

Distribution of microplankton and fish larvae related to sharp clines in a Patagonian fjord

Distribución del microplancton y larvas de peces relacionadas a clinas abruptas en un fiordo Patagónico

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Abstract.- Vertical distribution of microzooplankton and fish larvae was studied in a Patagonian fjord from Chile. Zooplankton collection, including larvae of the sprat *Sprattus fuegensis* (Clupeidae) and the lightfish *Maurolicus parvipinnis* (Sternoptychidae) were collected during a 25 h period inside Steffen fjord (47°S) during November 2008, using stratified sampling of zooplankton, prey field, and CTD casts. Most copepod nauplii, copepodites of *Acartia tonsa* and large *M. parvipinnis* larvae were collected in the vicinity of the pycnocline, while larval *S. fuegensis* did not show a spatial pattern. Therefore, some larval fish species may utilize stable water parcels to increase predator-prey encounter rates.

Key words: Vertical stratification, *Maurolicus parvipinnis*, *Sprattus fuegensis*

INTRODUCTION

From Lasker's stable ocean hypothesis (1981), several ideas have been constructed about the role of vertical stratification on feeding, survival and retention of fish larvae in the ocean (Pringle 2007, Woodson & McManus 2007, McManus & Woodson 2012). The pycnocline and the ocean fronts are often regions that provide optimal growth conditions for organisms at the base of the food web- the phytoplankton. These are frequently steep gradients in flow velocity and even reversals in flow direction associated with fronts and clines. Consequently, these regions are characterized by increased shear (McManus & Woodson 2012) and can aggregate thin layers of zooplankton (from tens of centimeters to several meters) when the water column of coastal ocean is stable and there is reduced flow, persisting for several days, and spanning several kilometers horizontally (McManus *et al.* 2005).

Zooplankton have been directly observed to counteract vertical flow and displacement through oriented swimming behavior (Genin *et al.* 2005), can consequently remain in preferred habitats (Seuront 2006) or cross the halocline according to dietary availability

(Metaxas & Young 1998, Breckenridge & Bollens 2010). These behaviors can lead to aggregations when turbulence intensity and vertical velocities are less than the swimming speed of the taxa being observed (Woodson & McManus 2007). Other studies show that aggregations can occur at haloclines in the absence of food, suggesting that some species use physical cues to maintain position (Lougee *et al.* 2002). However, it has been difficult to detect direct relationships amongst the vertical distribution of predator, prey and turbulence and stratification in the field (Reiss *et al.* 2002).

In fjords of southern Patagonia, chronic physical disturbance of natural origin associated with river discharge, ice melting from massive ice fields and release of suspended particulate material shape the ecology of pelagic (Vargas *et al.* 2011, Landaeta *et al.* 2012) and benthic communities (Quiroga *et al.* 2012) inhabiting these particular ecosystems. The water column is highly stratified and oligotrophic, with very low chlorophyll concentrations (<1.00 µg L⁻¹), almost exclusively caused by cyanobacteria. Turbidity is higher in surface waters and it increases near river mouths (Quiroga *et al.* 2012).

Because of these features, the area is utilized by few marine fish species as spawning and early nursery zone (Bustos *et al.* 2011). From those, biophysical interactions may vary among species; while fish larvae of mesopelagic habitat are affected in its diet and recent growth by the influence of freshwater input, larvae of pelagic fishes are unaffected (Landaeta *et al.* 2012).

In the present study, we describe in short-term (hours, meters) the variation of fish larvae distribution and the potential prey field (microplankton) in a glacier-influenced fjord of Chilean Patagonia, Steffen fjord (47°S).

MATERIALS AND METHODS

During 6-7 November 2008, an oceanographic station located at Steffen fjord (47°45.76'S, 73°41.63'W, Fig. 1A), southern Patagonia, was sampled each 3 h during 25 hours, onboard the research vessel AGOR Vidal Gormaz. Each sampling cycle consisted in the deployment of a Seabird SBE-25 CTD up to 200 m depth, the collection of seawater at 0, 5, 15, 35, and 125 m depth with a 5 L Niskin bottle for microplankton, and the collection of zooplankton with a Tucker trawl (1 m² mouth, 300 μm mesh size) with a General Oceanics flowmeter mounted the frame to estimate volume of filtered seawater. Four strata were sampled: 200-50 m, 50-25 m, 25-10 m, and 10-0 m depth. Filtered seawater fluctuated from 16.4 to 486.6 m³ (mean ± 1 standard deviation, SD; 120.75 ± 105.66 m³). Once onboard, nets were washed and plankton samples were preserved with 5% formalin buffered with sodium borate. For microplankton, the content of bottles was filtered by a 45-μm mesh, and the remains were preserved with 5% formalin buffered with sodium borate.

