Effects of a brief climatic event on zooplankton community structure and distribution in Arcachon Bay (France)

Article *in* Journal of the Marine Biological Association of the UK · January 2002

Impact Factor: 1.06 · DOI: 10.1017/S0025315402005143

Dorothée Vincent
Université du Littoral Côte d'Opale (U…

Benoît Sautour
University of Bordeaux

J. Mar. Biol. Ass. U.K. (2002), **82**, 21–30
Printed in the United Kingdom

Effects of a brief climatic event on zooplankton community structure and distribution in Arcachon Bay (France)

Dorothée Vincent*[‡], Christophe Luczak[†] and Benoît Sautour*

*Laboratoire d'Océanographie Biologique-Université de Bordeaux I, UMR EPOC 5805,
2, rue Professeur Jolyet, 33120 Arcachon, France. [†]UPRES A CNRS ELICO-Université Lille I,
Station Marine de Wimereux, 28, avenue Foch, BP 80, 62930 Wimereux, France.
[‡]Corresponding author, e-mail: d.vincent@biocean.u-bordeaux.fr

Short-term changes in zooplankton community structure and distribution in relation to changes in hydrological features were studied during summer in two distinct areas of Arcachon Bay (France) from July to September 1986. One sampling site was chosen in the northern part of the bay, influenced by oceanic inputs, and the other one in the south-eastern part of the bay, close to an estuarine zone, influenced by the River Leyre's inputs. Three different zooplankton assemblages were identified according to a temperature–salinity gradient: (i) an estuarine assemblage dominated by *Acartia bifilosa* and *Acartia tonsa*; (ii) an autochthonous assemblage composed of *Acartia discaudata*; and (iii) a coastal neritic one composed of *Paracalanus parvus*, *Oncaea venusta* and *Penilia avirostris*. All these latter assemblages remained stable during most part of the study period. However, a brief climatic event (storm event) occurred in mid-August and gave rise to a sharp decrease in temperatures along with significant changes in zooplankton structure and distributions in the bay. The estuarine community vanished and was replaced by the autochthonous community. In the northern part of the bay, the coastal neritic community succeeded the previously observed autochthonous community.

The effect of this brief climatic event was durable since recovery time lasted two weeks with regard to hydrological features and zooplankton communities. In addition, the climatic event also had ecological consequences since it permitted spreading of planktonic organisms from small-localized areas throughout the bay.

INTRODUCTION

In coastal areas, observed high production rates are often due both to continental and ocean inputs supporting autochtonous and allochtonous production, respectively (Kemp et al., 1997). In such environments, zooplankton and particularly copepods play a key role since they are able to exert a non-negligible predation pressure on both phytoplankton and microzooplankton (Stoecker & Capuzzo McDowell, 1990; Vincent & Hartmann, 2001). They also constitute important prey items for higher trophic level (e.g. young fish instars) and are remarkable tracers of water masses (Omori & Ikeda, 1984). In coastal areas, zooplankton community structure and distribution are closely linked to environmental factors and particularly to hydrological features (Laprise & Dodson, 1994; Suarez-Morales & Gasca, 1996). In these environments, zooplankton as a whole is therefore the result of the 'mixing' of distinct communities adapted to the balance between oceanic and estuarine water flows.

The space and time variability of these latter communities is often difficult to acknowledge as it is linked both to important space and time changes and exchanges between oceanic and estuarine waters. Within a small space and time scale, it is important to assess whether and how punctual events can impact on these zooplankton communities. Particularly, it is of interest to study the ability of the ecosystem to restore its initial properties or to maintain its new characteristics after punctual events. Since continental influences are greater in semi-enclosed coastal areas, particularly in a shallow environment (Siokou-Frangou, 1996), it is likely that such punctual events have durable consequences in both space and time.

To assess whether punctual events have durable or instantaneous impact on coastal ecosystems, Arcachon Bay was chosen as a study case area during summer 1986. It is a semi-enclosed ecosystem, which includes a variety of habitats due to its morphology, hydrology, and to both neritic and continental inputs. Zooplankton populations of Arcachon Bay have been previously studied qualitatively (Lubet, 1953) and quantitatively (e.g. Castel & Courties, 1982) as a function of phytoplankton and environmental parameters at a one year time scale. Three zooplankton communities have previously been identified in the bay and were found to be closely linked to the temperature–salinity gradient (D'Elbée, 1985; D'Elbée & Castel, 1995). The outer part of Arcachon Bay is characterized by a neritic community with species such as *Paracalanus parvus* and *Acartia clausi*, while the innermost part is occupied by an estuarine community with *Acartia bifilosa* and *A. tonsa*. An autochthonous community composed of the species *A. discaudata* and *Parapontella brevicornis* was also identified in Arcachon Bay and has the particularity of rarely leaving the bay throughout the year.

The question of whether and how a brief storm event impacts on the distribution and structure of zooplankton assemblages, investigating short-term changes in zooplankton assemblages of the innermost part of Arcachon Bay is investigated here. The study period was chosen during summertime in order to monitor the evolution of zooplankton communities during a period characterized by: (i) high secondary production (e.g. emission of meroplanktonic larvae); (ii) reduced freshwater inputs; and (iii) punctual climatic events.

MATERIALS AND METHODS

Study area and sample processing

Arcachon Bay (44°40′N 01°10′W) is a macrotidal triangular embayment of 155 km^2 located on the south-west coast of France (Figure 1). Hydrologic studies of Bouchet (1968) have shown that the bay is not homogeneous since the waters undergo temperature and salinity variations proportional to the distance 'upstream' from the inlet. Bouchet (1968) distinguished three water masses according to their temperature and salinity values: (i) external neritic waters (9.5–21°C; 34–35 psu); (ii) median neritic waters (6–22.5°C; 26.8–33.2 psu); and (iii) inner neritic waters (1–25°C; 22–32 psu). Those water masses are submitted to movements during low and high tides. At each cycle tide, inner neritic waters tend to mix with median neritic waters whereas external neritic waters mix with oceanic waters. Annual freshwater inputs average 1.25 10^6 m^3 with a major part (4/5) coming from the south-east with the Leyre River. The Lège canal (north of the bay) brings the remaining 1/5. As a consequence the north part is markedly isolated from the oceanic influence compared to the south (Manaud et al., 1997) and continental water inputs classically define two hydraulic sub-basins in Arcachon Bay: the north basin and the south basin.

