DISTRIBUTION OF MOLLUSC LARVAE IN THE ESTUARINE COMPLEX OF PARANAGUÁ BAY (PARANÁ, BRAZIL) (LAT. 25° 15' - 25° 30'S)

DISTRIBUIÇÃO DE LARVAS DE MOLUSCOS NO COMPLEXO ESTUARINO DA BAÍA DE PARANAGUÁ (PARANÁ – BRASIL) (LAT. 25° 15' - 25° 30'S)

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ABSTRACT

The spatial distribution of mollusc larvae was investigated in the estuarine complex of Paranaguá Bay (SE Brazil). Plankton samples were collected during April using horizontal tows of 1 minute duration, during the ebb and flood tides, at 06 (six) points on the estuary and at two depths (surface and bottom). A conical plankton net was used (mesh size: 225 μm; mouth diameter: 30 cm) and the samples were preserved in 4% buffered formaldehyde and sorted under a stereoscopic microscope. The biological results were analyzed, through PCA (Principal Component Analysis), to gather data for temperature, salinity, current velocity, turbidity and chlorophyll-*a*, and the variability in the number of larvae between locations, depths and tidal phases was compared by multifactorial ANOVA. Oyster larvae (*Crassostrea* sp.) were more abundant ($p<0.05$) in those locations with greater hydrodynamic forces (entrance to the estuary) and during the flood tide. Other bivalves and gastropods, negatively correlated with salinity, were more present in those locations with weaker hydrodynamic forces (interior of the bay). The marked presence of the three categories of larvae close to the bottom demonstrates the behaviour of larvae near settling stage.

Keywords: Larval distribution. Dispersion. Mollusk larvae. Meroplankton. Paranaguá Bay.

RESUMO

A distribuição espacial de larvas de moluscos foi investigada no complexo estuarino da Baía de Paranaguá (sudeste do Brasil). As amostras de plâncton foram coletadas em abril com arrastos horizontais de 1 minuto de duração, durante as marés de enchente e vazante, em 06 (seis) pontos no estuário e em duas profundidades (superfície e fundo). Uma rede de plâncton cônico foi usada (tamanho de malha: 225 | im; diâmetro da boca: 30 cm), e as amostras foram conservadas em formol tamponado a 4% e classificados sob um microscópio estereoscópico. Os resultados biológicos foram analisados por meio de PCA (Principal Component Analysis), para recolher os dados de temperatura, salinidade, turbidez velocidade atual, e, clorofila-a, e a variabilidade do número de larvas entre os locais, profundidades e as fases de maré foi comparada por análise multifatorial ANOVA. Larvas de ostras (Crassostrea sp.) foram mais abundantes ($p <0,05$) nos locais com maiores forças hidrodinâmicas (entrada do estuário) e durante a maré enchente. Outros bivalves e gastrópodes, negativamente correlacionados com a salinidade, foram mais presentes nesses locais com fracas forças hidrodinâmicas (interior da baía). A presença marcante das três categorias de larvas perto do fundo demonstra o comportamento de larvas de perto à resolução palco.

Palavras-chave: Distribuição de larvas. Dispersão. Larvas molusco. Meroplâncton. Baía de Paranaguá.

Introduction

The role of pelagic larvae is fundamental in the distribution, dominance, gene flow, natural selection, dispersion and speciation of benthic populations (THORSON, 1950; SCHELTEMA, 1975, 1986; STRATHMANN, 1985).

The mechanisms of transport, dispersion and retention of larvae in bays and estuaries, are still not completely understood, despite efforts made over a long period to explain and quantify such processes, which result in part from the dynamic complexity of these systems. Galtsoff (1964) and Andrews (1979 and 1983) attributed the discrepancies found between the various studies of the distribution of mollusc larvae mainly to differences in hydrographical regimes between the diverse systems studied.

