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# Acoustic study of the Río de la Plata estuarine front

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During December 1999, a transect 260 km long was carried out along the major axis of the Río de la Plata estuary. Acoustic (120 kHz), oceanographic, and zooplankton sampling were performed to extract a continuous, quasi-synoptic acoustic view of the estuary's salt wedge. Three different zones were identified. The riverine and marine zones were characterized by vertically homogeneous water and low volume-backscattering strength ($S_v$). The mixohaline zone was characterized by a strong vertical salinity gradient and the highest $S_v$ values. There were no relationships between the reflection value calculated from the salinity gradient and suspended matter (sediments) and measured $S_v$. The greatest abundance of acoustically detectable organisms was at the halocline depth, coincident with the echo recordings. The positions of the halocline and the two fronts were determined on the basis of aggregations of the different planktonic groups. The physical presence of the salt wedge, as shown by a "biological wedge", was well described by the acoustic technique employed.



Keywords: acoustics, estuary, fronts, plankton, Río de la Plata, salt wedge.

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## Introduction

Oceanographic fronts can be defined as regions where water properties change significantly over a relatively short distance. Owing to differing physical and biological factors, fronts are areas characterized by the retention and aggregation of organisms and, in general terms, high biological productivity. On the continental shelves of austral South America, several types of fronts can be differentiated: tidal, shelf break, upwelling, and estuarine (Acha *et al.*, 2004). Estuaries themselves are particularly important worldwide irrespective of their relatively small geographical size. The Río de la Plata (Figure 1) is a shallow (depth <20 m), large estuary located on the east coast of southern South America at approximately 35°S. It is orientated northwest to southeast and has a funnel shape approximately 300 km long that narrows from 220 km at its mouth to 40 km at its upper end (Mianzan *et al.*, 2001). The estuarine area is 35 000 km$^2$, and the fluvial drainage area is $3.1 \times 10^6$ km$^2$. The system drains the waters of the Paraná and Uruguay rivers, which constitute the second largest basin in South America. As a result, it has a huge discharge, with a mean of around 24 000 m$^3$ s$^{-1}$. A submerged bar, the Barra del Indio shoal, divides the system into an inner tidal river and an outer estuarine area. Density in the estuary is controlled by salinity, whereas changes in temperature, although important at a seasonal scale, only display small gradients (Guerrero *et al.*, 1997). The estuary is typically a two-layer system with a salt wedge most of the time: freshwater flows seawards on the surface and denser shelf water intrudes along the bottom (Figure 2). The maximum upriver penetration of the salt wedge is controlled by the submerged bar, where there is a well-developed bottom salinity front. The inner part of the estuary has a strong salinity stratification that gradually weakens in a seaward direction. The outer limit of the estuary is a surface salinity front whose salinity gradients are lower than those of the bottom front, and its location more variable. Physical forcing in the estuary is characterized by low seasonality in river run-off, mean river discharge estimated as 24 000 m$^3$ s$^{-1}$, a seasonal wind pattern (spring and summer dominated by onshore winds, autumn, and winter characterized by a balance between onshore and offshore

 