In the laboratory, microplankton samples taken from the Niskin bottles were counted, and the organisms were identified to the lowest possible taxon with an Olympus® SZ5145A dissecting stereomicroscope, and their abundance was standardized at individuals per cubic meter (ind. m⁻³). All fish larvae were removed from the zooplankton samples, and the two most abundant species were selected for this study, the sprat *Sprattus fuegensis* (Clupeidae) and the lightfish *Maurollicus parvipinnis* (Sternoptychidae). Larval abundance was standardized to individuals 1000 m⁻³ using the estimated filtered volume.

Aggregation of microzoo- and ichthyoplankton near pycnocline was tested by using least-square linear regressions between standardized abundance of selected taxa and Brunt-Väisälä frequency (BV, expressed as cycles h⁻¹). BV was calculated as follows:

$$N = \left[(g/\rho) \times (\partial\rho/\partial z) \right]^{1/2}$$

where, g is the gravity (9.8 m² s⁻¹), ρ is the density of the sea water, and z the depth. Largest values of BV will indicate the location of the pycnocline; therefore, if plankters accumulate at the pycnocline, it is expected larger values of abundance at larger values of BV (*i.e.*, slope of the regression, $\beta > 0$, with $P < 0.05$).

In order to characterize the vertical distribution of microplankton and fish larvae in Steffen fjord, the centre of mass (centroid, CD) of each taxa profile at each sampling cycle was calculated as: $CD = \Sigma (p_k \times z_k) / \Sigma p_k$, where p_k is the number of organisms in the stratum k , and z_k is the mean depth of the stratum k . Comparisons of CD were carried out between developmental stages of larval fish and between fish species by using Mann-Whitney U-tests. To test the spatial match of predators and preys, CD of preys (eggs, nauplii, *Acartia* and *Paracalanus* copepodites) were correlated with CD of predators (*Maurollicus* and *Sprattus*, by developmental stage and as a whole) with Spearman tests.

RESULTS

OCEANOGRAPHIC CONDITIONS

Throughout the study period, the water column at the Steffen fjord showed slight differences in temperature in the first 200 m depth (8.13-10.48°C, mean ± standard deviation: 9.03 ± 0.52°C); a thermal inversion was observed at ~50 m depth, caused by surface waters <9°C (Fig. 1B). Salinity showed a great increase with depth (from 4.70 in surface to 33.96 at ~170 m depth; surface waters (<10 m depth) fluctuated from 5 to 23 of salinity (Fig. 1C), because of glacier melting at the head of Steffen fjord and freshwater input of Baker river (Fig. 1A). Seawater density (expressed as sigma-t, Fig. 1D) showed the same spatio-temporal pattern than salinity (range: 3.48-26.39 units of sigma-t, 24.74 ± 3.64 units of sigma-t), with a steeped pycnocline located in the first 10 m depth. The whole water column was well oxygenated (6.35-7.98 ml L⁻¹), and at surface, isolines showed cyclic ascents separated by ~12 h (Fig. 1E), that suggest tidal influence in the surface waters. In the first 50 m of the water column, BV varied from 2.23 cycles h⁻¹ (well-mixed) to 73.32 cycles h⁻¹ (highly stable) (17.59 ± 14.38 cycles h⁻¹), and largest values were detected from 6 to 10 m depth (*i.e.*, depth of the pycnocline, 8.57 ± 1.61 m depth).