One of the most studied organisms with regard to the behaviour of its larvae among plankton is the American oyster *Crassostrea virginica* Gmelin. After extensive debate in the literature, there is currently a trend towards consensus about the distribution process of these larvae. This is the result of the interaction between hydrodynamic force and active swimming, with the larvae being influenced by particular environmental factors that determine their position in the water column. These spatial processes, added to the temporal sequence (such as the duration of the larval period, equally influenced by environmental factors), ultimately drives the success of larval settling and the establishment/maintenance of adult stocks in the interior of bays and estuaries.

Despite their ecological and economic importance, investigations of the distribution of mollusc larvae among plankton are still rare in Brazil. In the estuarine complex of Paranaguá Bay, existing studies are limited to those carried out by Boehs & Absher (1996, 1997), who investigated, in the W-E plane, the spatio-temporal variation of oyster larvae (*Crassostrea* sp.) at a stage close to metamorphosis.

The objective of the present study was to investigate the spatial distribution of mollusc larvae (oysters, other bivalves and gastropods) in the NNE-SSW plane of the estuarine complex of Paranaguá Bay, at several points, depths and tidal phases, with the establishment of correlations between the number of larvae, hydrological variables (temperature, salinity, transparency, current velocity) and chlorophyll-*a*.

Materials and Methods

The estuarine complex of Paranaguá Bay (ECPB) is situated on the north coast of the state of Paraná (SE Brazil). It possesses a liquid surface of 612 km² and comprises two main axes: the W-E sector (260 km²), occupied by the Antonina and Paranaguá bays, and the NNE-SSW sector (200 km²), occupied by the Laranjeiras, Guaraqueçaba and Pinheiros bays and Benito Cove (MARONE; NOERNBERG, 2000). The ECPB is bordered by extensive mangroves and hydrographical basins, and is linked to the Atlantic Ocean by three main channels: Superagui, North and Galheta (**Figure 1**). The tide is predominantly semi-diurnal (PORTOBRÁS, 1988; MARONE et al., 1995), with an average range of 2.2 m (MARONE; NOERNBERG, 2000). The estuary is classified as partially mixed type *b*, since a greater stratification occurs during periods of increased flow rate (KNOPPERS et al., 1987; MARONE et al., 1995). The regional climate is of the Cfa type, defined as mesothermic humid subtropical, with a hot summer (BIGARELLA et al., 1978). The extremes of the surface water temperature vary between 17ºC in the winter and 32ºC in summer (BRANDINI, 1985; BRANDINI et al., 1988).

Figure 1 - Map of the estuarine complex of Paranaguá Bay (ECPB), with indication of the bays (A-F), channels (α, β and γ) and the sampling points (1-6)
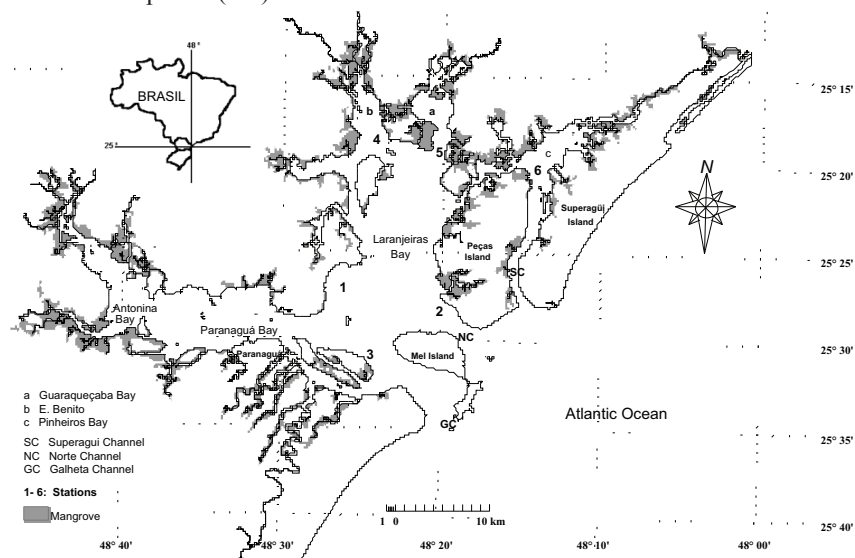
Sampling was carried out during the month of April (spring and neap tides); at this time of the year there is a conspicuous presence of mollusc larvae among plankton in the region (BOEHS; ABSHER, 1996). Six sampling points were established: St. 1, St. 2 and St. 3, close to the entrance of the ECPB, and St. 4, St. 5 and St. 6, in more internal sectors (Figure 1). A conical plankton net was used (mesh opening: 225 µm and mouth diameter: 30 cm), for horizontal tows of 1 minute duration, at a speed of approximately 2 knots, at two depths (surface and bottom), during the flood and ebb tides, with two repetitions. The biological samples were preserved in 4% buffered formaldehyde. The mollusc larvae were identified and quantified under a stereoscopic microscope (40 x magnifications) and grouped in three categories: oysters (*Crassostrea* sp.), other bivalves and gastropods.

