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Sampling estuarine copepods at different scales and resolutions: a study in Rio de la Plata

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Abstract

In the Rio de la Plata salinity, temperature, chlorophyll *a* (chl *a*), and densities (ind. m^{-3}) of the copepods *Acartia tonsa* and *Paracalanus parvus* were measured from January to November in 2003 by following a nested weekly and monthly design. Such sampling yielded two separate datasets: (i) Yearly Dataset (YD) which consists of data of one sampling effort per month for 11 consecutive months, and (ii) Seasonal Weekly Datasets (SWD) which consists of data of one sampling effort per week of any four consecutive weeks within each season. YD was assumed as a medium-term low-resolution (MTLR) dataset, and SWD as a short-term high-resolution (STHR) dataset. The hypothesis was, the SWD would always capture (shorter scales generally captures more noise in data) more detail variability of copepod populations (quantified through the regression relationships between temporal changes of salinity, temperature, chl *a* and copepod densities) than the YD. Analysis of both YD and SWD found that *A. tonsa* density was neither affected by seasonal cycles, nor temporal variability of salinity, temperature and chl *a*. Thus, compared to STHR sampling, MTLR sampling did not yield any further information of the variability of population densities of the perennial copepod *A. tonsa*. Analysis of SWD found that during summer and autumn the population densities of *P. parvus* had a significant positive relationship to salinity but their density was limited by higher chl *a* concentration; analysis of YD could not yield such detailed ecological information. That hints the effectiveness of STHR sampling over MTLR sampling in capturing details of the variability of population densities of a seasonal copepod species. Considering the institutional resource limitations (e.g. lack of long-term funding, manpower and infrastructure) and the present hypothesis under consideration, the authors suggest that a STHR sampling may provide useful complementary information to interpret results of longer-term natural changes occurring in estuaries.

Introduction

Choice of appropriate temporal scale and resolution of sampling is at the heart of any hypothesis testing because it has a decisive effect on interpretation of the results of a field study (Green, 1979; Baker & Wolff, 1987; Livingston, 1987; Baretta & Malschaert, 1988). There exists little guidance on sampling scales for estuaries because of extreme variability of the main variables such as salinity, temperature, chl *a* which change with every tide and with seasonal cycles (Weglenska, 1976; Green, 1979; Baker & Wolff, 1987; Livingston, 1987; Baretta & Malschaert, 1988; David *et al.*, 2005). Temporal scale and resolution of sampling must take into account the environmental and ecological complexities of estuaries (Weglenska, 1976; Millard & Lettenmaier, 1986; Baker & Wolff, 1987; Baretta & Malschaert, 1988). For most estuaries of developing/poor nations, sampling efforts are curtailed by lack of sustained funding and infrastructure, and inadequate logistics for long-term studies. These factors negatively affect the process of hypothesis testing; for such reasons, many estuarine studies provide ecological perspectives from limited field surveys (Baker & Wolff, 1987; Baretta & Malschaert, 1988; Devreker *et al.*, 2010).

Copepods often dominate estuarine zooplankton assemblages (Baretta & Malschaert, 1988; David *et al.*, 2005; Costa *et al.*, 2009; Paul *et al.*, 2016). Many long-term estuarine copepod studies have examined their density changes in relation to variation of salinity, temperature and chl *a*. Depending on the temporal scales of study, copepod density, taxonomic richness and dominance change in specific season(s) because seasonal changes bring changes in temperature which in turn bring variability in primary production (Livingston, 1987; Taylor, 1987, 1993; Baretta & Malschaert, 1988; Cloern, 1999; Warwick *et al.*, 2002; Hoffmeyer, 2004; David *et al.*, 2005; Devreker *et al.*, 2008; Jang *et al.*, 2013). Temporal changes in copepod densities are suggested as ecological indicators of salinity and temperature stress for large open estuaries (Paul *et al.*, 2016), so could be used for long-term monitoring of environmental and or anthropogenic stress of estuaries. Generally, a short-term high-resolution (STHR) sampling protocol better captures the time variability of copepod densities compared to a medium-term low-resolution (MTLR) sampling protocol because shorter scales capture more noise within a data set. Despite this, consensus on the temporal scale and resolution of sampling for