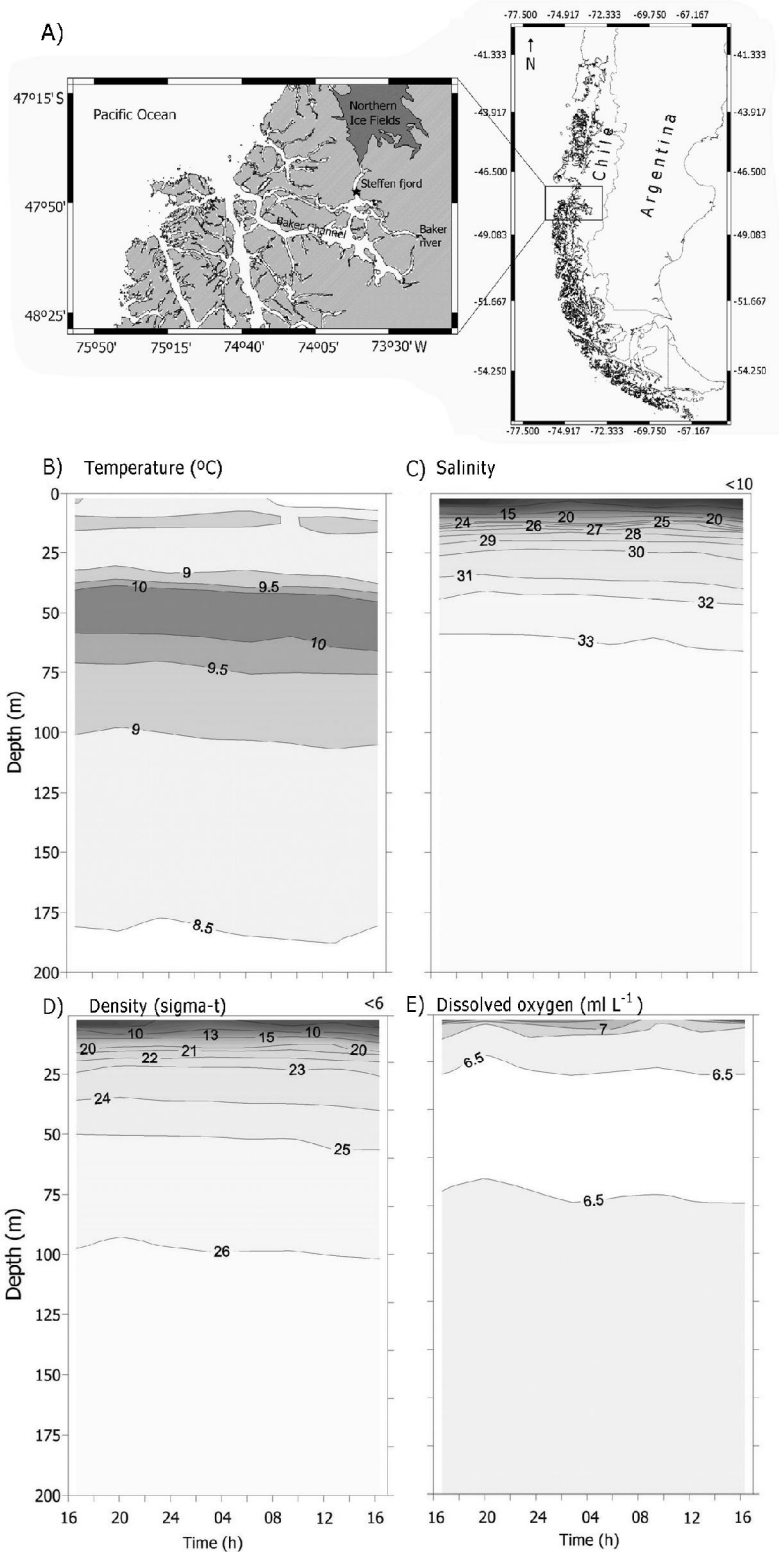


Figure 1. A). Map of the study area. Black star indicates the location of the station studied during 6-7 November 2008. B-E). Temporal sections of oceanographic conditions, B) temperature, C) salinity, D) seawater density and E) dissolved oxygen, during the 25 h cycle during November 2008 at Steffen fjord, southern Chile / A) Mapa del área de estudio. La estrella negra indica la ubicación de la estación estudiada durante el 6 y 7 de noviembre de 2008. B-E). Secciones temporales de las condiciones oceanográficas, B) temperatura, C) salinidad, D) densidad del agua de mar y E) oxígeno disuelto, durante un ciclo de 25 h en Noviembre de 2008 en el fiordo Steffen, sur de Chile