The parameters of depth, salinity and temperature were measured with a STD device (Mini STD/CTD-Sensordata, Model SD 201) and the current velocity was measured with a current meter (SD/30). The water transparency was assessed with a Secchi disk. For the analyses of chlorophyll-*a*, water samples from the surface were collected with a Van Dorn bottle, from which 50 cm^3 were filtered through Whatmann GF/C filters ($\phi = 24$ mm). The filters were sealed in envelopes and frozen until analysis, which followed Parsons et al., 1984 with a Turner Designs fluorimeter (model AU-10), calibrated according to Arar & Collins (1992).

The number of individuals.m^{-3} was estimated from the volume of water filtered ($V = \pi r^2.h = 4.32$ m^3), calculated on the basis of the mouth diameter of the net (0.07 m^2), boat speed (2 knots) and tow time (1') (61.73 m/min). Significant variations in the number of larvae between sampling points, tidal phases, depths and repetitions, were assessed by multifactorial analyses of variance (ANOVA, $\alpha = 0.05$). Unifactorial analysis of variance was used to compare the variability of each hydrological parameter and chlorophyll-*a*. Least significant difference (LSD, 95%) test was used to verify significant differences between treatments *a posteriori*. To identify the main trends in the variability of the number of larvae in relation to the environmental parameters and chlorophyll-*a*, the data were submitted to Principal Components Analysis (PCA).

Results

The environmental descriptors exhibited the following hydrographical conditions:

(1) Tide: average range of 0.5 m at neap tide and 1.9 m at spring tide, with a more marked difference in those areas of greater depth (St. 2 and St. 6) (**Table 1**);

(2) Temperature: mean values of 25.1ºC (±1) (23 - 27.6ºC), highest values in the internal sector and no significant thermal variations ($p > 0.05$), both between the flood and ebb tides and between the surface and the bottom (**Table 2**);

(3) Salinity: average of 25.8 (±5.8) (11 - 33.8), lowest values ($p < 0.05$) in the internal sector (St. 4 and 5), less marked variations ($p > 0.05$) between tidal phases and significantly higher values on the bottom (**Table 2**), with average stratification between the surface and the bottom, of 3;

(4) Currents: highest velocities ($p < 0.05$) at St. 2 (average: 56.1 cm.$^{-s}$), strongest currents during the ebb (reverse situation only at St. 6) and highest velocities on the surface at all the sampling points (**Table 2**);

(5) Transparency: average extinction of the Secchi disk 1.6 m (±0.4) (0.7 - 2.8 m) and waters predominantly more turbid ($p < 0.05$) during the ebb (**Table 2**);

(6) Chlorophyll-*a*: average of 11.0 mg.m^{-3} (±7.4) (1.3 - 28.4 mg.m^{-3}), highest ($p < 0.05$) at St. 3 and St. 6 and, in the latter location, markedly higher values ($p < 0.05$) during the ebb (**Table 2**).