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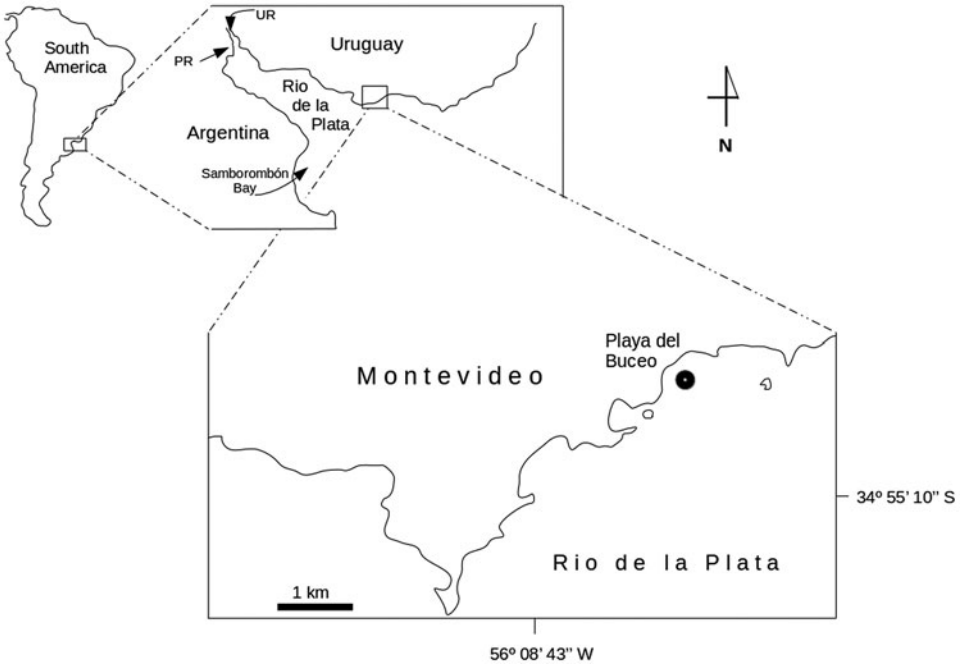


Fig. 1. Sample collection site in Rio de la Plata off Montevideo, Uruguay.

providing consistent information on the temporal variability of an estuarine copepod population density has yet to be reached.

Rio de la Plata (RdlP) is an estuary of South America which is bordered by Uruguay and Argentina (Acha *et al.*, 2008). Temporal changes of its salinity and temperature bring variability in chl *a* production which sustains high plankton densities (Calliari *et al.*, 2005; Carreto *et al.*, 2008). Zooplankton assemblages of RdlP are often dominated by copepods of various size classes (Berasategui *et al.*, 2006). *Acartia tonsa* is a copepod species that is perennial in nature and dominates (in terms of abundance) the copepod community of RdlP (Paul *et al.*, 2017). *Paracalanus parvus* is a seasonal copepod species which remains within a typical copepod assemblage but is generally associated with more saline waters (Berasategui *et al.*, 2006). For the present investigation *A. tonsa* and *P. parvus* were respectively used as examples of perennial and seasonal copepods within the brackish zone of RdlP. We hypothesized that a short-term high-resolution (STHR) sampling protocol would better capture the time variability of copepod population densities in relation to salinity, temperature and chl *a* changes than a medium-term low-resolution (MTLR) sampling protocol could. This study may provide a better understanding of sampling frequency of an estuarine copepod for studying its population density.

Materials and methods

Sample collection

Sampling (all of which was conducted at low tide) was intended for studying seasonal changes in copepod population densities, so samples were collected in every month of 2003 (except December). At least in one month of each season samples were taken on a weekly basis except in winter when the samples were collected at fortnightly intervals because of economic resource limitations. Samples were collected at Playa del Buceo (a coastal site off Montevideo) in waters about 1.5 m deep just after sunset (Figure 1). Sub-surface (~1.5 m water depth) tows were made using a 35 cm mouth plankton net fitted with 180 μm pore size mesh. Volume of water sampled was about 19 m^3 on each tow. Samples were preserved in 4% formalin solution (final concentration). Copepods were identified and counted under a low magnification microscope. Abundance of each species was expressed as individuals per cubic metre (ind. m^{-3}).