MICROZOOPLANKTON AND LARVAL FISH DISTRIBUTION DURING A DIEL CYCLE

A total of 25 different microzooplankton taxa were identified (Table 1), largely dominated by holozooplankton, mainly copepods (88%). Meroplanktonic components correspond to larval polychaeta and decapod larvae. All taxa were more recurrent at subsurface, around 15 m depth (Table 1). To compare spatio-temporal distribution of microzooplankton and fish larvae, some taxa (*i.e.*, copepodite) were pooled together. Both nauplii and copepodites of *Acartia tonsa* were located near surface, with its centroid depths located above 10 m depth (Fig. 2B, 2C). Abundance of both taxa was positively related to the water column stability, *i.e.*, β of regression between Brunt-Väisälä frequency and abundance was different from zero ($\beta_{\text{nauplii}} = 35.07$, $P = 0.04$; $\beta_{\text{cop } Acartia} = 74.78$, $P = 0.02$). These results indicate

that large abundances of both taxa were collected near the pycnocline. On the other hand, copepod eggs and *Paracalanus indicus* copepodites were found below the pycnocline (Fig. 2A, 2D), and no significant relationships were detected among abundance and BV, nor for copepods egg ($\beta = -2.09$, $P = 0.72$) or *Paracalanus indicus* copepodites ($\beta = 7.34$, $P = 0.61$). Therefore, these latter taxa were not aggregate at the pycnocline.

None fish larvae were collected in the deepest sampled strata (50-200 m) and therefore, only the vertical distributions in the upper 50 m depth are showed (Fig. 2E, 2F). Larval abundance was low throughout the water column, 12.15-109.26 and 5.52-60.93 ind. 1000 m⁻³, for pre- and postflexion stages of *M. parvipinnis*, respectively; preflexion larvae of *S. fuegensis* varied from 5.94 to 105.82 ind. 1000 m⁻³, and from 12.42 to 176.36 ind. 1000 m⁻³ for

Table 1. Composition and vertical abundance of microplankton collected at Steffen fjord, south Patagonia, during 6-7 November 2008. Abundance expressed as individuals m⁻³. SD = 1 standard deviation. C= indicates different copepodite stages / Composición y abundancia vertical del microplankton recolectado en el fiordo Steffen, Patagonia austral, durante el 6-7 de noviembre 2008. La abundancia está expresada en individuos m⁻³. SD = 1 desviación estándar. C= indica diferentes estadios de copepodito

Taxa	0 m Mean	SD	5 m Mean	SD	15 m Mean	SD	35 m Mean	SD	125 m Mean	SD
Copepod eggs	666.7	-	600.0	278.9	666.7	298.1	333.3	-	-	-
Copepod nauplii	2000.0	1536.6	3259.3	1891.3	1925.9	924.6	833.3	471.4	666.7	0.0
<i>Paracalanus indicus</i> C1	333.3	-	666.7	333.3	888.9	750.3	888.9	509.2	-	-
<i>Paracalanus indicus</i> C2	333.3	-	444.4	192.5	833.3	752.8	444.4	509.2	333.3	0.0
<i>Paracalanus indicus</i> C3	333.3	-	333.3	-	833.3	192.5	444.4	192.5	-	-
<i>Paracalanus indicus</i> C4	333.3	-	-	-	500.0	192.5	333.3	-	-	-
<i>Paracalanus indicus</i> C5	333.3	-	-	-	666.7	-	333.3	0.0	-	-
<i>Paracalanus indicus</i> adults	-	-	-	-	555.6	384.9	-	-	-	-
<i>Acartia tonsa</i> C1	1111.1	779.4	1190.5	1152.4	444.4	192.5	666.7	-	333.3	-
<i>Acartia tonsa</i> C2	777.8	509.2	1277.8	1083.5	888.9	910.8	500.0	235.7	-	-
<i>Acartia tonsa</i> C3	1388.9	800.5	1740.7	1199.3	500.0	235.7	-	-	333.3	-
<i>Acartia tonsa</i> C4	1166.7	693.9	952.4	558.7	333.3	-	-	-	333.3	-
<i>Acartia tonsa</i> C5	1000.0	-	1055.6	443.1	333.3	-	333.3	0.0	333.3	-
<i>Acartia tonsa</i> adults	1083.3	957.4	1000.0	745.4	777.8	384.9	-	-	1166.7	1178.5
<i>Rhincalanus nasutus</i> C2	-	-	-	-	333.3	-	-	-	-	-
<i>Rhincalanus nasutus</i> C3	-	-	-	-	333.3	-	333.3	-	333.3	-
<i>Microsetella</i> sp.	-	-	-	-	1000.0	-	-	-	-	-
<i>Oithona</i> spp. C1	-	-	333.3	-	666.7	-	-	-	-	-
<i>Oithona</i> spp. C2	-	-	333.3	-	500.0	235.7	333.3	-	-	-
<i>Oithona</i> spp. C3	-	-	-	-	833.3	707.1	333.3	-	-	-
<i>Oithona</i> spp. C4	-	-	333.3	-	666.7	-	333.3	-	-	-
<i>Oithona</i> spp. adults	-	-	666.7	-	777.8	344.3	333.3	-	-	-
Larval polychaeta	-	-	333.3	-	333.3	0.0	-	-	-	-
<i>Oikopleura</i> sp.	-	-	-	-	333.3	-	-	-	-	-
Decapod larvae	333.3	-	-	-	-	-	333.3	-	-	-