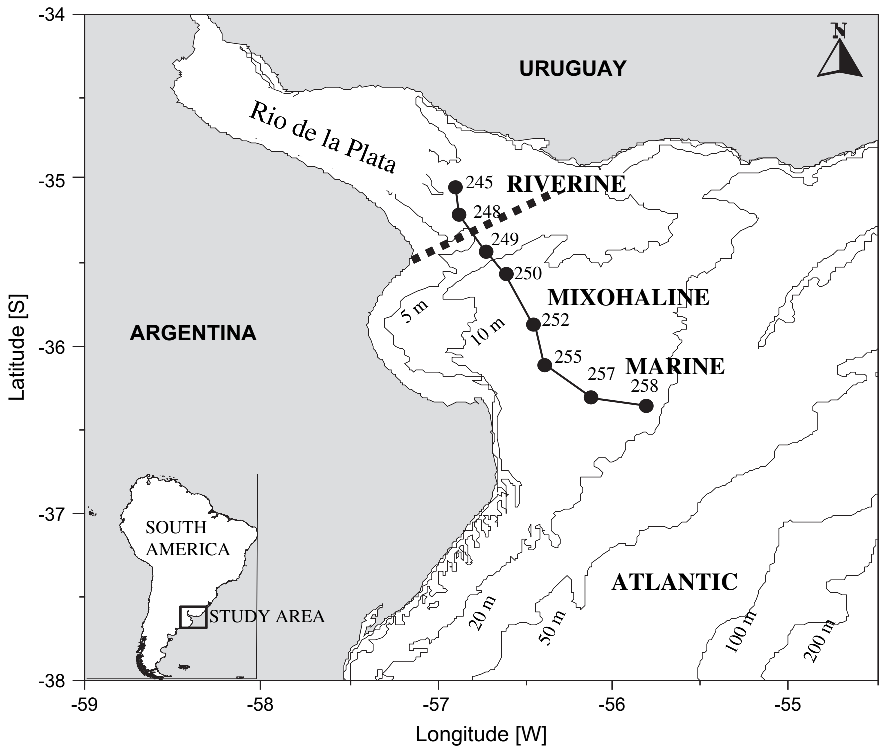


Figure 1. Map of the study area, showing the acoustic transect (black line), the CTD and plankton stations (dots), and the Barra del Indio shoal (dotted line).

winds), and low tidal amplitude (0.3−1-m tidal range; Mianzan *et al.*, 2001). The dynamics of the upper water layer discharging over the continental shelf is mainly driven by windstress, and the bottom layer is topographically controlled (Guerrero *et al.*, 1997). Water column stratification is disrupted and the salt wedge becomes well mixed after several hours of strong onshore winds (>11 m $s^{-1}$; Guerrero *et al.*, 1997). Winds are extreme in the Río de la Plata region throughout all seasons, with no defined temporal pattern. The mean regularity of such events is some 30−40 days, and they persist for 2−3 days, or exceptionally for 5 days (Guerrero *et al.*, 1997). In the inner estuary near the bottom salinity front, the flocculation of suspended matter at the tip of the salt wedge and the resuspension of sediment through tidal current friction at the bottom results in the development of a turbidity front (Framiñan and Brown, 1996).

Aquatic life is unevenly distributed within the salt wedge, with the distribution strongly dependent on the physical environment. For example, phytoplankton (Carreto, 1995), copepods (Mianzan *et al.*, 2001; Marrari *et al.*, 2004), ctenophores (Mianzan and Guerrero, 2000), salps (Alvarez Colombo *et al.*, 2003), and ichthyoplankton (Acha *et al.*, 1999; Berasategui *et al.*, 2004) have been reported to aggregate at different positions within the structure. The presence of a strong halocline has been mentioned as a boundary where marine plankton tend to aggregate (Madirolas *et al.*, 1997), and meso- and macroplanktonic organisms are very scarce in the upper dilute layer above the halocline (Mianzan *et al.*, 2001). However, most of the documented information relating to the description of the hydrography and the distribution of different planktonic groups was based on discrete sampling stations of CTD and stratified plankton bottles, nets, and submerged pumps. Therefore, the shape of the salt wedge and the allocation of plankton groups along it were inferred by interpolating these discrete sampling units.

The large spatial scale and dynamic environment make it difficult, both technically and financially, to sample in the estuary (Framiñan and Brown, 1996). Application of acoustic technology allows data to be obtained in a remote, non-intrusive manner, providing continuous monitoring in quasi-real time, with high resolution in both horizontal and vertical aspects. Because of the scattering properties of marine organisms at certain frequencies, acoustic techniques have proven to be a powerful method to obtain quasi-synoptic images of frontal areas (Orlowski, 1999). In recent years, acoustic techniques have been employed to study fine-scale oceanic events in systems such as eddies (Zimmerman and Biggs, 1999), upwelling (Liao *et al.*, 1999), internal waves (Proni and Apel, 1975), and thermoclines (Nash *et al.*, 1987).