On every sampling occasion water temperature and salinity were measured (from ~1.5 m water depth) using a multi-probe sensor (Horiba U 10, Japan) and water samples were collected for chl *a* analysis whenever copepods were collected. 50 ml subsamples were filtered through GF/F filters, and pigments extracted in 96% ethanol in the dark at 4°C for 24 h. The fluorescence of the resulting extract was read before and after acidification (HCl 1.2 N) in a Turner 111 Fluorometer calibrated against standard chl *a* extract. These data were collected in order to evaluate if the temporal variations of temperature, salinity and chl *a* had significantly affected the population densities of copepods *A. tonsa* and *P. parvus*.

Dataset arrangement

The study aimed to identify the scale and resolution of sampling effort that provides the maximum information on variability of copepod population densities in relation to temporal physico-chemical changes in their habitat. To address these, two separate data sets were analysed. (1) 'Yearly Dataset (YD)' (see Table 1) was essentially the monthly data (one measurement/month) and included salinity, temperature, chl *a*, and densities of *A. tonsa* and *P. parvus*. YD was assumed as an example of a MTLR dataset. (2) 'Seasonal Weekly Datasets (SWD)' was essentially the data of four consecutive weeks (one measurement/week) of sampling effort and had information on salinity, temperature, chl *a*, and densities of the copepods *A. tonsa* and *P. parvus* (see Table 2). SWD was assumed as an example of a STHR dataset. Analysis of SWD was run separately for each season (because it is essentially a seasonal sampling effort) except for winter because of very limited economic resources available for sampling so the resultant data set was too small to include in the statistical analysis.

Statistical analysis

The Shapiro–Wilk normality test found salinity ($W = 0.93$; $P = 0.16$), temperature ($W = 0.95$; $P = 0.44$) were normally distributed

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Table 1. Yearly Dataset (YD) that consists of monthly data of copepod *Acartia tonsa* and *Paracalanus parvus* densities (ind. m^{-3}) along with salinity, temperature, and chl *a* data collected from Rio de la Plata off Montevideo, Uruguay, between January and November 2003

Month	Temperature	Salinity	Chl *a*	*A. tonsa* (ind. m^{-3})	*P. parvus* (ind. m^{-3})
January	24.4	10.87	20.19	2895	14
February	24.33	7.3	21.21	3127	0
March	24.9	8.73	1.84	941	11
April	20.7	4	1.58	7263	238
May	16.7	5.95	3.19	2950	58
June	13.9	4.1	0.58	37	18
July	12.9	8.5	0.46	7006	59
August	11.45	8.3	1.95	28	1
September	14.2	17.7	1.33	36	19
October	18.6	13.9	5.19	10,782	45
November	19	14.83	3.03	2899	23

Table 2. Seasonal Weekly Datasets (SWD) that consist of four consecutive inter-week data of copepod *Acartia tonsa* and *Paracalanus parvus* densities (ind. m^{-3}) along with salinity, temperature, and chl *a* data of Rio de la Plata off Montevideo, Uruguay, in summer, autumn and spring of 2003

Sampling date	Season	Temperature	Salinity	Chl *a*	*A. tonsa* (ind. m^{-3})	*P. parvus* (ind. m^{-3})
16 January 2003	Summer	26.8	7.6	43.57	2895	0
23 January 2003	Summer	22.4	13.8	5.04	0	68
29 January 2003	Summer	24	11.2	11.97	5241	14
04 February 2003	Summer	24.5	7.3	4.41	918	0
06 May 2003	Autumn	16	2	3.78	0	0
14 May 2003	Autumn	16.9	14.3	1.32	5555	1023
21 May 2003	Autumn	19.5	6	6.06	12,442	113
29 May 2003	Autumn	14.4	1.5	1.58	346	3
27 October 2003	Spring	18.6	13.9	5.19	10,782	45
05 November 2003	Spring	19.5	16.3	3.11	2899	10
12 November 2003	Spring	17.9	24.7	4.11	1728	23
20 November 2003	Spring	19.6	3.5	1.87	5333	58