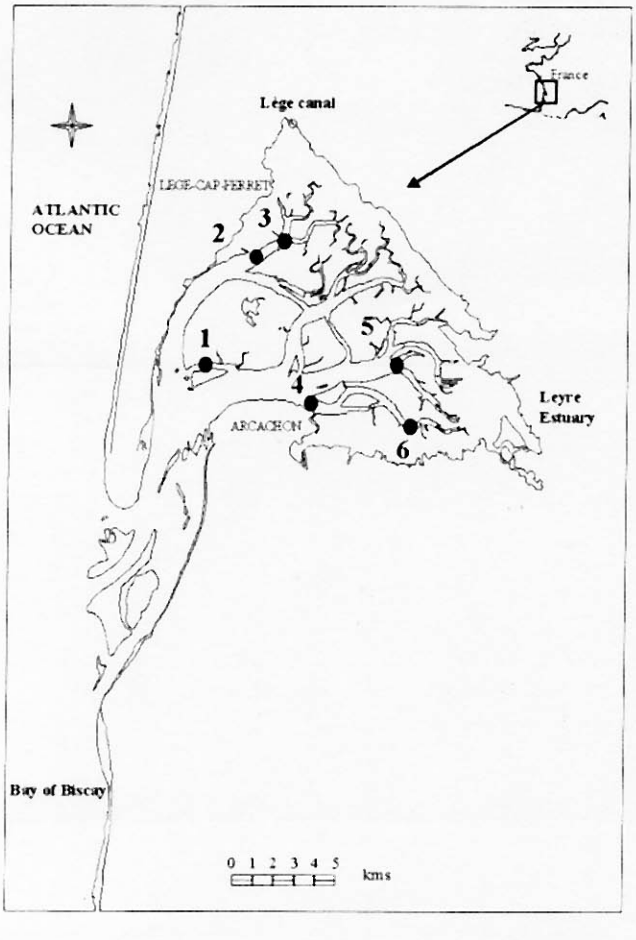

Figure 1. Arcachon Bay. Station locations.

The innermost part of the bay was surveyed every 3–5 days from July to September 1986 at six sampling sites. Three stations were positioned in the northern basin (1, 2 and 3) and three others in the southern basin (4, 5 and 6). Each sampling series were centred on low tide, providing the best chances to sample inner water masses. Samples were taken to describe hydrology and zooplankton abundance and composition. Meteorological conditions were recorded at the time of sampling. Meteorological data were obtained from the Gironde regional centre of meteorology.

Seawater temperature and salinity were obtained with a thermosalinometer (MC5).

Zooplankton was sampled with a pump (average discharge: 5 m^3 h^{-1}; volume filtered: 1 m^3) at 1 m below surface and collected on a 200-μm mesh sieve in order to capture only mesozooplankton. Samples were then rinsed with filtered seawater, concentrated and immediately stored in buffered 4% seawater formalin. The 200-μm mesh sieve was selected to avoid clogging during periods of high production and/or resuspension of benthic materials. In the laboratory, organisms were counted and identified (copepods to the species level) in up to three counts on sub-samples.

Data analysis

Multivariate analyses were carried out to identify zooplankton species assemblages, to describe their spatial and temporal variability and to understand whether and how the environment impacted on them in both space and time. Correspondence analysis (Benzécri, 1979) was applied to the whole data set of zooplankton (samples × species matrix) to assess the global distribution of zooplankton communities in the bay. A factorial map of the station scores in the plane of the two first axis of the correspondence analysis was created to study the community patterns and their evolution during the study period. Finally, species abundances were mapped to acknowledge their contribution to the structuring of zooplankton communities. All multivariate analyses were performed using ADE-4 (Thioulouse et al., 1997). Observations (i.e. stations 1–6) were coded using different symbols and numbers. These latter corresponded to the sample number: stations coded from 1 to 8 were sampled in July while stations coded from 9 to 18 were sampled in August. Variables (i.e. zooplankton groups and copepod species) were abbreviated as shown in Table 1.

RESULTS

Climatic conditions and hydrology

Anticyclonic conditions predominated in July. As a consequence, air temperatures were 1°C higher than

Table 1. *Abbreviations list of zooplankton groups, cladocerans and copepod species.*

Zooplankton groups	
HYD	Hydrozoans
SIP	Sipnonophores
NEM	Nematodes
TREM	Trematodes
POLY	Polychaetes
PHO	Phorodinians
CHE	Chaetognaths
GAS	Gastropods
BIV	Bivalves
CIRR	Cirripeds
DEC	Decapods
ISOP	Isopods
MYS	Mysidaceans
APP	Appendicularians
Cladoceran species	
P AV	*Penilia avirostris*
EVA	*Evadne* sp.
POD	*Podon* sp.
Copepod species	
A BI	*Acartia bifilosa*
A CLA	*Acartia clausi*
A DI	*Acartia discaudata*
A GR	*Acartia grani*
A TO	*Acartia tonsa*
C HA	*Centropages hamatus*
ISI	*Isias clavipes*
P PA	*Paracalanus parvus*
P BRE	*Parapontella brevicornis*
PSE	*Pseudocalanus elongatus*
T LO	*Temora longicornis*
HAL	*Halicyclopina nana*
OIT H	*Oithona helgolandica*
OIT N	*Oithona nana*
OIT P	*Oithona plumifera*
COR A	*Corycaeus anglicus*
ONC S	*Oncaea subtilis*
ONC V	*Oncaea venusta*
E AC	*Euterpina acutifrons*

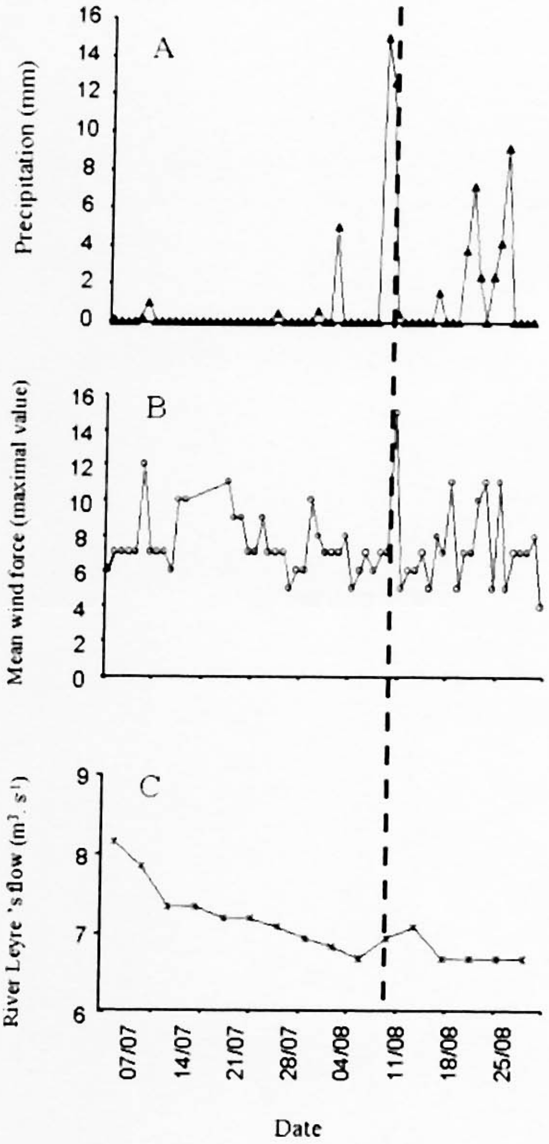

Figure 2. Climatic context of the study period. (A) Evolution of rainfalls intensity (mm) during the study period; (B) short-term variability of the mean maximum wind force during the survey; (C) evolution of the Leyre's flow (m^3 s^{-1}) during the study period. Dotted line refers to the mid-August storm event.