Table 1 - Depth and tidal range in the ECPB, during April, for quadrature and spring tides (n=40)

Sampling points and locations	Average depth (m)	Tidal range (m)	
		Quadrature	Spring
St. 1 - Laranjeiras Bay	6	0	2
St. 2 - North Channel, Laranjeiras Bay	13	0.6	2.6
St. 3 - Galheta Channel, Paranaguá Bay	6	0	1.9
St. 4 - Benito Cove	3	1.1	1.2
St. 5 – Guaraqueçaba Bay	5	0.1	1.2
St. 6 – Pinheiros Bay	9	1.6	2.5
Average:	7	0.56	1.9

Table 2 - Variability in hydrographic factors in the ECPB during April/98, between sampling points, tidal stages and depths (Unifactor ANOVAs and LSD tests, α=0.05)

Factor	Sampling points	Tidal stages	Depths
Temperature (n=154)	p=0.0002 St.6>1-5; St. 4 and 5>1; St. 5>2	p=0.6148	p=0.9278
Salinity (n=154)	p=0.0000 St. 4 and 5< others	p=0.8339	p=0.0004 Bottom>Surface
Current velocity (n=154)	p=0.0000 St. 2> others	p=0.0001 Ebb>Flood	p=0.0005 Surface>Bottom
Water transparency (n=77)	p=0.4251	p=0.0133 Ebb<Flood	-
Chlorophyll-*a* (n=22)	p=0.0469 St. 3>1,2,4 and 5; St. 6 >1	p=0.6115	-

Table 3 - Summary table of the results of multifactorial analyses of variance (α=0.05) and *a posteriori* tests (LSD, 95%) between treatments, of mollusc larvae distribution in the ECPB, between sampling points (Stations), tidal phases, depths and repetitions, during April/98 (n=154). NS – no significant difference

Source of Variation	Sum of Squares	d.f.	Mean Square	F-ratio	Sig. Level	95% LSD diff.
Oyster larvae:						
A. Stations	3185.0719	5	637.0144	2.980	0.0137	St. 1 - 3 > St. 4 – 6
B. Tides	882.2575	1	882.2575	4.128	0.0440	Flood > Ebb
C. Depths	2085.1504	1	2085.150	9.756	0.0022	Bottom > Surface
D. Repetitions	192.7731	1	192.7731	0.902	0.3540	NS
Other Bivalvia:						
A. Stations	22655.386	5	4531.077	6.098	0.0000	St. 4 and 5 > St. 1, 3 and 6
B. Tides	13.528	1	13.528	0.018	0.8943	NS
C. Depths	16634.67	1	16634.67	22.386	0.0000	Bottom > Surface
D. Repetitions	435.947	1	435.947	0.587	0.4532	NS
Gastropoda:						
A. Stations	38388.387	5	7677.677	13.562	0.0000	St. 4 and 5 > St. 1, 2, 3 and 6
B. Tides	421.247	1	421.247	0.744	0.3990	NS
C. Depths	17380.63	1	17380.63	30.70	0.0000	Bottom > Surface
D. Repetitions	196.832	1	196.832	0.348	0.5627	NS

Oyster larvae were more abundant in the external sector (St. 1 – 3) and during the flood tide. Other bivalves and gastropods were more common in the internal sector (St. 4 and St. 5) and exhibited a similar distribution (p>0.05) between tidal phases. The three categories of larvae exhibited higher densities (p<0.05) on the bottom in relation to the surface. Variations between repetitions were not significant (p>0.05) (**Table 3; Figure 2**).

The higher abundance of gastropod and bivalve larvae (except oysters) in the more internal sectors of less saline waters (St. 4 and St. 5) and the clear presence of oyster larvae close to the entrance banks (St. 2 and St. 3), was also shown by the PCA, whose components 1 and 2 explained 65.2% of the overall variability of these data. This analysis also revealed the highest salinity at the outermost sampling points (St. 2 and St. 3) and in Pinheiros Bay (St. 6 - flood), the greatest current velocity in the North Channel (St. 2), the highest transparency at St. 1 and the highest values, during the ebb, for chlorophyll-*a* at sampling points St. 3 and St. 6 (**Figure 3**).

Discussion

The hydrographical data obtained in the present study confirm, in part, the division of the NNE-SSW plane of the ECPB established by Brandini (2000), in which sampling points St. 1-3 and St. 6 belong to an area greatly influenced by the coastal zone, whilst St. 4 and St. 5 are located in a sector of more protected waters, with higher levels of nutrients and CO_2 and heavily influenced by continental drainage, in which, at the same time, resources would be less available to the phytoplankton, due to the low light availability which results, in turn, from the high turbidity.