Sampling in winter was limited due to economic constraints.

but chl *a* ($W = 0.49$, $P < 0.001$) was not. Seasonal variations of physicochemical factors were checked either by ANOVA or by Kruskal–Wallis (for non-Gaussian data) followed by Tukey's or Nemenyi post-hoc test (if required). Copepod densities followed a quasi-Poisson distribution so the generalized linear models of quasi-Poisson distribution family were built to evaluate if there were significant temporal changes in the densities of copepods *A. tonsa* and *P. parvus* due to time variability of salinity, temperature and chl *a*. 'glmmPQL' function of the 'MASS' package of CRAN-R3.4.1 for x86_64-apple-darwin15.6.0 (64-bit) was used for this purpose. Confidence intervals were set at 95% and respective *W*, *t*, *P*, df were reported.

Results

Analysis of the YD

Mean temperature was 18.28 ± 4.8°C (range 11.45–24.9°C); temperature fluctuated between seasons (ANOVA: df = 3, $F = 19.5$, $P = 0.0008$) (Table 1). Mean salinity was 9.47 ± 4.43 which fluctuated between seasons (ANOVA: df = 3, $F = 13.75$, $P = 0.002$) especially in autumn and winter when the salinity dropped considerably (4–4.1) but increased in spring (17.7) (Table 1). Chlorophyll *a* (median) was 1.95 μg l^{-1}, and was highest in summer (21.21) and lowest in winter (0.46) (Table 1).

Density of the *A. tonsa* population did not vary significantly between seasons but was relatively lower in June and August and the maximum density was recorded in October (Table 1). Density of *A. tonsa* was not much affected by temporal variability of salinity, temperature and chl *a* (Tables 1 and 3). *Paracalanus parvus* density was significantly lower in summer (df = 7, $t = -2.93$, $P = 0.02$), andpeaked in autumn (Tables 1 and 3), but was not significantly influenced by the temporal variability of temperature, salinity and chl *a* (Tables 1 and 3).

Analysis of the SWD

In summer the mean temperature, salinity and chl *a* (median) were 24.42 ± 1.81°C, 9.97 ± 3.1 and 8.50 μg l^{-1}, respectively (Table 2). *Acartia tonsa* density ranged from 0 to 5241 ind. m^{-3} and peaked in late January (Table 2) but the density was not

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Table 3. Comparison of different temporal scales and resolutions of variability of *Acartia tonsa* and *Paracalanus parvus* densities (ind. m^{-3}) in relation to salinity, temperature and chl *a*. P values in bold are statistically significant ($P < 0.05$)

Data set	Copepod	Season	Salinity (*P*-values)	Temperature (*P*-values)	Chlorophyll-*a* (*P*-values)
Yearly dataset (YD) i.e. One data collection/month	*A. tonsa*		0.98	0.96	0.90
	P. parvus	Summer ($P = \mathbf{0.02}$)	0.24	0.91	0.08
Seasonal Weekly dataset (SWD) i.e. one data collection/week for four consecutive weeks of a season	*A. tonsa*	Summer	0.90	0.66	0.63
	P. parvus		**0.02**	0.07	**0.04**
	A. tonsa	Autumn	0.30	0.07	0.4
	P. parvus		**0.03**	0.46	0.68
	A. tonsa	Spring	0.37	0.71	0.71
	P. parvus		0.25	0.73	0.76