normal values (mean in July: 14.2°C) and excess insulation was 20–40 h higher than normal. Northerly winds dominated during the month and depleted storm events and rainfalls. An important storm event was recorded from 8 to 11 August with high rainfalls (12 to 14 mm; Figure 2A) and strong winds from the north-west reaching 80–100 km h^{-1} (Force 14; Figure 2B). Thereafter, from 13 to 17 August, the weather calmed down, little rainfalls were observed, excess insulation (+17 h) and temperatures 1°C higher than normal were recorded. From 20 August until the end of the study, depressions coming from the Atlantic Ocean caused a great change in climatic conditions. Strong local rainfall and median north-west winds (up to 60 km h^{-1}) alternated with lull periods. River Leyre's inputs decreased from 8.15 to 6.7 m^3 s^{-1} throughout the study period (Figure 2C). Values showed a slight increase in input during the storm event to 6.95 m^3 s^{-1} and remained constant thereafter.

The mean seawater temperature was 21.3 ±1.1°C and the same global pattern was observed for both groups of stations (Figure 3). Changes in temperature were often important both: (i) from one day to the other; (ii) and from one group of stations to the other (from 0.5 to 2°C) (Figure 3A,B). From the mid-August storm event until the end of the study period, temperature variability was higher compared with the beginning of the study. It resulted from a sharp general decrease in seawater temperatures of 2 to 3°C in mid-August reaching values of about 19.5–20°C in both parts of the bay. Thereafter, temperatures all over the bay followed the same evolution pattern. Mean salinity values reached 31.1 ±1.6 psu and patterns were markedly different from one area to the other (Figure 3C,D). Smallest values (e.g. 25.6 psu for station 5) were observed in the southern part of the bay and in the northern part, increasing salinity values of about 3.0 psu were recorded during the study period.

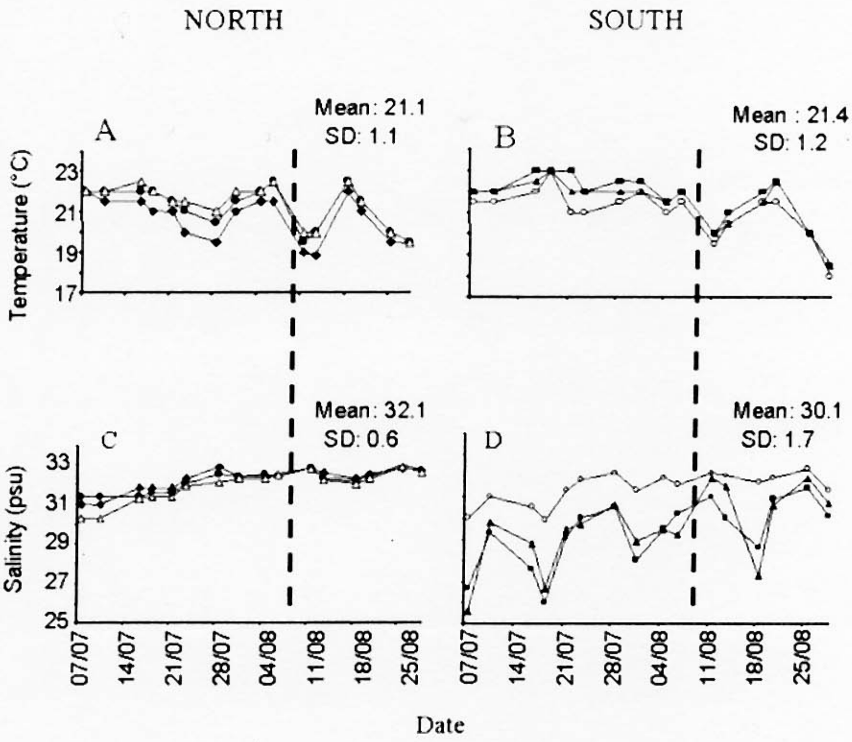

Figure 3. Short-term variability of seawater temperature (A, B) and salinity (C, D) in the north and south of Arcachon Bay. Stations: ◆, 1; ●, 2; △, 3; ○, 4; ▲, 5; ■, 6. Dotted line refers to the mid-August storm event.

Zooplankton composition and abundance

Mean zooplankton abundance was 1.6 10^4 (SD ±1.3 10^4) and 1.3 10^4 (SD ±1.2 10^4) ind m^{-3} in the northern and southern part of the bay, respectively.

Holoplankton and mainly copepods dominated during the whole study (63.6 ±18.4% of total zooplankton; Table 2). Appendicularians were the second most important group (16.9 and 13.7% of total zooplankton) in southern and northern stations, respectively. Polychaetes represented the third most abundant group, contributing 8.1 and 6.8% of the total planktonic community for southern and northern stations, respectively. Other groups of plankters namely gastropods larvae, cirripeds larvae and the cladoceran *Penilia avirostris* were also present with distinct proportions between northern and southern stations (Table 2). Total zooplankton evolution patterns were quite similar from one area to the other (Figure 4A,B). Indeed, though the variability within stations was high, three abundance peaks (>4.0 10^4 ind m^{-3}) were observed in both areas at the beginning and end of each sampled month. The two first peaks were mainly due to an increase in copepod abundance as in both parts of the bay, relative abundance values as high as 80.0% were recorded for this group (e.g. mid-August). Nevertheless, the third peak was no more due to copepods but also to other zooplankters. The decrease in copepod relative abundance after the storm in northern stations was linked to the increase of all zooplankter's relative abundance and particularly to the development of the cladoceran *P. avirostris* among 'others' (Figure 4C–G). In the south, this copepod decrease was accompanied by the development of appendicularians and polychaetes reaching relative abundance values as high as 40.0 and 30.0% respectively, particularly in station 6 (Figure 4D–H).

The mean copepod composition is presented in Figure 5. Southern stations (4–6) were dominated by congeneric species of the genus *Acartia* sp., namely *Acartia bifilosa*, *A. discaudata*, *A. grani* and *A. tonsa* reaching 21.9 ±15.9, 12.9 ±9.8, 6.9 ±4.2 and 2.8 ±3.6% of total zooplankton, respectively. Northern stations seemed to be mainly characterized by *A. discaudata*, *Euterpina acutifrons*, *Isias clavipes* and *Paracalanus parvus* with means of 19.4 ±5.2, 11.1 ±0.9, 10.5 ±2.5 and 6.2 ±1.9% of total zooplankton, respectively.

