspended particulate matter (SPM) and particulate organic matter (POM). For determination of Chl *a*, water samples were filtered onto Whatman GF/C glass-fiber followed by extraction following the protocol of Parsons et al. (Parsons et al. 1985). POM was estimated by filtering water through pre-combusted and pre-weighted Whatman GF/C filters, and dried at 60ºC for 72 hours and combusted at 450ºC for 8h (APHA, 1995).

Table 1 - Sampling stations and respective beaches. Each beach was given a code to facilitate the future analysis, for example NS1, North Sandy beach one, matches Praia de Espinho

Location	**Sandy B.**	**Lat.**	**Rocky S.**	**Lat.**
North Coast	Praia de Espinho (N.S1)	41º0'N	Valadares (N.R1)	41º5'N
	Praia do bairro piscatório (N.S2)	41º0'N	Francelos (N.R2)	41º4'N
Central North (CN)	Praia da Gala (C.S1)	40º7'N	Praia de Buarcos (C.R1)	40º9'N
	Praia do Hospital (C.S2)	40º7'N	Praia Tamargueira (C.R2)	40º9'N
Central South (CS)	Fonte da Telha (P.S1)	38º34’N	Portinho da Arrábida (P.R1)	38º28'N
	Fonte da Telha (P.S2)	38º34’N	Galapos (P.R2)	38º28'N
South Coast	Galé poente (S.S1)	37º4'N	Evaristo (S.R1)	37º4'N
	Albufeira (S.S2)	37º4'N	Manuel Lourenço (S.R2)	37º4'N

At the laboratory, the zooplankton samples were transferred to a solution of 80% alcohol and examined under a stereoscopic microscope. Due to logistic constrain a total of 56 samples were examined, corresponding to 24 samples from the North, 24 from the Central North, 4 from the South and 4 from the Central South. Samples were split for enumeration with a Folsom plankton splitter. The total fraction counted was adjusted such that a minimum of 100 individuals were counted per taxonomic group. The fraction counted varied between the entire sample and 1/16th.

All organisms were identified to the lowest taxon possible, groups like amphipoda, bivalvia, cirripedia and polychaeta were not possible to identify to the species level. Nevertheless copepoda, mysidacea, isopoda, cladocera,

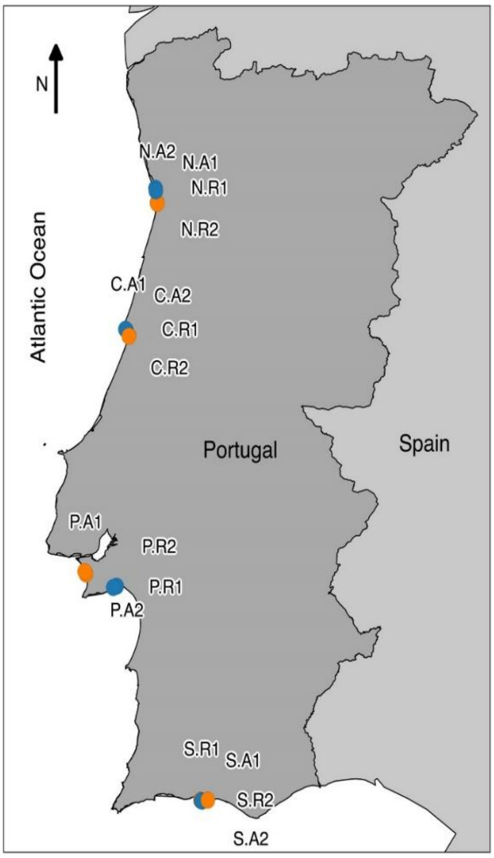

Figure 3 – Sampling stations along the Portuguese shore, the four areas (N, C, P and S) with the respective sandy beaches (blue dots) and rocky shores (yellow dots).

cumacea and decapoda were identified, at least, to the genus level and most of them to the species level. Abundance estimations of the organisms were standardised as the number of individuals per m^3.

Statistical analysis

Univariate analysis

In order to investigate the zooplankton community diversity at all study sites species richness (S') and the Shannon-Wiener diversity index were calculated. The data was log (x+1) transformed and a similarity matrix was calculated using the Bray-Curtis index, one of the most (dis)similarity indexes used in ecology (Legendre & Gallagher, 2001).