significantly affected by time variability (inter-week) of temperature, salinity and chl *a* (Table 3). *Paracalanus parvus* density ranged from 0 to 68 ind. m^{-3} and the highest density was in mid-January (Table 2). Density of *P. parvus* population did increase in high salinity (df = 2, $t = 7.2$, $P = 0.02$) but the higher availability of chl *a* limited their density (df = 2, $t = -4.68$, $P = 0.04$) (Table 3). In autumn the mean temperature and salinity were 16.7 ± 2.13°C and 5.95 ± 5.91 respectively. Chlorophyll *a* (median 2.68 µg l^{-1}) ranged between 1.32 and 6.06 µg l^{-1} (Table 2). *Acartia tonsa* density ranged from 0 to 12,444 ind. m^{-3} and the highest density was recorded in mid-autumn (Table 2), but density was not affected by time variability (inter-week) of temperature, salinity and chl *a* (Table 3). *Paracalanus parvus* density ranged from 0 to 1023 ind. m^{-3} with the highest density recorded in mid-autumn (Table 2). Density of *P. parvus* increased with the salinity (df = 2, $t = 5.05$, $P = 0.037$), but chl *a* had no such effect on its density (Table 3).

In spring the mean temperature was 18.9 ± 0.8°C; salinity was 14.6 ± 8.72; chl *a* (median) was 3.61 µg l^{-1} and ranged between 1.87 and 5.19 µg l^{-1} (Table 2). *Acartia tonsa* density ranged from 1728 to 10,782 ind. m^{-3} with the highest density recorded in late October, and *P. parvus* density ranged from 10 to 58 ind. m^{-3} with the highest density recorded in late November (Table 2). Densities of *A. tonsa* and *P. parvus* were not much affected by the temporal changes (inter-week) of temperatures, salinity and chl *a* (Table 3).

Discussion

Given that shorter scales always capture more noise within a dataset, we predicted that STHR sampling (exemplified through SWD analysis) would capture more variability of temporal changes in copepod densities in relation to physicochemical changes of RdlP than a MTLR sampling (exemplified through YD analysis) could do. STHR sampling found *P. parvus* density to increase with salinity in summer and autumn but to decrease with high concentration of chl *a* in summer; MTLR sampling failed to show such relationships of population density changes of *P. parvus*, which supports the prediction. Analysis of YD found that the *A. tonsa* density was neither significantly affected by seasonal cycles nor by temporal variability of salinity, temperature and chl *a*. Similarly, analysis of SWD found that the variability of *A. tonsa* population density in association with inter-week changes of salinity, temperature and chl *a* was not significant. Thus, STHR and MTLR sampling protocols ended up providing similar information on the variability of *A. tonsa* population densities in association with temporal changes of the physicochemical characteristics of RdlP; such results contradict the hypothesis.

Acartia tonsa is a typical estuarine and coastal marine copepod well adapted to the fluctuations of salinity, temperature and chl *a* gradients of its habitats (Baretta & Malschaert, 1988; Mauchline, 1998; Cervetto *et al.*, 1999; Castro-Longoría, 2003; Hubareva *et al.*, 2008). This could be a reason that the species is found in tropical to temperate coastal-marine waters (González, 1974; Cervetto *et al.*, 1999; Paul *et al.*, 2017). In the RdlP, irrespective of season, *A. tonsa* numerically dominates zooplankton assemblages compared with other meso-zooplankton (Berasategui *et al.*, 2006; Paul *et al.*, 2017). In the Bahia Blanca estuary of temperate Argentina, the temperature cycle is the main driver of species succession of *A. tonsa* dominance (Hoffmeyer, 2004). In the Patos Lagoon of Brazil during the colder season higher salinities favour dominance of *A. tonsa* (Montú, 1980; Montú *et al.*, 1997). In the subtropical estuaries of USA, *A. tonsa* density peaks in summer, especially towards the more saline zones (Lawrence *et al.*, 2004). The sampling location Playa del Buceo is characterized by an oligohaline to mesohaline salinity profile and moderate temperature variability (Paul *et al.*, 2017), and is not a habitat characterized by high phytoplankton biomass throughout the seasons. Considering such conditions in RdlP, the perennial presence and dominance of *A. tonsa* are not that surprising (Berasategui *et al.*, 2006; Paul *et al.*, 2017). We suggest that in such a case, extrapolation of the temporal scale and resolution of sampling *A. tonsa* may not lose much information on variability of population densities in association with physicochemical parameters. Long-term monitoring of estuaries is often discouraged by institutions because of resource constraints such as lack of sustained funding, skilled manpower, infrastructural facilities etc., so for perennial copepods such as *A. tonsa* a STHR strategy can be followed.