For the Río de la Plata, Madirolas *et al.* (1997) demonstrated the strong coincidence of a scattering layer and

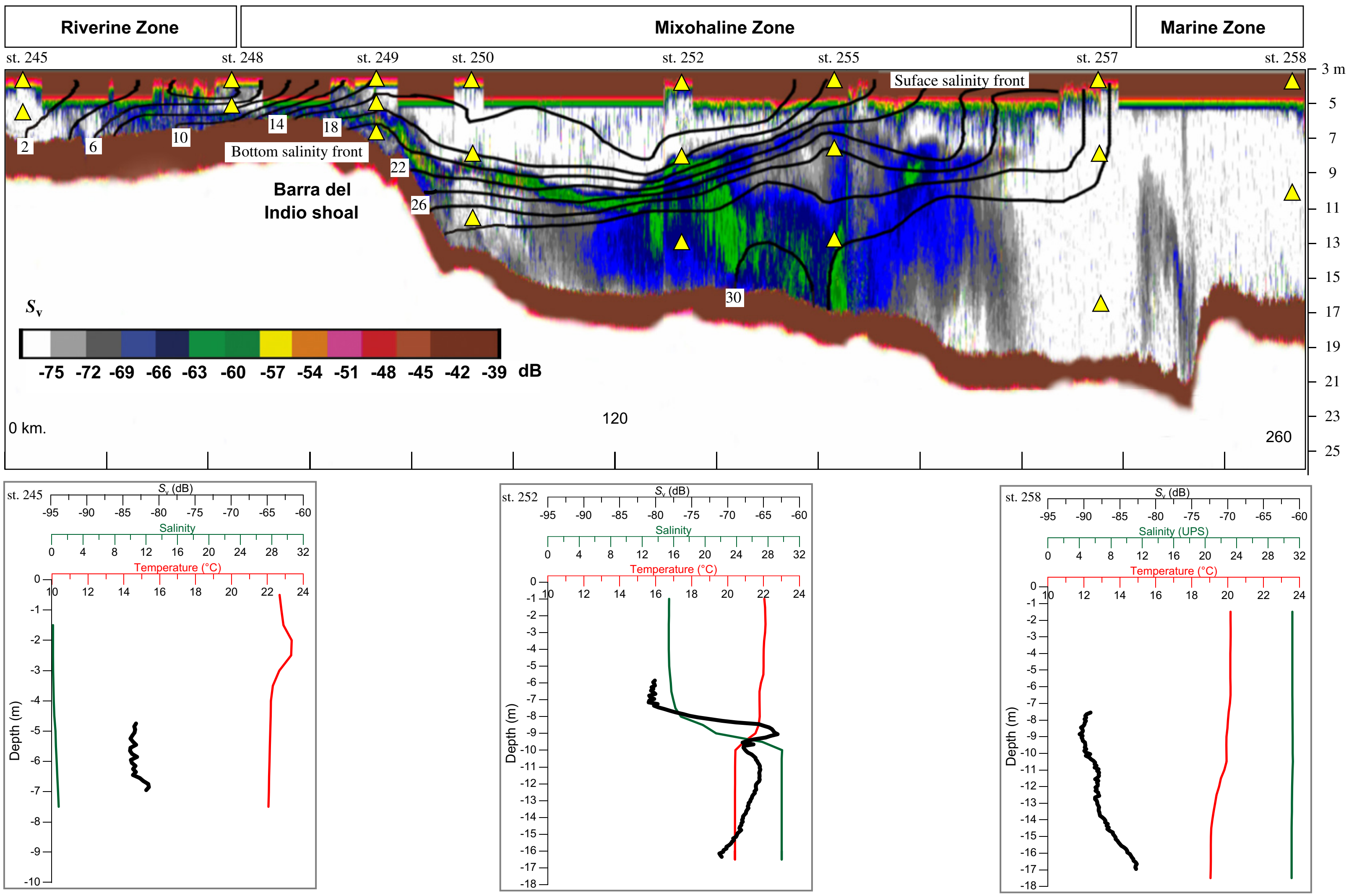


Figure 2. Volume backscattering strength ($S_v$) and salinity cross-section, obtained along the Río de la Plata estuary (triangles denote positions of plankton net sampling). The profiles below show salinity, temperature, and $S_v$ distribution for the three differentiated zones of the estuary (note that the vertical scales differ).

halocline at the stratified portion of the estuary, concluding that the distribution of some planktonic groups (zooplankton and ichthyoplankton) would be related to the physical parameters of the salt wedge. We intend with this work, therefore, to determine the pattern of the physical structure of the estuary by acoustically detecting the organisms associated with the salt wedge. In other words, our hypothesis is that the distribution of the acoustically characterized biota reflects the pattern of the oceanographic structure. The main objective of the study is to analyse a continuous, quasi-synoptic acoustic record of the Río de la Plata salt wedge, and its relationship with the physical and biological factors associated with the frontal areas.