Figure 2 - Spatial distribution of mollusc larvae in the ECPB during April/98. Averages of two repetitions on the surface and on the bottom, during the flood and ebb tides (n=154)
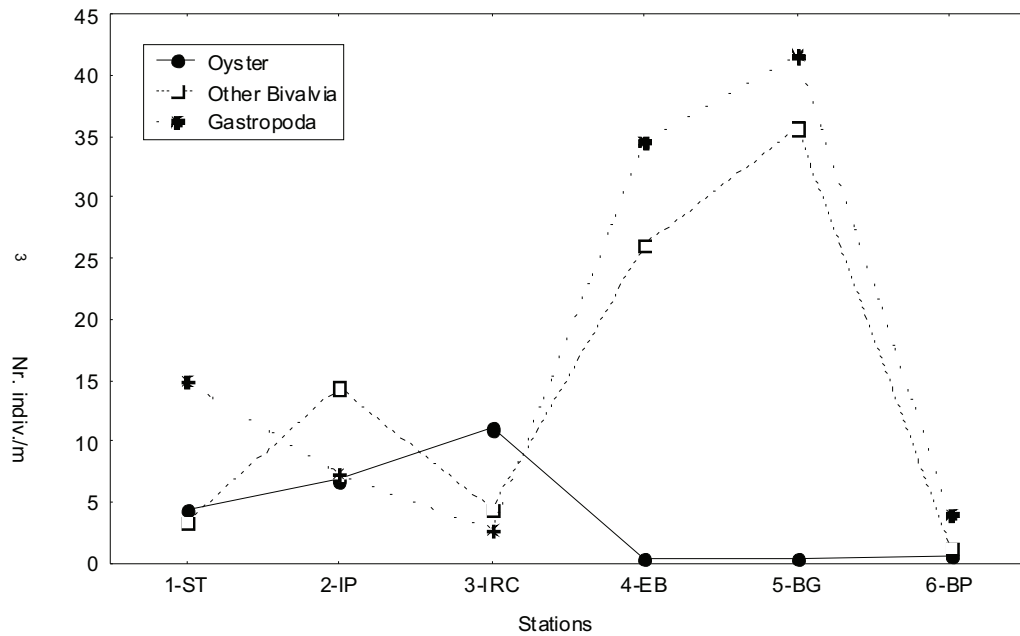