Structure of zooplankton assemblages

The plane of the first two axes of the correspondence analysis describes 43.5% of the total inertia (Figure 6A,B). The 'horseshoe' distribution of both species and samples allows the discrimination between southern (4–6)

Table 2. *Mean zooplankton composition (% of total zooplankton ±SD) during the study period in northern and southern stations.*

	Copepods	Appendicularians	Polychaetes	Gastropods	Cirripeds	*Penilia avirostris*
North	63.3 ±15.6	13.7 ±9.4	6.8 ±7.3	5.5 ±3.8	2.2 ±2.4	4.4 ±7.8
South	63.9 ±21.0	16.9 ±16.0	8.1 ±11.3	3.0 ±3.7	3.6 ±4.4	0.3 ±0.9

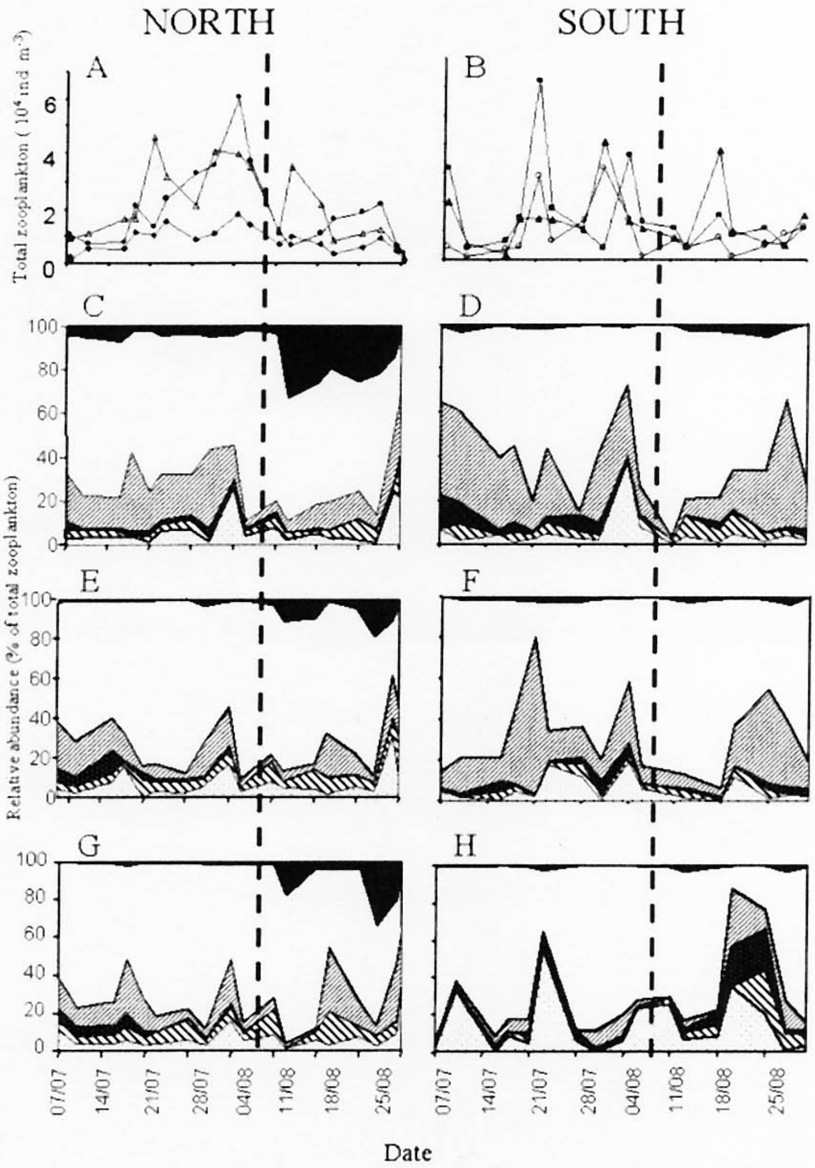

Figure 4. (A&B) Short-term variations of total zooplankton abundance (ind m^{-3}). Stations: ◆, 1; ●, 2; △, 3; ○, 4; ▲, 5; ■, 6. (C–H) Relative abundance of mean zooplankton taxa (% of total zooplankton) during the study period in northern (C–G) and southern stations (D–H). Dotted line refers to the mid-August storm event. Only zooplankton components contributing >5% to total zooplankton were represented. See Table 1 for abbreviations. ▢ Polychaetes; ■, Cirripeds; □, Copepods; ▨ Appendicularians; ▧, Gastropods; ■, Others.

and northern stations (1–3) as well as the identification of three zooplankton communities. The first assemblage on the left negative side of axis I is represented by samples from stations 5 and 6 (e.g. the southern part of the bay) and by the species *A. bifilosa* and *A. tonsa* (*Oithona plumifera* absolute contribution being less than 0.1% along this axis). All variables have high negative scores along the first axis and mainly contribute to its structuring. The absolute contributions to this axis for station 6, *A. bifilosa* and *A. tonsa* reach values as high as 19.5%, 68.9% and 11.2%, respectively. Stations from the northern part (1–3) with *Parapontella brevicornis* are represented on the right positive side of axis I and reach absolute contribution of 1.0% and 0.3%, respectively. Therefore, axis I clearly features space since it is mainly structured by southern stations and discriminates northern from southern stations.

Axis II structuring is mainly due to samples from northern stations (1, 2 and 3). The latter axis essentially features time since along axis II are opposite: (i) on the negative part a zooplankton community composed of northern stations sampled at the beginning of the study period (numbers 1–7) with the species *A. discaudata* and *A. grani* (both of them being projected close to the first axis); (ii) on the positive part a zooplankton assemblage composed of northern stations sampled at the end of the study period (numbers 12–17) with absolute contributions averaging 20.9% with the species *Penilia avirostris*, *Paracalanus parvus* and *Oncaea venusta* showing high positive scores along axis II and absolute contributions of 35.8%, 20.0% and 5.5%, respectively (*Evadne* sp. absolute contribution being less than 0.1%). Axis II seems to be exclusively related to northern stations characterizing their evolution and thus, features both space and time.

The factorial map of stations' scores in the plane of the two first axes permits to acknowledge the temporal evolution of both groups of stations (Figure 7). From the

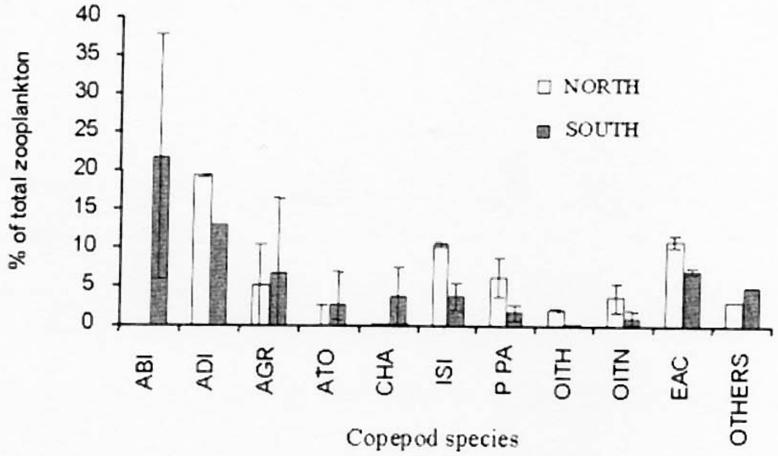

Figure 5. Mean copepod contribution to total zooplankton. Error bars represent the standard deviation (SD). Light bars: northern stations (1, 2 and 3). Dark bars: southern stations (4, 5 and 6). See Table 1 for abbreviations.