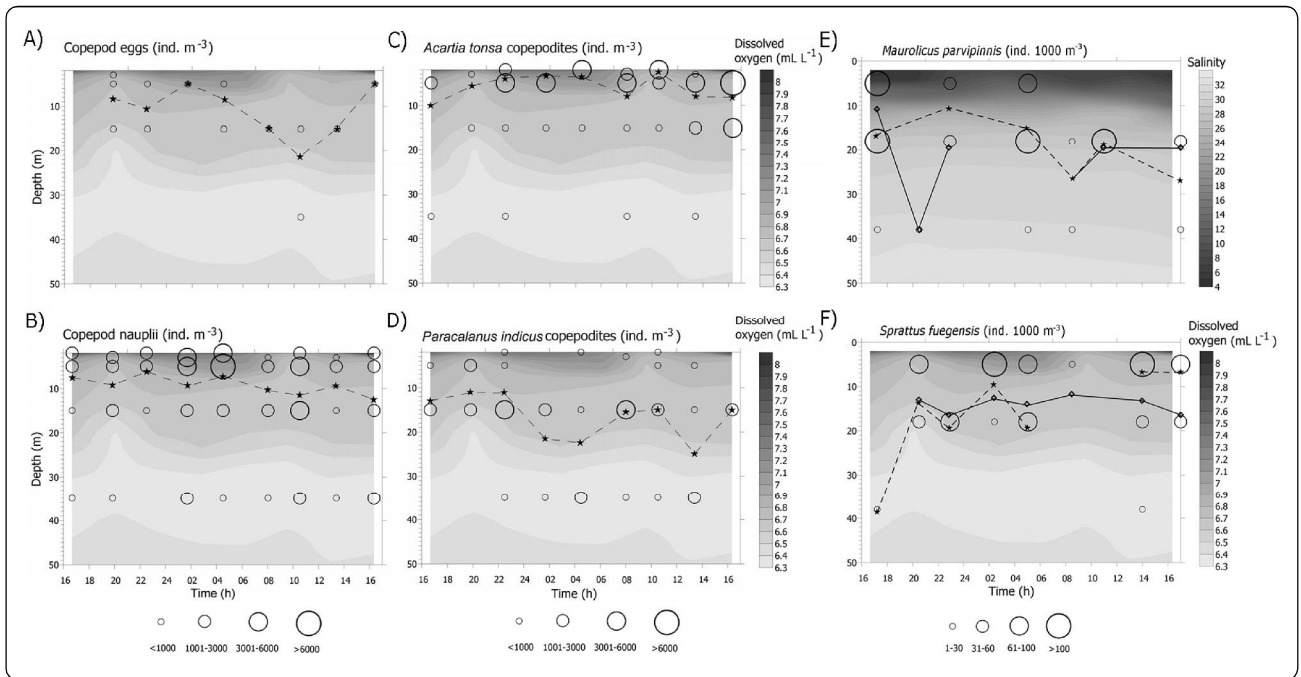


Figure 2. Temporal variations in abundance (ind. m⁻³) and centroid depth (m) of potential prey field (copepod eggs, nauplii and adults, ind. m⁻³) and fish larvae (ind. 1000 m⁻³) collected in Steffen fjord. Overimposed it is the temporal sections of salinity and dissolved oxygen / Variaciones temporales en la abundancia (ind. m⁻³) y profundidad de centroide (m) del potencial alimento (huevos de copépodos, nauplii y adultos, ind. m⁻³) y larvas de peces (ind. 1000 m⁻³) recolectados en fiordo Steffen. Superpuesto se encuentran las condiciones de salinidad y oxígeno disuelto

postflexion larvae. Only postflexion larvae of *M. parvipinnis* showed a significant relationship with BV ($\beta = 1.81, P = 0.002$); preflexion *M. parvipinnis* and larval *S. fuegensis* did not show significant relationships or correlations with BV ($P > 0.05$).