Univariate PERMANOVAs with 999 random permutations were used to test for differences on total abundance of the main taxa between local and beach type. This analysis was used instead of the parametric alternatives because for most variables the data was highly skewed and the transformation was not able to correct the non-normality. Subsequently pairwise comparisons, using 999 random permutations, were performed when PERMANOVA tests were significant at the 0.05 level.

Multivariate analysis

A permutational multivariate ANOVA (PERMANOVA) was used to test differences in zooplankton community structure with local and beach type both as fixed factors. For some data in the analysis there were not enough permutable units to get a reasonable test by permutation, therefore the p-value was obtained using a Monte Carlo random sample from the asymptotic permutation distribution (Anderson & Robinson, 2003).

Variations in zooplankton community structures among all study sites and beach types were analysed by Principal Coordinate analysis (PCO, i.e. metric multidimensional scaling) based on the Bray-Curtis similarity matrix. The percentage similarity procedure (SIMPER) was then used to calculate the contribution of each species to the similarity between groups according to the PERMANOVA and PCO results. Multivariate analyses were carried out using the PRIMER v7 + PERMANOVA package (Clarke & Gorley 2015).

Environmental parameters

The Biota-Environmental routine (BIO-env) was carried out for the environmental parameters in order to explore relationships between the zooplankton community structure and the selected environmental data. The selected environmental variables included temperature, pH, dissolved oxygen, wave period, wave height, wind and chlorophyll *a*. All data was previously checked for normality and the Spearman correlation coefficient was used to test for collinearity between continuous variables. The data concerning wave height, wave period and wind data were obtained from the WindGuru website (http://windguru.cz, accessed on May, 2014).

CHAPTER 3

– Results –

3. RESULTS

ENVIRONMENTAL CHARACTERIZATION

As expected, South beaches showed increased water temperature, followed by Central South, and Central North. North showed the lowest water temperature. Rocky and sandy beaches presented similar water temperatures and differences between beaches seem to be higher in Central North and South.

Regarding chlorophyll *a*, analysed locals showed similar patterns with rocky beaches presenting higher values, except in the Central South. Moreover, values in the rocky areas were highly variable, mainly in the Central North.