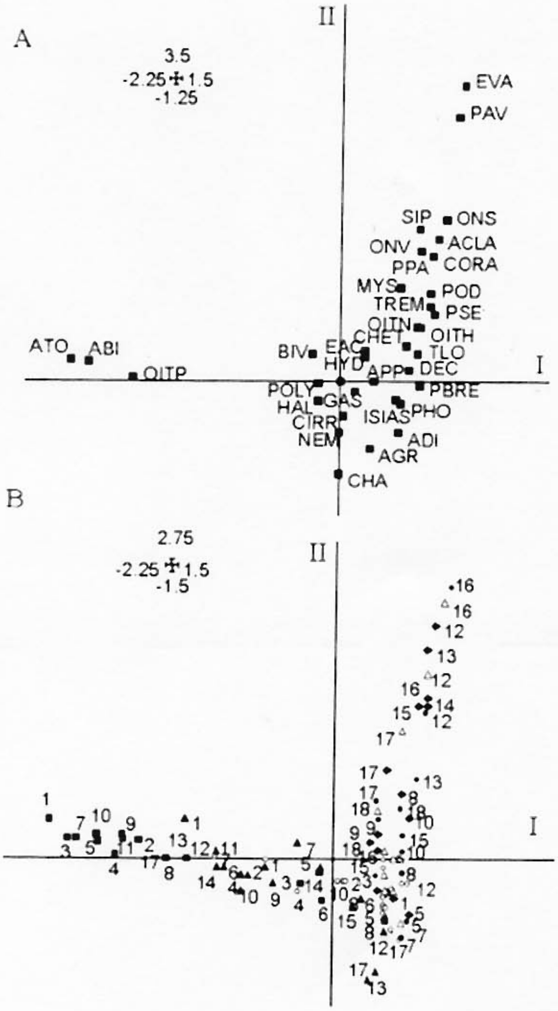

Figure 6. Results from correspondence analysis on the plane of the two first axes (total variance: 43.5%). Projection of the variables (species; (A)) on the I–II plane, see Table 1 for species abbreviations; Projection of the codified stations (B) on the I–II plane. Stations: ◆, 1; ●, 2; △, 3; ○, 4; ▲, 5; ■, 6. Numbers 1–8 refer to stations sampled in July; numbers 8–18 refer to stations sampled in August. ✛, scale of the axes.

beginning of the study period until the punctual storm event (11 August), northern and southern stations were clearly discriminated along axis I. After the storm event, southern stations tended towards a northern July community pattern as scores moved from negative to positive values along axis I. On and after the storm event, axis II clearly discriminated northern from southern stations and both groups of stations showed two distinct stable patterns: (i) negative scores of northern stations along the second axis from 7 until 28 July; and (ii) positive scores during August indicating a change in the northern zooplankton community. Southern stations globally had the same

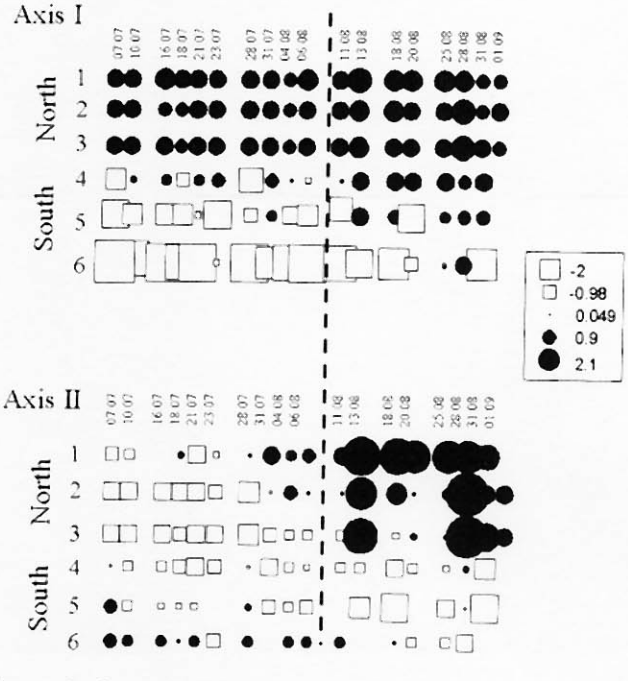

Figure 7. Results from the correspondence analysis on the I–II plane. The stations scores are mapped according to the date of sampling. Numbers 1–6 refer to the number of the station. Dotted line refers to the mid-August storm event. ☐, negative score value; ●, positive score value.