## Material and methods

The study was carried out in the Río de la Plata estuary from 12 to 14 December 1999 onboard the RV "Capitán Cánepa". Acoustic, oceanographic, and zooplankton sampling were performed along a transect 260 km long, sailed along the axis of the estuary (Figure 1), starting in the riverine zone (vertically homogeneous freshwater) and ending in the marine zone (vertically homogeneous seawater).

Acoustic sampling was carried out in daylight with a calibrated SIMRAD EY-500 portable echosounder operating at 120 kHz and a split-beam transducer. Acoustic data were stored electronically and post-processed with SonarData Echoview software v. 3.0. The processing method was based on echo integration (Knudsen, 1990; Foote *et al.*, 1991), and the $S_v$ values were computed. The applied $S_v$ threshold was −80 dB. Echosounder calibration took place post-survey in a sheltered area near Mar del Plata, south of the main estuary, by means of standard targets as suggested by Foote *et al.* (1987). The instrument calibration values obtained are presented in Table 1 and were consistent with previous calibration results, showing stability of the system. The study area is characterized by a highly variable oceanographic environment, from freshwater to seawater, and sound propagation is affected by the changing water conditions, mostly the sound velocity ($c$) and absorption coefficient ($\alpha$). In order to account for this, average values of $c$ and $\alpha$ were computed as defined by the equations recommended by Foote *et al.* (1987) for each of the three zones: riverine (1489 m $s^{-1}$, 32 dB $km^{-1}$); mixohaline (1510 m $s^{-1}$, 31.4 dB $km^{-1}$); and marine (1516 m $s^{-1}$, 41 dB $km^{-1}$). Consequently, all the sound-scattering values presented herein were computed for each zone according to the corresponding sound propagation characteristics. Nevertheless, owing to the limited depth range in the study area, differences in $S_v$ values computed with the fixed and the true set-up of $c$ and $\alpha$ only reached 0.22 dB in the marine zone (at the deepest end) and 0.06 dB for the mixohaline and riverine zones.

Table 1. Echosounder system set-up and calibration data.

| | |
|---|---|
| Echosounder | SIMRAD EY-500 |
| Transducer | ES-120 |
| Frequency | 120 kHz |
| $\psi$ | −18.5 dB |
| $\varphi_{ath}$ | 9° |
| $\varphi_{along}$ | 9° |
| $S_v$ gain | 21.7 dB (pulse length 0.3 ms) |
| $S_v$ gain | 21.7 dB (pulse length 1 ms) |

In order to determine the contribution of the halocline itself to total sound scattering, the reflection coefficient at a plane interface was calculated (Clay and Medwin, 1977). Further, a comparison was made between the *in situ* measured area backscattering strength ($S_a$), and the hypothetical $S_a$. Theoretical values were estimated from the abundance of different plankton groups and employing sound-scattering models, as suggested by Stanton and Chu (2000), Lavery *et al.* (2003b), and the references in those papers. Oceanographic and plankton sampling took place at eight stations located along the transect (Figure 1). The positions of the sampling stations were based on previous knowledge of the hydrography and biota. Oceanographic data were collected with an SBE 9 CTD profiler, leading to a final vertical resolution of 0.5 m. Plankton were caught with a multiple opening−closing sampler (Hydrobios) with 0.25 $m^2$ mouth area and nets with 300-μm mesh (see Berasategui *et al.*, 2004, for details). In order to sample the smaller zooplankton fraction and to calculate the quantity of suspended sediments, a portable pump was deployed at each station and operated continuously from surface to bottom. At each sampling depth, 1 l of water was filtered through a previously weighed cellulose acetate filter of 0.45 μm pore size, and the matter retained after drying the filter at 105°C for 24 h was weighed. Ichthyoplankton data were based on Berasategui *et al.* (2004). Plankton were classified into four functional groups on the basis of their acoustic properties, following Madirolas *et al.* (1997).

## Results

Figure 2 is a continuous acoustic section obtained along the discharge axis of the Río de la Plata, superimposed on the salinity field. Volume-backscattering strength ($S_v$) profiles and typical salinity and temperature profiles of the three principal sectors (riverine, mixohaline, marine) are also presented.

The riverine zone is characterized by shallowness (depth <7 m) and a vertically homogeneous water column occupied by freshwater (average salinity 0.225). While sampling, temperature was 22.68°C at the surface and 23.06°C at the bottom (Station 245; Figure 2). Low values of volume-backscattering strength (average −84.05 dB) were registered.