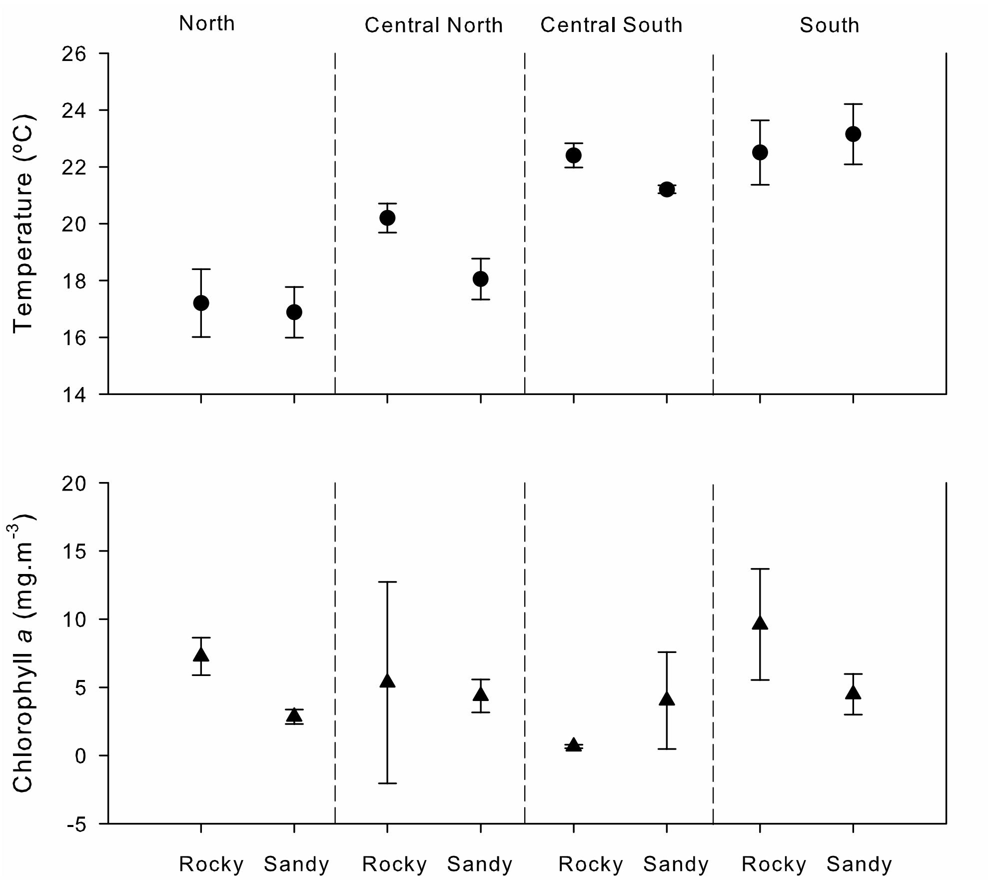

Fig. 2. Environmental variables.

ZOOPLANKTON SPATIAL VARIABILITY

The mean abundance of zooplankton revealed a peak of abundance in the North sandy beaches, while Central south rocky beaches presented the lowest values (Fig. 3). In fact, zooplankton abundance analysis showed that differences between locals/beach types varied according to beach types/locals (PERMANOVA, Pseudo-F= 9.35, p = 0.001). Zooplankton abundance was similar in all the rocky beaches whereas sandy beaches from the North showed higher values (*post hoc* test, $p<0.05$) (Fig. 3). Moreover, only North beaches showed different abundances between sandy and rocky beaches, with the first presenting the highest abundance of zooplankton (*post hoc* test, $p<0.05$) (Fig. 3).

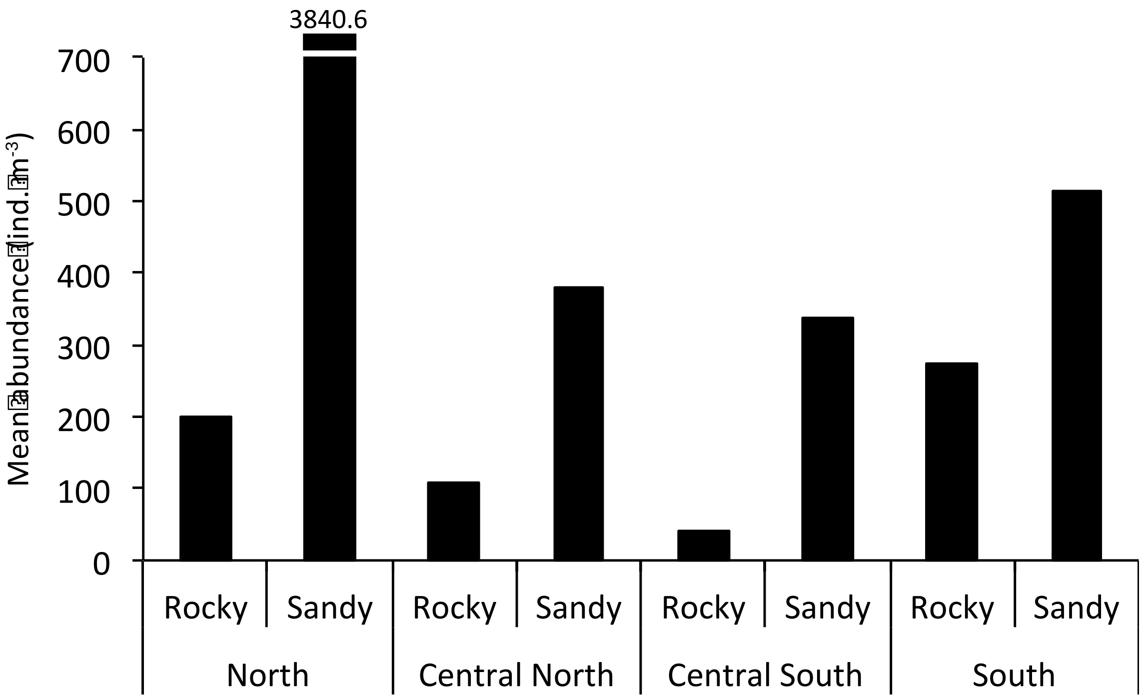

Figure 3. Mean zooplankton abundance (ind. m^{-3}) collected during the sampling period.