Figure 3 - Graphic presentation of the principal components analysis (PCA) (biplot of first two principal components) with the projection of vector-variables (number of mollusc larvae: G – Gastropoda, OB – Other Bivalvia, Oy – Oyster, and hydrographic parameters: Ch – Chlorophyll-*a*, CV – Current Velocity, S – Salinity, T – Temperature and Tr – Transparency) and observations (sampling points: 1 to 6 and tidal phases: F – Flood and E – Ebb), in the ECPB during April/98. Averages of two repetitions (each variable: n=154) and, except water transparency (n=77) and Chlorophyll-*a* (n=22 – surface measurement), averages of the surface and the bottom
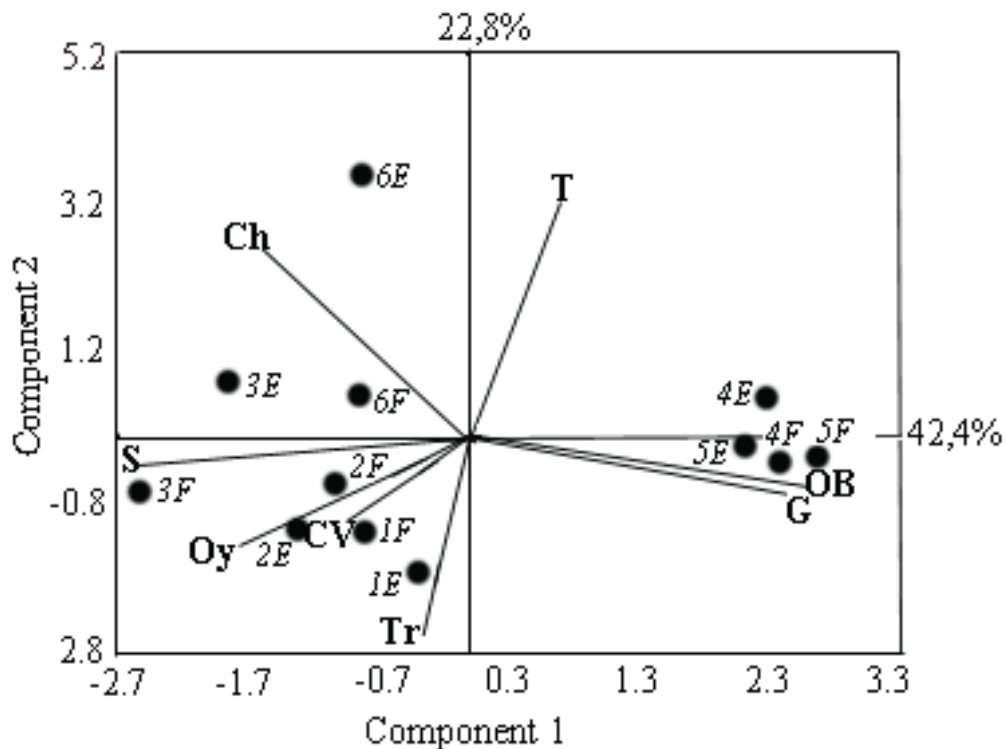
Our results obtained in Pinheiros Bay (St. 6) confirm the conclusion of Soares & Barcelos (1995), that this is a distinct sector that is practically isolated from the rest of the complex, whose connection (with Laranjeiras Bay) is limited to a narrow and shallow channel ('Furo do Tibicanga') that probably enables small exchanges between the two sectors. The high salinity data obtained in this sector, also noted by Brandini (2000), and the finding that the flood currents were significantly stronger than those of the ebb at St. 6 (in spite of their internal location), indicate that Pinheiros Bay is strongly influenced by the waters of the coastal platform with regard to its hydrographical conditions. On the other hand, the high concentration of chlorophyll-*a* (>20 mg.m^{-3}) on the surface of St. 3, may be the result of a concentration of nutrients (and consequent increase in productivity) generated by the frequent formation and merging of estuarine fronts in this region, as shown by Marone & Noernberg (2000).

The greater velocity of the ebb currents in the ECPB is attributed to the damming of the flow waters at high tide (BIGARELLA et al., 1978), as well as the influence of lateral friction and of depth, gradually increasing towards the head and gradually decreasing towards the mouth of the system (CAMARGO, 1998). In the middle sector of the W-E plane, Knoppers et al. (1987), observed velocities between 100 and 125 cm.$^{-s}$ on the surface and Marone et al. (1995) reported maximum currents of 80 cm.$^{-s}$ (flood) and 110 cm.$^{-s}$ (ebb), on the surface, between Antonina Bay and the banks at the entrance to the estuary. Along the NNE-SSW axis, according to the data obtained in the present investigation, surface currents above 100 cm.$^{-s}$ were observed only at St. 2, situated in the North Channel (maximum of 132 cm.$^{-s}$ – ebb). In the internal sector on this axis, the velocities were found to be markedly lower (maximum of 71.2 cm.$^{-s}$ - ebb, St. 4 and 65.8 cm.$^{-s}$ - flood – St. 5), revealing, generally (except in the North Channel), reduced hydrodynamics in this sector. This finding is very probably due to the W-E sector exceeding the NNE-SSW sector in terms of the volume of fresh water runoff from the continental drainage basins, in addition to the width, average depth and total volume of water, according to observations made by Knoppers et al. (1987).