The mixohaline zone is characterized by a strong salinity gradient both vertically and horizontally, as well as pronounced changes in volume-backscattering strength.

Salinity fronts (surface and bottom) were clearly identified, revealing a horizontal extension of the salt wedge of about 170 km (Figure 2). The halocline separates an upper fresher and thinner water layer (salinity values <20) from a bottom, salty, thicker water layer (salinity in the range 22–30). Stratification was strongest at Station 252, where salinity values changed from a minimum of 15.41 near the surface to 29.8 at the bottom; the steepest vertical gradient was some 5.9 units $m^{-1}$ between 8 and 10 m deep. At the same depth as the halocline, there was a weak thermocline. Temperature values were 22°C at the surface and 20°C near the bottom.

The acoustic transect showed a pattern that closely matched the oceanography. Volume-backscattering strength correlated to a wedge shape, which corresponded with the salty waters below the halocline. The surface salinity front was associated with high values of $S_v$ in most of the water column. $S_v$ peaked at the halocline depth in the inner half of the mixohaline zone (Stations 249–252; Figure 2). At Station 252, echoes indicated the greatest concentration of scatterers within a thin layer located approximately at 9 m deep. The volume-backscattering strength varied from −83 dB at 6 m to −63 dB above and at the halocline depth, decreasing with depth to −71 dB near the bottom.

In the marine zone, the water column was vertically homogeneous and characterized by high salinity (>30). Temperature was vertically homogeneous, with a mean value of 19.73°C (Station 258; Figure 2). Backscattering values were very low, ranging from −89 dB at 7 m to −83 dB at 17 m.

To detect possible non-biological sources of scattering, the contribution of the salinity gradient at the halocline was estimated, obtaining a low reflection value ($R_{12} = 0.13$). The concentration of suspended matter (sediments) and the $S_v$ distribution were also investigated. The density of the suspended matter did not relate to the backscattering values (Figure 3), highest values of suspended matter being near the bottom.

The distribution of the main planktonic groups along the transect is shown in Figure 3. In the riverine zone, zooplankton was scarce. Only fish larvae (order Siluriformes) were present. In the mixohaline zone, several groups of macroplanktonic crustaceans (*Neomysis americana* and a few *Peisos petrunkevitchii*), decapod larvae (zoeas), copepods (mainly *Acartia tonsa*), fish larvae (Sciaenidae, *Engraulis anchoita*, and *Trachurus lathami*), scyphozoa medusae (*Chrysaora lactea*), and chaetognaths (*Sagitta* sp.) were found mostly beneath the halocline. The highest values of