Paracalanus parvus is a neritic species distributed along the margins of the South-west Atlantic (Mauchline, 1998). In the San Francisco Bay of the USA it is distributed towards the seaward boundary (Ambler *et al.*, 1985). In the present study, analysis of SWD found a significant positive association of salinity and *P. parvus* population density which clearly reflects their preference for salty conditions. A 10-year weekly/bi-weekly survey in the sub-tropical Korean waters showed that *P. parvus* biomass closely followed a seasonal pattern of abundance with high densities when the water temperature exceeded 20°C (Jang *et al.*, 2013). In RdlP, *P. parvus* densities increased in late summer–autumn when the temperature ranged between 16 and 26°C, which agrees with the Korean study. Analysis of SWD (not of YD) indicated that in summer the population density of *P. parvus* was limited by the presence of high chl *a* in RdlP. Such a result is somewhat paradoxical considering *P. parvus* is an herbivorous copepod (Morales *et al.*, 1991). It could be the case that the

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observed negative correlation of *P. parvus* density and chl *a* was due to the effect of a third variable associated with both, for example salinity, and thus would not represent a causal or mechanistic relationship. In future more frequent sampling (for example daily) is advised to better understand how the changes in chl *a* concentration in RdlP affects *P. parvus* density. Since *P. parvus* is mostly present in the warmer months (e.g. autumn) a STHR sampling is advised during that time to gain detailed insights of the population characteristics (e.g. density change, changes in age class) of *P. parvus* and also its relationships with the physicochemical characteristics of RdlP.

The results demonstrated that STHR and MTLR sampling for studying the variability of copepod densities in relation to physicochemical changes of RdlP yielded similar ecological information for *A. tonsa*. A detailed insight of the variability of population density of *P. parvus* was achieved only through the STHR sampling. Such contrasting outcomes highlight the issue of what amounts to appropriate scaling to address spatial and or temporal questions relating to estuaries (Green, 1979; Baker & Wolff, 1987; Livingston, 1987; Baretta & Malschaert, 1988). Livingston (1987) while extrapolating weekly to monthly sampling results of a decade of study of the Apalachicola Bay system suggested that temperature can be adequately represented by monthly data but salinity cannot because of its high variability. In the present study the MTLR sampling failed to find statistically significant effects of salinity and chl *a* changes on the variation in *P. parvus* density which the STHR sampling successfully found. Thus, to understand the relationships of temporal variability of salinity and chl *a* with densities of seasonal copepods like *P. parvus*, STHR sampling is possibly a recommended way because of the higher variability of salinity and Chl-a in large open estuaries. The present study suggests that for a highly abundant, perennial and highly tolerant copepod such as *A. tonsa* its association with temperature, salinity and chl *a* changes in estuaries could be adequately studied by either the MTLR or STHR approaches depending on the availability of resources (e.g. economic, manpower, logistics etc.). Understanding the impact of longer-term processes linked to climatic change and low frequency oscillations (for example, the ENSO cycles) requires observations at scales matching the processes of interest. However, due to limited institutional resources (i.e. economic and infrastructural) any long-term data of zooplankton or copepods may remain unavailable for some of the most economically important estuaries because they are in poor and developing countries (e.g. the RdlP, Amazon River, Nile River, Ganges River, Mekong River). Copepod sampling can provide an ecological indication of abiotic/anthropogenic stressors and food web health quality of a given coastal zone which may be important for regional fisheries (David *et al.*, 2005; Paul *et al.*, 2016). Thus in future, copepod sampling within a very limited budget directed to explore a specific hypothesis of species-specific responses to water quality or environmental variability is more feasible than long-term monitoring programmes (Livingston, 1987; Baretta & Malschaert, 1988; David *et al.*, 2005; Devreker *et al.*, 2010). In such cases, short-term approaches as discussed here could provide complementary information for the interpretation of results from a long-term observation.

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