Zooplankton were grouped in nine taxa: Amphipoda, Bivalvia, Cirripedia, Cladocera, Copepoda, Echinodermata, Foraminifera, Isopoda and Polychaeta (Fig. 4). Copepoda was one of the most abundant and frequent taxa throughout the studied locals, followed by Cladocera, Bivalvia and Amphipoda. Generally, Copepoda represented higher importance in North and Central North communities, while Amphipoda had stronger representation in the South and Central South (Fig. 4). Zooplankton communities of sandy beaches of North and South showed increased abundances of Cladocera while Bivalvia contribution was higher in the sandy beaches of North and Central South (Fig. 4).

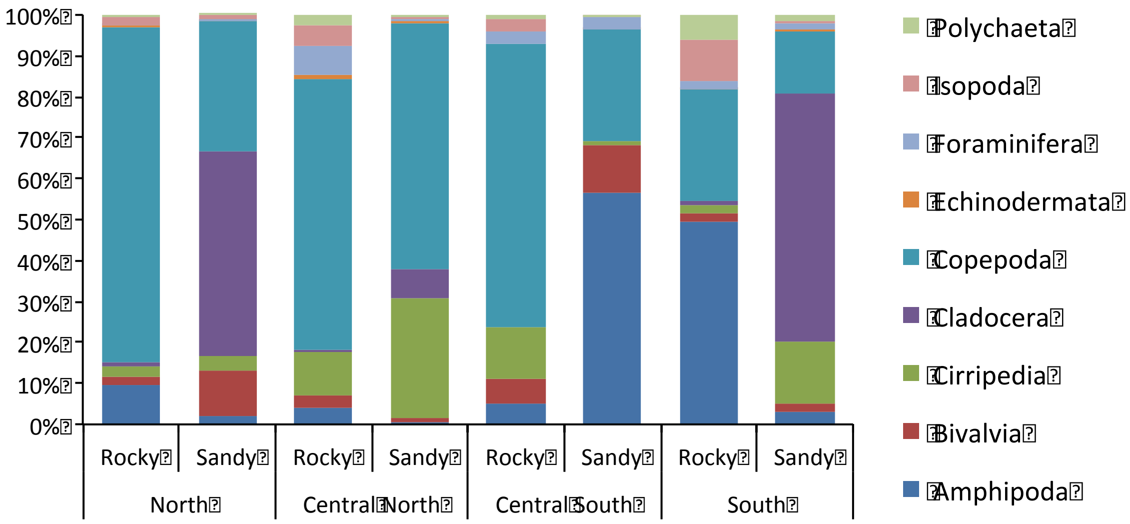

Figure 4. Relative contribution (%) of each taxa for total zooplankton abundance.

Despite the patterns observed, only Amphipoda, Copepoda, and Polychaeta presented differences in abundances between locals and/or beach type (Table 2). In the North Copepoda showed a higher abundance than the other locals (*post hoc* test, p<0.05), especially in the sandy beaches (*post hoc* test, p=0.001). Central North presented significantly lower Amphipoda than the southern locals. In fact, Amphipoda maximum occurred in Central South beaches (*post hoc* test, p<0.02), mainly in sandy beaches (*post hoc* test, p=0.009). South presented the highest Polychaeta abundances, particularly when compared with Central North (*post hoc* test, p=0.043).

ZOOPLANKTON COMMUNITY STRUCTURE AND LINK WITH ENVIRONMENT

Zooplankton community structure showed differences among the beach types and between the four locals along the Portuguese coast as shown by the PCO ordination (Fig. 5, Table 4). PCO axes explain more than 46% of total variation, 32% of which is explained by the first axis (Fig. 5). Mainly, the first axis drove the division between rocky and sandy beaches of all locals except Central South, while the second separated Central North and the rocky beaches of central south from the rest.