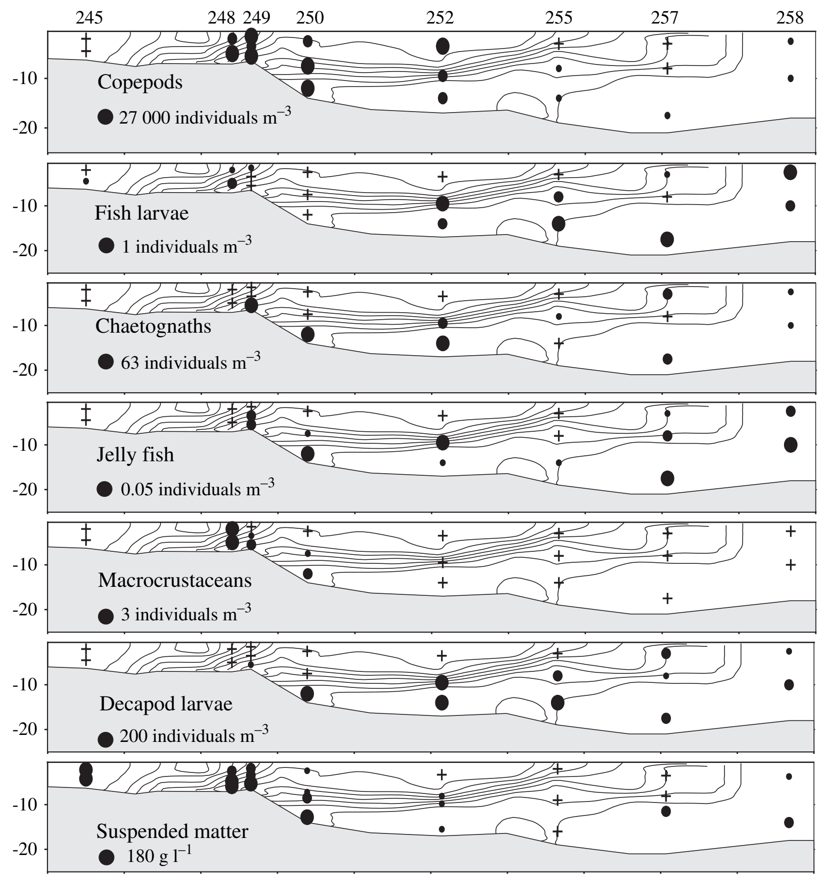


Figure 3. Vertical cross-section of the functional groups as obtained from the Multinet and a portable pump. The size of circles is proportional to density (individuals $m^{-3}$) and suspended matter ($g\ l^{-1}$). Plus signs indicate zero values.

macroplanktonic crustaceans and chaetognaths were close to the bottom (Stations 248 and 249), at the tip of the salt wedge. Fish larvae length ranged from 2 to 13 mm, and decapod larvae were at high density near the halocline (Station 252). Zooplankton density in the marine zone was much lower. In the absence of stratification, those groups identified were not restricted to a specific depth (Figure 3).

Generally, the distribution of the main groups revealed the prevalence of marine species occupying the whole water column at the offshore portion of the estuary, penetrating the estuary in the salt wedge and reaching their greatest concentration at the halocline. This biological pattern closely matches the continuous acoustic transect and also matches the general physical parameters (Figure 2). $S_v$ was highest in the bottom layer within the inner portion of the wedge (bottom salinity front) in the mixohaline zone, and at the halocline in the central sector of the wedge. Both riverine and marine zones had lower $S_v$ values.

Figure 4a compares the measured total area backscattering strength ($S_a$) and the "expected" values from the planktonic groups found. Theoretical scattering of the different types of organisms was obtained from sound-scattering models. The total predicted scattering at a station was calculated as the linear total of the scattering contribution from each plankton group present in the sample, weighed by its relative percentage of the total catch in terms of number of individuals. Simple linear correlation analysis between measured and predicted scattering was significant ($r^2 = 0.98$) and is shown in Figure 4b.

## Discussion

In estuarine systems, areas of maximum salinity gradient are characterized by the retention and aggregation of planktonic organisms (Hesse *et al.*, 1989). As such organisms can be detected acoustically and it is possible to use them as a link between acoustic backscattering and oceanographic structures (Madirolas *et al.*, 1997). In our study, we obtained an acoustic image along the major axis of the Río de la Plata estuary coincident with the spatial pattern of planktonic organisms with different acoustic properties, whose distribution seems to be strongly related to the physical environment.

The vertically homogeneous riverine and marine zones were characterized by the lowest densities of organisms estimated from net sampling and the acoustic transect, whereas in the mixohaline zone, both techniques showed plankton to be most abundant. Maximum abundance of most of the acoustically detectable organisms at the working frequency (120 kHz) was concentrated from the halocline to the bottom, coincident with the echo recordings, and agreeing with the results of earlier studies. Mianzan *et al.* (2001) found few zooplanktonic organisms in the upper freshwater layer. Also, this estuary is used for spawning by several marine fish species (Acha *et al.*, 1999). Therefore, the lower abundance of prey items for fish larvae in the upper layers could be a cause of the scarcity of ichthyoplankton in the upper layers.

At the working frequency of 120 kHz, most groups are detectable in the size range obtained in net samples. Among crustaceans, however, the presence of copepods in the samples at high densities did not correlate with any sound-scattering layer owing to their small size (Sameoto, 1980). We consider that fish larvae and scyphozoa medusae were the principal source of the sound scattering, in the case of fish larvae because of the presence of a swimbladder (Foote, 1980). Madirolas *et al.* (1997), in an acoustic study of the halocline, found that ichthyoplankton were the most significant scattering source. The greatest abundance of fish larvae during this cruise was in the mixohaline zone at the depth of the halocline (Berasategui *et al.*, 2004). As far as scyphozoan medusae are concerned, previous work has shown that gelatinous zooplankton are abundant along the coast of the southwest Atlantic and that they can penetrate the estuary in the more saline water below the halocline (Mianzan and Guerrero, 2000; Alvarez Colombo *et al.*, 2003). Therefore, strong scattering values from jellyfish were obtained at 38 kHz and 120 kHz. Moreover, associations between medusae and small fish in the Río de la Plata estuary have been recorded through direct observation, observation that may enhance the backscattering associated with the presence of medusae (Alvarez Colombo *et al.*, 2003).