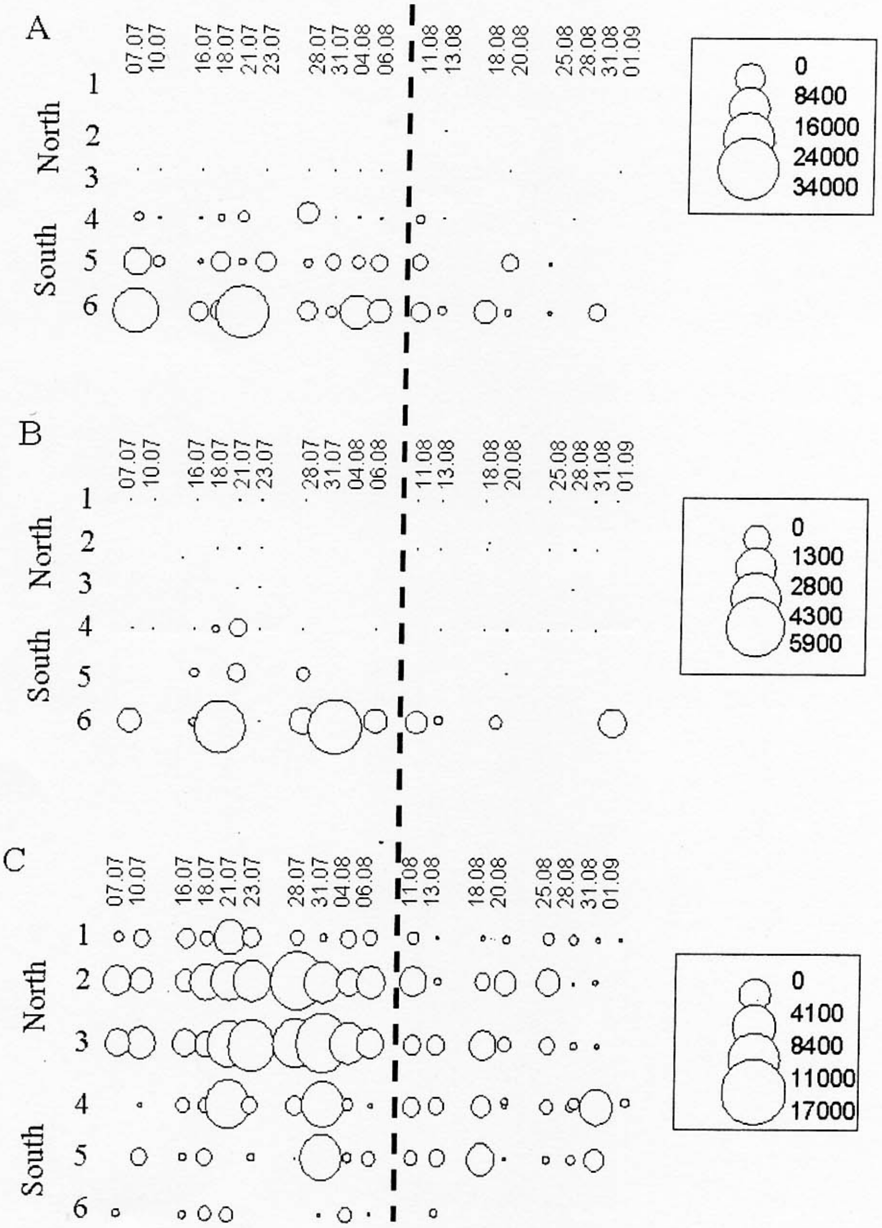

Figure 8. Map of species abundance (ind m^{-3}) in the southern part of Arcachon Bay according to the date of sampling. (A) *Acartia bifilosa*; (B) *Acartia tonsa*; (C) *Acartia discaudata*. Only copepod species having absolute contribution values >8% on the I–II plane of the correspondence analysis were represented. Numbers 1–6 refer to the number of the station.

pattern along axis II but for station 6 positive scores were more frequently recorded.

Spatio–temporal variability of zooplankton assemblages

Mapping species having absolute contributions higher than 8.0% along the two axes of the correspondence analysis shows that three species belonging to the genus *Acartia* spp. are mainly responsible for axis I structuring: *A. discaudata* is clearly discriminated from *A. bifilosa* and *A. tonsa* along this axis (Figure 6). The latter species showed high abundance values at southern stations during July. Both of them peaked twice during this month reaching abundance values as high as 3.4 10^4 and 4.3 10^3 ind m^{-3} for *A. bifilosa* and *A. tonsa*, respectively (Figure 8A,B). On and after the storm event, *A. bifilosa* and *A. tonsa* disappeared from southern stations and were replaced by an assemblage dominated by *A. discaudata* which peaked to 4.1 10^3 ind m^{-3} (Figure 9C).

Northern zooplankton communities were first characterized by *A. discaudata* and *A. grani*, which peaked at 1.7 10^4 and 3.6 10^3 ind m^{-3} during July, respectively (Figures 8C & 9A). After the storm event, this assemblage tended towards a more neritic pattern since: (i) species such as *P. parvus*, *O. venusta* and *Penilia avirostris* appeared (Figure 9B–D); and (ii) *A. discaudata* and *A. grani* nearly disappeared.

Briefly, the estuarine community characterized by *A. bifilosa* and *A. tonsa*, found in the south at the beginning of the study, disappeared on and after the punctual storm

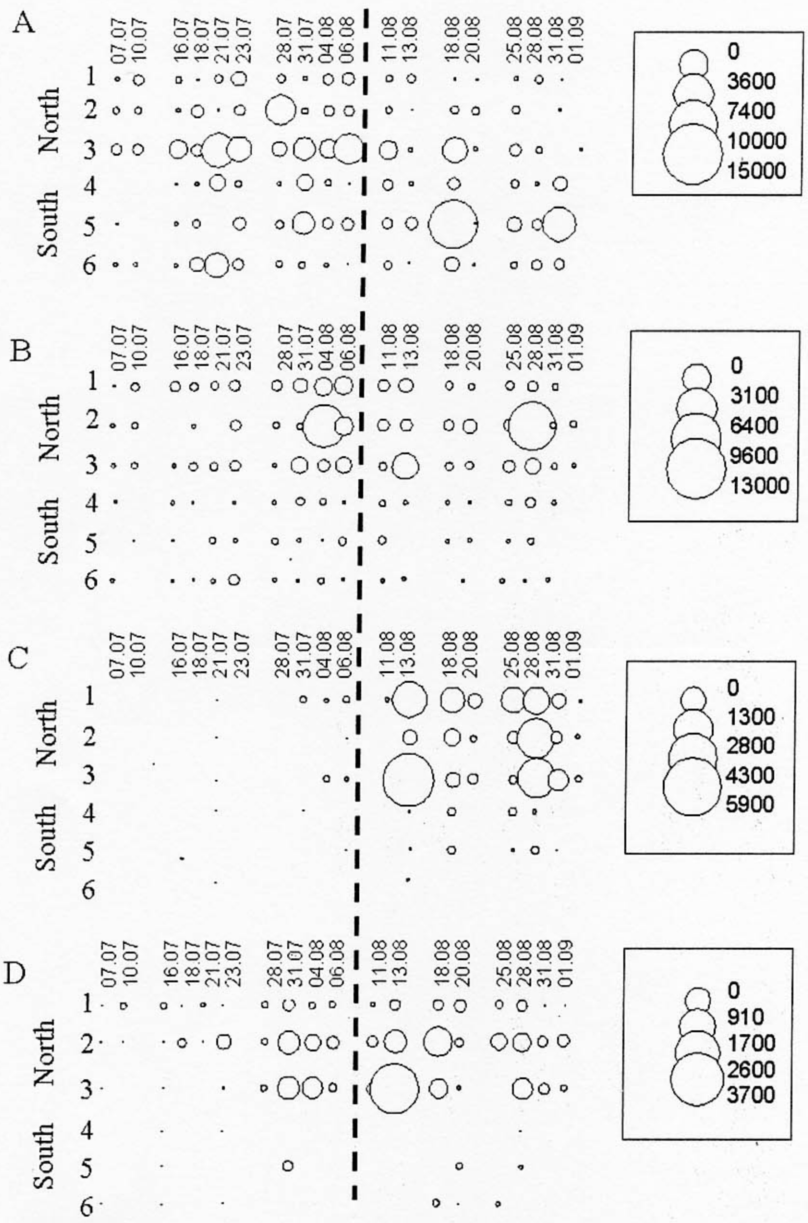

Figure 9. Map of species abundance (ind m^{-3}) in the southern part of Arcachon Bay according to the date of sampling. (A) *Acartia grani*; (B) *Paracalanus parvus*; (C) *Penilia avirostris*; (D) *Oncaea venusta*. Only copepod species having absolute contribution values >8% on the I–II plane of the correspondence analysis were represented. Numbers 1–6 refer to the number of the station.

event. Conversely, the autochthonous assemblage observed in the north at the beginning of the study (*A. discaudata*, *A. grani*), disappeared, was replaced by a neritic community (*Paracalanus parvus*, *O. venusta* and *Penilia avirostris*), and then appeared in the south after the storm as the estuarine assemblage vanished.