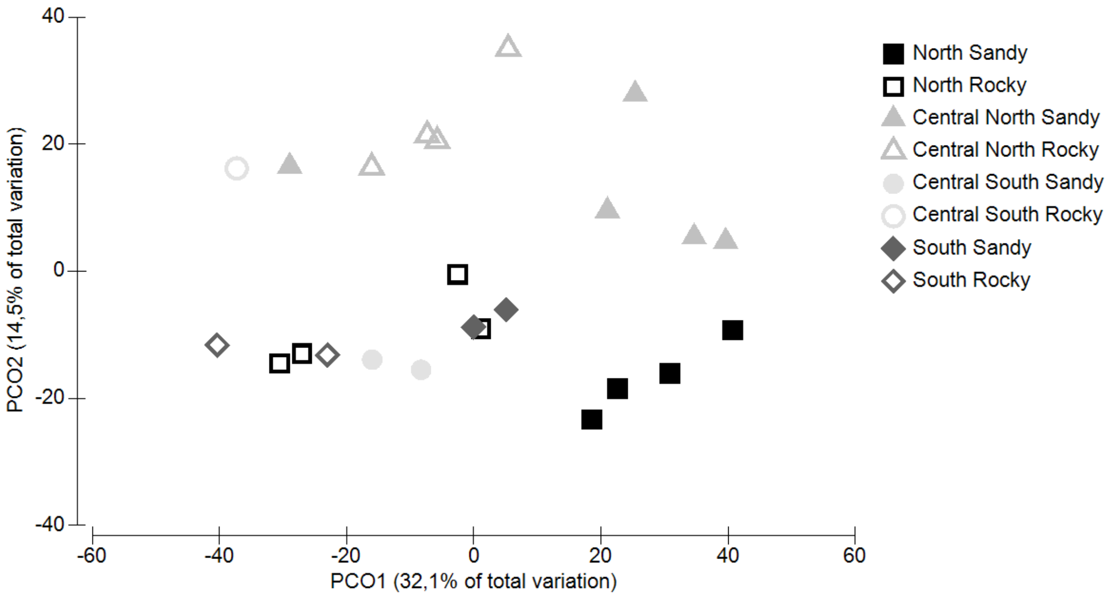

Figure 5 - Principal coordinate analysis (PCO) of beach types in the four locals based on the Bray-Curtis similarity matrix.

Table 2. PERMANOVA results of the nine taxa identified.

	Amphipoda					Bivalvia					Cirripedia				
	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$
Local	3	27843.0	9280.9	4.10	0.020	3	$2.4x10^5$	81112.0	1.06	0.390	3	13163.0	4387.7	0.36	0.830
Beach	1	4623.7	4623.7	2.04	0.150	1	76022.0	76022.0	0.99	0.403	1	30392.0	30392.0	2.47	0.140
Local:Beach	3	50865.0	16955.0	7.49	0.005	3	$2.4x10^5$	80469.0	1.05	0.408	3	12450.0	4150.1	0.34	0.820
Residuals	16	36219.0	2263.7			16	$1.2x10^6$	76400.0			16	$1.9x10^5$	12323.0		
Total	23	$1.2x10^5$				23	$1.9x10^6$				23	$2.7x10^5$			
	Cladocera					Copepoda					Echinodermata				
	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$
Local	3	$4.5x10^6$	$1.5x10^6$	2.23	0.120	3	$1.8x10^6$	$6.2x10^5$	20.94	0.001	3	22.9	7.6	1.68	0.180
Beach	1	$1.7x10^6$	$1.7x10^6$	2.50	0.130	1	$5.5x10^5$	$5.5x10^5$	18.77	0.001	1	15.9	15.9	3.50	0.080
Local:Beach	3	$4.5x10^6$	$1.5x10^6$	2.23	0.130	3	$1.3x10^6$	$4.2x10^5$	14.27	0.001	3	21.1	7.0	1.54	0.260
Residuals	16	$1.1x10^7$	$6.7x10^5$			16	$4.7x10^5$	29491			16	72.9	4.6		
Total	23	$2.3x10^7$				23	$4.6x10^6$				23	144.5			
	Foraminifera					Isopoda					Polychaeta				
	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$	df	SS	MS	$_{Pseudo}F$	$p_{(perm)}$
Local	3	23.9	7.9	0.12	0.950	3	1533.6	511.2	1.78	0.180	3	295.9	98.7	4.39	0.030
Beach	1	75.7	75.7	1.16	0.320	1	4.81	4.8	$1.69x10^{-2}$	0.910	1	4.4	4.4	0.19	0.690
Local:Beach	3	341.0	113.7	1.74	0.180	3	2485.6	828.5	2.89	0.060	3	171.4	57.1	2.54	0.080
Residuals	16	1046.5	65.4			16	4584.9	286.6			16	359.3	22.5		
Total	23	1461.9				23	8793.1				23	827.1			

PERMANOVA analysis revealed that differences in zooplankton community varied according to locals/beach (PERMANOVA, Pseudo-F= 3.02, p = 0.001). Community of sandy beaches varied along the coast, however only a few rocky beaches showed differences in community structure: North rocky beaches showed the most distinct community, mainly from the Central region (*post hoc* test, $p<0.05$), while south rocky beaches were similar to all the locals. According to SIMPER analysis, Harpacticoids, *Temora longicornis*, and *Paracalanus parvus* were the taxa that most contributed for these differences in the rocky beaches (Table 3). In sandy beaches, cladocerans *Evadne nordmanni*, *Pleopis polyphemoides* and *Penilia avirostris* seem to be the main contributors to the differences between locals (Table 4).