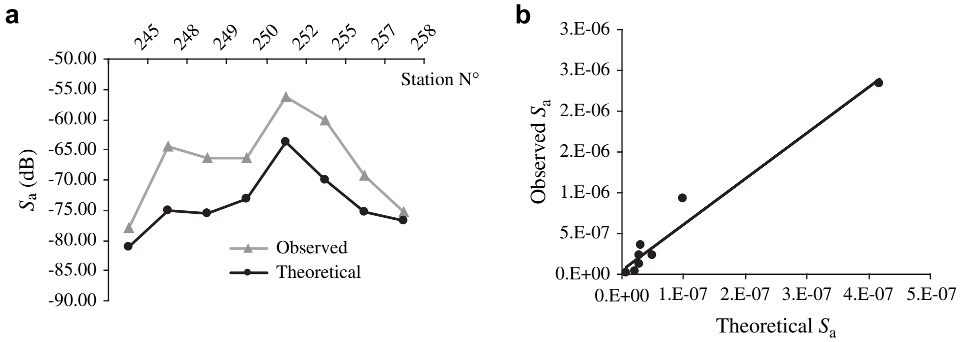


Figure 4. (a) Area backscattering strength ($S_a$) measured and expected for each plankton sampling station. (b) Simple linear correlation analysis between measured and predicted scattering.

Crustaceans were denser in the inner portion of the estuary, close to the tip of the salt wedge. Both species (*Neomysis americana* and *Peisos petrunkevitchii*) have been recorded previously in great abundance in this frontal zone (Mianzan *et al.*, 2001; Schiariti *et al.*, 2006).

Considering the marked correlation between plankton net samples and sound scattering, both in depth and along the acoustic transect, we conclude that the $S_v$ values registered in the Río de la Plata estuary had a biological origin. Contribution from local microstructures in the water density field cannot be discarded (Stanton *et al.*, 1994; Lavery *et al.*, 2003a; Ross and Lueck, 2003), but as shown by Seim *et al.* (1995) and Seim (1999), the expected contribution from this source of sound scattering at the working frequency of 120 kHz is likely to be only slightly above the applied $S_v$ threshold (−80 dB).

The comparisons made between the expected backscattering and the measured values at the plankton sampling stations correlated well, but there was a constant bias along the stratified zone, with the theoretical values being somewhat higher than those measured by the echosounder. This difference appears to have been much smaller at the ends of the transect, where the water column is more homogeneous. As observed here, the contribution from the water interface to the total backscattering, in terms of the coefficient of reflection at a plane interface, could possibly account for this difference.

Zooplankton have been long considered passive members of patches that are the product of large-scale physical processes. It is also now accepted that biological processes contribute to zooplankton patchiness. The area described is characterized by a typical estuarine circulation (Mann and Lazier, 1991), where freshwater and saltwater meeting results in a mean flow seawards at the surface and a net inflow landwards along the bottom, as confirmed by ADCP measurements (Guerrero *et al.*, 2004). Moreover, the convergence of water masses and the resulting strong halocline at the tip of the salt wedge result in accumulation and retention of organic matter and plankton. Marine species aggregate at and below the halocline by advective processes, or penetrate the estuary actively probably to take advantage of the high biological productivity of this system. Behavioural processes, such as vertical migration as a retention mechanism used by fish larvae (Weinstein, 1979; Berasategui *et al.*, 2004), or searching for prey at the halocline (Lougee *et al.*, 2002), could combine with physical processes to create the spatial heterogeneity we observed in this large-scale estuary.

A broad spatial and temporal view of the Río de la Plata estuary has been presented. Using acoustic detection of the zooplankton aggregations, we were able to obtain for the first time a continuous view of this salt-wedge system and the adjacent waters in a quasi-synoptic way. The position of the halocline and the two fronts were determined on the basis of aggregations of different planktonic groups which were concentrated at the various structures. In this way, acoustic monitoring allowed us to observe the physical structure of the salt wedge as a "biological wedge".

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