The average data for the tidal range (approximately 2 m at spring and 0.5 m at neap tide) for the NNE-SSW plane are in agreement with the data obtained by Knoppers et al. (1987) and Marone et al. (1995) in the W-E sector of the system. Small horizontal and vertical thermal variations and a negative horizontal salinity gradient upstream, with a strong influence of climatic factors (pattern of rain and winds) over stratification (KNOPPERS et al., 1987; REBELLO; BRANDINI, 1990; MACHADO et al., 1997; BRANDINI, 2000) also represent a standard for the ECBP. Moreover, the low extent of variation in these parameters between the surface and the bottom (such as the average salinity of 3 - present study), may have great ecological significance in the vertical disposition of zooplankton and, consequently, in their distribution in the estuary.

Larvae perform various types of vertical movements in the water column (MILEIKOVSKY, 1973). Their horizontal distribution appears to result from the interaction between this vertical regulation (by means of active swimming) and passive dispersion caused, mainly, by the action of currents (MANN, 1988; MANN et al., 1991). Oyster larvae, in particular, considerably increase their swimming activity in parallel with their increased size (HIDU; HASKIN, 1978) and migrate in the water column in response to variations in specific environmental factors. Salinity is reported as being the factor that most affects the vertical position of these larvae (WOOD; HARGIS, 1971; DEKSHENIEKS et al., 1996). Thus, the swimming activity of oyster larvae would be directly proportional to the values for this parameter, which would therefore be implicated in descending movements during the ebb tide (determined by the decrease in their swimming activity) and ascending during the flood (determined by the increase in their swimming activity in response to the rise in salinity). According to Wood & Hargis (1971), this process serves as a primary transport mechanism for these larvae in bays and estuaries and enables their return to the interior of these systems.

On the other hand, diverse previous studies (CARRIKER, 1951; KUNKLE, 1957; HASKIN, 1964; WOOD; HARGIS, 1971, MANN 1988, DEKSHENIEKS et al., 1996; BOEHS; ABSHER, 1997) and also the results obtained in the present investigation indicate that, independent of the tidal phase, the oyster larvae closest to metamorphosis, in particular, occupy, in the water column, a preferential position nearest to the bottom, which is related not

only to their considerable swimming speed in this phase but also to the increase in their mass and density (mainly as a result of growth of the shell), that determines, in part, their inevitable sinking to the bottom. This preferential distribution near to the bottom also appears to be influenced by other factors. Baker & Mann (1998) observed experimentally that oyster larvae in the phase next to settling respond to the greater portion of the visible light spectrum and, when there are substrates with greater and lesser light intensity available, they settle themselves, preferentially, on the latter. The development of photo negativity by mature oyster larvae has already been reported and discussed by Medcof (1955), Thorson (1964) and Andrews (1979), and this would favor some form of selection of areas for their adhesion, due (as a consequence of their position close to the bottom) to the possibility of greater contact with the substrate.

Conclusion

The preferential disposition of the mature larvae in the lower strata of the water column would still be influenced by the release of pheromones by metamorphosed individuals (HIDU, 1969; HIDU; HASKIN, 1971; HIDU et al., 1978), which would act as an important factor in the settling of these larvae. This stimulus may also explain, in part, the aggregation (bank formation) of benthic oyster populations (and possibly of other organisms) in the interior of bays and estuaries.

By contrast to the preferential disposition close to the bottom, which was shared by the three categories of larvae investigated, oysters had a distribution distinct from the other larvae, since they were found to be more abundant near to the mouth of the estuary in locations of greater hydrodynamic forces and in more saline waters. This may indicate a greater relative dispersion of these organisms and may, in addition, explain the broad distribution and the conspicuous distribution of the adult populations of this bivalve in the intertidal regions of the interior of the ECPB. The marked presence of these larvae during the flood tide, particularly at the entrance to the estuary, further confirms the conclusions of Wood & Hargis (1971) regarding the primary transport mechanism of these larvae in bay and estuary

environments and may, therefore, indicate a return of the larvae to the internal sectors, where they will find areas potentially favourable to recruitment. On the other hand, the marked presence of the remaining categories of mollusc larvae independent of the tidal phase, in the more internal sectors of the estuary, with lower salinity and less marked hydrodynamic forces, presumes meroplanktonic organisms belonging to benthic populations with low levels of dispersion, inhabitants of more internal areas of the system.

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