Table 3. Results of the BIOENV analysis defining a subset of environmental variables that best explains the community structure. K, number of variables.

K	Correlation (ρw)	Environmental variables
Best result for each number of variables		
1	0.283	Temp
2	0.330	Temp, Chla
3	0.334	Temp, O2, WaveP
4	0.337	Temp, O2,WaveP, Chla
5	0.338	Temp, pH, O2, WaveP, Chla
Best results		
5	0.338	Temp, pH, O2, WaveP, Chla
4	0.337	Temp, O2,WaveP, Chla
5	0.336	Temp, O2, WaveP, WaveH, Chla
3	0.334	Temp, O2, WaveP

When comparing zooplankton communities of rocky and sandy beaches, only North, Central North and Central South showed distinct communities (*post hoc* test, $p<0.05$). SIMPER analysis pointed out cladoceran *Evadne nordmanni*, copepod *Paracalanus parvus* and *Euterpina acutifrons* as the main species responsible for these differences (Table 4).

Table 4. Results of SIMPER analysis to the BeachxLocal factor showing the three species with higher contribution to the dissimilarity between local/beach.

Beach x Local		Av. dissimilarity (%)	Species
Rocky	N *vs* CN	62.7	*Sapphirina* sp. 2 *Temora longicornis* Harpacticoid 3
	N *vs* CS	65.1	*Paracalanus parvus* Harpacticoid 3 Harpacticoid 1
Sandy	N *vs* CN	51.9	*Evadne nordmanni* Post-veliger bivalve *Euterpina acutifrons*
	N *vs* CS	58.5	*Evadne nordmanni* *Acartia clausi* *Acartia clausi* (copepodite)
	N *vs* S	57.8	*Pleopis polyphemoides* *Penilia avirostris* *Evadne nordmanni*
	CN *vs* CS	64.2	Amphipoda Post-veliger bivalve Mytilus (juv.)
	CN *vs* S	58.0	*Pleopis polyphemoides* *Penilia avirostris* *Temora longicornis*
	CS *vs* S	51.4	*Pleopis polyphemoides* *Penilia avirostris* Amphipoda
North	Rocky *vs* Sandy	63.1	*Evadne nordmanni* *Euterpina acutifrons* *Acartia clausi*
Central North	Rocky *vs* Sandy	60.1	*Paracalanus parvus* *Cypris* Cirripedia *Acartia clausi*
Central South	Rocky *vs* Sandy	62.5	Amphipoda *Paracalanus parvus* *Mytilus* sp. (juv.)

A set of seven data measurements were incorporated into the Biota and Environment (BIO-ENV) matching routine to determine which environmental factors had the strongest correlations with the zooplankton community structure along the Portuguese coast: temperature, pH, dissolved oxygen, wave period, wave height, wind and chlorophyll *a*. According to the highest Spearman correlation (ρ) ranking temperature, pH, dissolved oxygen, wave period and chlorophyll *a* had the strongest association with the variance in zooplankton community structure for all the locals (ρ=0.338) (Table 3).

CHAPTER 4

– Discussion –

1. DISCUSSION

The present study is a significant contribution to the knowledge of surf zone communities along the Portuguese coast. The Portuguese coast, even though it is vast and diverse, is lacking a good spatial description. Therefore, in this thesis we aimed to provide a study of the zooplankton community structure along the four major sections of the coast.

Concerning the total zooplankton abundance the north sandy beaches stand out as the richest in individuals. This result can be explained because the sandy beaches in the north are associated with fisheries, which are characterized by higher abundances of zooplankton (Nakane et *al*. 2013). Moreover, only the north beaches showed differences in zooplankton abundance between sandy and rocky shores, what corroborates the hypothesis presented by Nakane et *al*. (2013).