DISCUSSION

Climate and hydrology

Climatic conditions observed in Arcachon Bay during our study are typical for summer (Manaud et al., 1997). Sporadic rainstorms such as the one recorded in mid-August are not rare in summer though north-westerly winds generally deplete storm events (Manaud et al., 1997).

Mean seawater temperatures (21.1 ± 1.1 and 21.4 ± 1.3°C) found at northern and southern stations, respectively are about 2°C smaller than those given by Bouchet & Real (1969), Robert et al. (1987) and Auby et al. (1999), all of them observed summertime temperature values as high as 23°C. As seawater temperature in Arcachon Bay is closely linked to short-term variations of atmospheric features (Amanieu, 1966; Le Dantec, 1960), our lower values are linked to lower air temperatures and to the brief storm event in mid-August which led to a drastic drop in seawater temperature (2–3°C).

The marked difference in salinity between northern and southern stations is a commonly reported feature in Arcachon Bay linked to its hydrology (Robert et al., 1987; Manaud et al., 1997). Southern stations with relatively low salinity are strongly influenced by River Leyre's inputs

(Bouchet, 1968; Manaud et al., 1997) whereas at northern stations, oceanic waters from the Bay of Biscay flow into the Bay at each flood tide. Moreover, the sharp decrease of the Lège canal flow in summer can also explain high salinity values at northern stations (1, 2 and 3).

Zooplankton assemblages composition

Multivariate analyses revealed the presence of three zooplankton assemblages during summer. Species composition and structure of these assemblages remained stable for a month and a half (i.e. from July to mid-August). Variations in the spatial distribution of these assemblages were in fact related to climate since the latter impacted on hydrology, especially on the salinity distribution. Indeed, salinity has been considered to be the main factor responsible for the distribution of zooplankton in coastal zones directly influenced by freshwater inputs (Lam-Hoai & Amanieu, 1989; D'Elbée & Castel, 1991; Soetaert & Van Rijswijk, 1993). For instance, in Marennes Oléron Bay, Sautour & Castel (1993) observed an estuarine community characterized by *Acartia bifilosa* and species having a pronounced lagoonal pattern (*Bosmina* sp. and *Eurytemora hirundoides*), a neritic community with *Paracalanus parvus* and *Centropages hamatus* and an intermediate community with *Acartia discaudata* and *Euterpina acutifrons*. D'Elbée & Castel (1995) emphasized the importance of the temperature–salinity gradient in Arcachon Bay; while the population density is essentially under temperature control, salinity is mainly responsible for the species spatial distribution along the gradient. This permanent salinity gradient was therefore reported to be responsible for the installation of three zooplanktonic communities linked to a defined water mass: a neritic one at the outer part composed of *P. parvus* and *Acartia clausi*, an autochthonous one rarely leaving the bay with the species *A. discaudata* and *Parapontella brevicornis* and, an inner one in the innermost part characterized by *A. bifilosa* and *Acartia tonsa* (Castel & Courties, 1982; D'Elbée, 1985; D'Elbée & Castel, 1991, 1995). Our study performed at a smaller space and timescale also showed that the same three stable zooplankton communities were developing in the innermost part of the bay during summer. This zooplankton community distribution i.e. the creation of a spatial gradient in the zooplankton community composition from the entrance to the innermost part of estuaries has also been observed in other coastal environments such as the Ems Estuary of the North Sea (Baretta & Malschaert, 1998) and the Thau coastal lagoon (Lam Hoai et al., 1984) and might result from different recruitment and mortality patterns (Kimmerer, 1991). Apart from the latter physico–chemical parameters, other factors such as pollution (Siokou-Frangou, 1996), tidal heights (Lindhal & Perissinotto, 1997) and turbulence (Villate, 1994) have certainly also played a role in structuring these zooplankton communities.

Space and time variability of zooplankton assemblages

Our results are also consistent with published data that consider climate the main factor responsible for zooplankton community changes (Stubblefield & Vecchione, 1985; Viitasalo et al., 1995; Siokou-Frangou et al., 1998). Climate impacts are different according to the ecosystem and strongly depend on both its topography and hydrology. Villate et al. (1997) reported that local climatic changes towards dry conditions from 1988 to 1990 were responsible for great modifications in zooplankton abundance and composition in the Bay of Biscay. On a smaller scale, in Habra Harbour (Spain), Villate (1994) highlighted the importance of wind induced turbulence in structuring zooplankton communities and showed that during tough sea conditions, horizontal and vertical segregation patterns of zooplankton communities were less clear than during a lull period. In the innermost part of Arcachon Bay, it has been shown that the observed punctual storm event has durable consequences on zooplankton assemblages (i.e. two weeks) in both space and time with regard to their location and structure. Indeed, at the beginning of September: (i) each sampled station recovered their initial scores values (Figure 7); and (ii) species characterizing each zooplankton assemblage reappeared in parts of the Bay where they previously were knocked out by the storm event. These results are consistent with studies comparing ecosystems recovery times with regard to magnitude and duration of stress (Locke et al., 1994; Lukaszewski et al., 1999). In Little Rock Lake, examining the ability of additional zooplankton species to persist when introduced into mesocosms, the latter authors observed that zooplankton communities recovered their initial properties within a three week time delay. Recovery times can be longer and attain 10–15 years as observed by Keller & Yan (1991) and Yan et al. (1996) in limed lakes of Ontario, therefore suggesting that initial degrees of impact, water mass properties as well as dispersal capacities of potential colonizers can either lower or enlarge the ecosystem recovery times.

To conclude, we have shown in this study that the zooplankton community structure and distribution in Arcachon Bay is closely linked to environmental factors such as topography, tides and climatic conditions. These findings are crucial for ecological reasons since they help to better assess the ecological role played by punctual events on zooplankton communities structure and dispersion. For example, the storm event largely impacted on the bay hydrology, leading to a better homogenization of the area. Moreover, the study was performed during a period of high secondary production linked to the emission of meroplanktonic larvae. It is therefore likely that such a climatic event allowed a better dispersion of planktonic organisms from small localized areas to the whole bay thus permitting zooplankton colonization of new sites. However, zooplankton distribution not only depends on environmental factors. Feeding behaviour and species interactions (e.g. predation, competition) are also worth considering (Gaudy et al., 1995). These are topics of ongoing studies in Arcachon Bay.

Thanks are due to E. His for his help and to the whole staff of IFREMER Arcachon (France) for their assistance; to G. Slawyk and A. Herbland for their critical comments on the manuscript and to anonymous referees for useful comments improving the manuscript.

REFERENCES

Amanieu, M., 1966. *Recherches écologiques sur les faunes des plages abritées et les étangs saumâtres du Bassin d'Arcachon*. PhD thesis, University of Bordeaux I, Bordeaux, France.

Auby, I., Trut, G., D'Amico, F. & Beliaeff, B., 1999. Réseau hydrologique du Bassin d'Arcachon: synthèse des résultats 1988–1997. *Rapport Interne DEL/AR*, Arcachon, 60 pp.

Baretta, J.W. & Malschaert, J.F.P., 1988. Distribution and abundance of the zooplankton of the Ems Estuary (North Sea). *Netherlands Journal of Sea Research*, **22**, 69–81.