In the other locals, differences in the zooplankton abundance between rocky and sandy beaches were not significant even though sandy beaches always showed a higher number of organisms. These results may be explained by the larger amount of particulate organic matter present in the sandy beaches and also by the superior wave energy dissipation that these beaches are exposed to when compared to rocky shores (Sumich & Morrissey, 2004), not all organisms are able to cope with the great wave energy impact that happens on rocky shores. The fluctuations in the degree of wave exposure, sediment particle size and turbidity also have a strong influence on the relative abundance of certain species and may alter the composition and species richness of surf zone assemblages (Granda et *al*. 2004).

In this study, the zooplankton of the surf zones were dominated by copepods, cladocerans, bivalves and amphipods. Copepods are known by their extreme flexibility in adapting to environmental fluctuations, their existence is reported in almost all of the aquatic environments and their ability of maintaining a stable stock even in the presence of variable food sources is amazing (Christou, 1997; Huys & Boxshall, 1991). Here upon the constant presence of copepods through the Portuguese coast line is just another evidence of the pliability of this taxa.

Has hypothesised in the beginning of this study, zooplankton community structure showed differences along the Portuguese coast and beach types. The decreasing gradient of temperature observed from the south to the north of the coast line has proven to be the one of the most important environmental factors for the difference observed in communities throughout the coast. In addition, the chlorophyll *a* levels showed higher values and higher variances for rocky shores, this can be explained by the nature of rocky shores themselves: the settlement of algae, the presence of grazing species and the superior turbulence when compared to sandy beaches (Knox et *al*. 2003) increase the amount of chlorophyll *a* levels. However this was not verified for the beaches of central south.

In Portinho da Arrábida and in its vicinity (central south) the beaches, aside from beautiful, are all very little and near each other. Sampling there had a purpose, to see if even in close surf zones the morphology of the beaches influenced the zooplankton community structure and, as a matter of fact, it does. When comparing the communities of rocky and sandy beaches of this local we found out that they were very distinct, in sandy beaches amphipods were the most abundant taxa contrasting with the dominance of copepod species in rocky shores. The copepod *Paracalanus parvus*, amphipods and juveniles of the bivalve *mytilus* ssp. were the tree major contributors for the differences in this local. Lock et *al*. (2011), Sahu et *al*. (2012) and Araújo et *al*. had already addressed and proved spatial variabilities on the surf zone but none of them in such a small scale as presented in this study.

Differences in community structure between beach types within locals were also found in the north and central north communities. Apart from the great differences in abundance, north sandy beaches were also proved to have different community structures compared to north rocky shores. We hypothesise that these differences are due to morphological differences between beach types and also by fish assemblages in those areas. Nakane et *al*. (2013) found out that zooplankton communities are associated with beach type and can structure fish assemblages, we propose a different approach for this case: perhaps zooplankton abundance can influence fish assemblages, and these structure the composition of zooplankton communities by predation.

At a larger scale zooplankton communities of sandy beaches were proved to be different along the entire Portuguese coast, the same cannot be said about the communities of the rocky shores. In the rocky shore environment the most distinct community was found in the north, particularly when compared with the central regions, on the other hand the south zooplankton communities were statistically equal to all the other zooplankton assemblages of the Portuguese coast. This lack of differences is probably the result of the dissimilarity of the processed data. The south and central south regions, due to technical complications, had a significant lower number of samples, this absence of data might have compromised the comparisons of the overall differences along the coast. Even so, differences in sandy beaches were detected, we estimate that these differences were possible to detect by the statistical processes because of the larger abundance found on sandy beaches.

CHAPTER 5

– Final Remarks –

2. FINAL REMARKS

The description of the spatial variability of zooplankton communities along the coastal zone of Portugal is a preliminary and essential step that allows further experimentations of hypothesis on the surf zone.

With this study we could observe that the structure of zooplankton communities varies through the Portuguese coast and is influenced, even in a small geographical scale, by the morphology of the shore. The spatial variation was one more prove of the influence of tides and temperature on the assemblages of zooplankton communities (Lock et *al*. 2011).

The beach type induced differences on zooplankton community structures were the greatest features discovered, this issue had not been addressed before. The results obtained in central south suggest a strong influence of beach morphology in the local zooplankton communities of each beach. These results open a variety of possible experimentations that can be performed in small scaled studies, such has tidal and seasonal influences in zooplankton assemblages.

Following this study further ecological approaches can be realized. In the future an approach focused on the influences of temperature on the zooplankton communities of the surf zone could be executed and possibly linked to the effects of climate change on coastal zones.

CHAPTER 6

- References -

3. REFERENCES

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