Benzécri, J.P., 1979. *L'analyse des données. Tome II: l'analyse des correspondances*. Paris: Dunod.

Bouchet, J.M., 1968. *Etude océanographique des chenaux du Bassin d'Arcachon*. PhD thesis, University of Bordeaux I, Bordeaux, France.

Bouchet, J.M. & Real, G., 1969. Etude de quelques relevés et enregistrements de températures des eaux de circulation de la station biologique et des chenaux du Bassin d'Arcachon, de 1961 à 1965. *Actes de la Société Linéenne de Bordeaux*, **106**, 1–24.

Castel, J. & Courties, C., 1982. Composition and differential distribution of zooplankton in Arcachon Bay. *Journal of Plankton Research*, **4**, 417–433.

D'Elbée, J., 1985. *Ecologie et évolution structurelle des peuplements zooplanctoniques du bassin d'Arcachon; interactions avec l'océan Atlantique*. PhD thesis, University of Bordeaux I, Bordeaux, France.

D'Elbée, J. & Castel, J., 1991. Zooplankton from the continental shelf of the southern Bay of Biscay; exchange with Arcachon Basin, France. *Annales de l'Institut Océanographique*, **67**, 35–48.

D'Elbée, J. & Castel, J., 1995. Evolution spatio-temporelle du zooplancton dans le bassin d'Arcachon: le rôle des variables de milieu. *Cahiers de Biologie Marine*, **36**, 33–45.

Gaudy, R., Verriopoulos, G. & Cervetto G., 1995. Space and time distribution of zooplankton in a Mediterranean lagoon (Etang de Berre). *Hydrobiologia*, **300/301**, 219–236.

Keller, W. & Yan, N.D., 1991. Recovery of crustacean zooplankton species richness in Sudbury area lakes following water quality improvements. *Canadian Journal of Fisheries and Aquatic Sciences*, **48**, 1635–1644.

Kemp, W.M., Smith, E.M., Marvin-DiPasquale, M. & Boynton, W.R., 1997. Organic carbon balance and net ecosystem metabolism in Chesapeak Bay. *Marine Ecology Progress Series*, **150**, 229–248.

Kimmerer, W.J., 1991. Predatory influences on copepod distributions in coastal waters. *Bulletin of Plankton Society of Japan*, special volume, 161–174.

Lam Hoai, T. & Amanieu, M., 1989. Structures spatiales et évolution saisonnière du zooplancton superficiel dans deux écosystèmes lagunaires nord-méditerranéens. *Oceanologica Acta*, **12**, 65–77.

Lam Hoai, T., Amanieu, M. & Lasserre, G., 1984. Distributions d'abondances du zooplancton d'un écosystème lagunaire méditerranéen: la lagune de la Sarrazine. *Acta Oecologia*, **5**, 301–315.

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*, **107**, 67–81.

Le Dantec, J., 1960. Observations complémentaires sur les conditions de milieu du Bassin d'Arcachon. *Procès-Verbaux des Réunions du Conseil permanent pour l'Exploration de la Mer*, **28**, 1–12.

Lindhal, O. & Perissinotto, R., 1987. Short-term variations in the zooplankton community related to water exchange processes in the Gullmar fjord, Sweden. *Journal of Plankton Research*, **9**, 113–132.

Locke, A., Sprules, W.G., Keller, W. & Pitblado, J.R., 1994. Zooplankton communities and water chemistry of Sudbury area lakes: changes related to pH recovery. *Canadian Journal of Fisheries and Aquatic Sciences*, **51**, 151–160.

Lubet, P., 1953. Variations saisonnières du zooplancton du bassin d'Arcachon. *Bulletin de la Société Zoologique de France, Paris*, **77**, 204–216.

Lukaszewski, Y., Arnott, S.E. & Frost, T.M., 1999. Regional versus local processes in determining zooplankton community composition of Little Rock Lake, Wisconsin, USA. *Journal of Plankton Research*, **21**, 991–1003.

Manaud, F. et al., 1997. *Etude intégrée du bassin d'Arcachon. Tome 1: Physique*. Arcachon, France: IFREMER.

Omori, M. & Ikeda, T., 1984. *Methods in marine zooplankton ecology*. New York: J.W.S. Inc.

Robert, R., Guillocheau, N. & Collos, Y., 1987. Hydrological parameters during an annual cycle in the Arcachon Basin. *Marine Biology*, **95**, 631–640.

Sautour, B. & Castel, J., 1993. Distribution of zooplankton populations in Marennes-Oléron Bay (France), structure and grazing impact of copepod communities. *Oceanologica Acta*, **16**, 279–290.

Siokou-Frangou, I., 1996. Zooplankton annual cycle in a Mediterranean coastal area. *Journal of Plankton Research*, **18**, 203–223.

Siokou-Frangou, I., Papathanassiou, E., Lepretre, A. & Frontier, S., 1998. Zooplankton assemblages and influence of environmental parameters on them in a Mediterranean coastal area. *Journal of Plankton Research*, **20**, 847–870.

Soetaert, K. & Van Rijswijk, P., 1993. Spatial and temporal patterns of the zooplankton in the Westerschelde estuary. *Marine Ecology Progress Series*, **97**, 47–59.

Stoecker, D.K. & Capuzzo McDowell, J., 1990. Predation on protozoa: its importance to zooplankton. *Journal of Plankton Research*, **12**, 891–908.

Stubblefield, C.L. & Vecchione, M., 1985. Zooplankton distribution in a wind-driven estuary before and after a major storm. *Contributions in Marine Science*, **28**, 55–67.

Suarez-Morales, E. & Gasca, R., 1996. Planktonic copepods of Bahia de la Ascension, Carribean coast of Mexico: a seasonal survey. *Crustaceana*, **69**, 162–173.

Thioulouse, J., Chessel, D., Dolédec, S. & Olivier, J.M., 1997. ADE-4: a multivariate analyses and graphical display software. *Statistics and Computing*, **7**, 75–83.

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*, **17**, 1857–1878.

Villate, F., 1994. Temporal variability of the spatial distribution of the zooplankton community in a coastal embayment of the Basque country in relation to physical phenomena. *Hydrobiologia*, **288**, 79–95.

Villate, F., Moral, M. & Valencia, V., 1997. Mesozooplankton community indicates climate changes in a shelf area of the inner Bay of Biscay throughout 1988 to 1990. *Journal of Plankton Research*, **19**, 1617–1636.

Vincent, D. & Hartmann, H.J.H., 2001. Contribution of ciliated microprotozoans and dinoflagellates to the diet of three copepod species in the Bay of Biscay. *Hydrobiologia*, **443**, 193–204.

Yan, N.D., Keller, W., Somers, K.M., Pawson, T.W. & Girard, R.E., 1996. Recovery of crustacean zooplankton communities from acid and metal contamination: comparing manipulated and reference lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**, 1301–1327.

Submitted 20 May 2001. Accepted 13 November 2001.