Centroid depth distribution of larval fish ranged from 5 to 38 m depth (Fig. 2E), and did not differ during the development for both taxa (*M. parvipinnis*, $U = 13.5, P = 0.515$; *S. fuegensis*, $U = 24, P = 0.949$, Fig. 2F) nor between species ($U = 18, P = 0.141$). No significant correlations were detected between the depth distribution of potential preys (eggs, nauplii, *Acartia* and *Paracalanus* copepodite) and larval fish predators (*Maurolicus* and *Sprattus* larvae), except for a significant negative correlation between nauplii and preflexion stages of *S. fuegensis* ($R = -0.836, P < 0.05$).

DISCUSSION

In a fjord environment of southern Patagonia, where strong vertical stratification and sharp pycnocline was evident in near surface waters (6-10 m depth), some potential prey items for fish larvae, such as copepod nauplii and *Acartia*

tonsa copepodites, were aggregated near pycnocline, as well as postlarval *Maurolicus parvipinnis*. Other prey, such as *Paracalanus indicus* and copepod eggs, together with larval sprat *Sprattus fuegensis*, were collected below pycnocline.

Salinity has important biological implications for marine animals due to associated physical parameters including osmolality, relative proportions of solutes, absorption and saturation of dissolved gasses, density, viscosity, surface tension, absorption of radiation, and transmission of sound. Vertical salinity gradients, or haloclines are thought to control the vertical distribution of organisms (ascidian larvae, Vásquez & Young 1996, pluteus larvae, Metaxas & Young 1998, zoea, Brekenridge & Bollens 2010, fish larvae, Grønkjær & Wieland 1997), and the responses of smaller species (*i.e.*, *Acartia*) to haloclines is stronger than the responses of larger species (*i.e.*, fish larvae) (Lougee *et al.* 2002, this study). When sharp haloclines occur in the water column, they had major consequences for the structure of the plankton community (Andersen & Nielsen 2002, Bustos *et al.* 2008, 2011). However, in shallow environments such as estuaries, pycnoclines not

always increase the feeding success of fish larvae (Ochoa-Muñoz *et al.* 2013).

Sharp pycnocline affected the distribution of microplankton in the Steffen fjord. While *Acartia tonsa* copepodites were collected in larger abundance near the pycnocline, *Paracalanus indicus* copepodites were found below it. The microplankton, particularly copepod nauplii and copepodite, showed similar vertical distribution patterns described in other coastal waters from central Chile and other nearshore waters around the world. *Acartia tonsa* and *Paracalanus indicus* are found very near the surface and at subsurface waters, respectively (Castro *et al.* 2007), although in other fjord environments, *Acartia* and *Paracalanus* copepodites can be found at 30 and 20 m depth, respectively (Titelman & Fiksen 2004).

Results indicate similar spatial patterns with other fjord ecosystems around the globe. In Storfjorden, on the west coast of Norway, zooplankton was more abundant in a superficial layer of low salinity (23 to 34), warm (8 to 12°C) water, and eggs and larvae of *Sprattus sprattus* and *Maurolicus muelleri* were found in the first 50 m depth (Halliday *et al.* 2001).

Changes in predator-prey vertical distribution also can reduce prey ingestion. A negative correlation was detected between copepod nauplii and larval *Sprattus fuegensis*. Similarly, *Acartia tranteri* nauplii were negatively correlated with distribution of larval flounders *Rhombosolea tapirina* and *Ammotretis rostratus* (Jenkins 1988). Also, zooplankton prey can limit both detection and encounter with predators by reducing their motility. By spending more time in a low velocity type of behaviour, such as sinking, a prey may reduce the hydrodynamic signal that can be perceived by a predator, and thus limit the time exposed to predators (Titelman 2001). On the other hand, at low food densities fish larvae may search an increasing water volume for food particles, by increasing swimming activity and reactive distance (Munk & Kjørboe 1985).

Finally, our results show that, in a Patagonian fjord influenced by ice melting and freshwater input, the presence of sharp pycnocline increase aggregation of microplankton and the most mobile fish larvae (postflexion stages) during a diel cycle. These results suggest that large stratification related to sharp pycnoclines may increase the total prey volume per gut of larval *M. parvipinnis* detected in coastal zones with stability around 0.07-0.2 cycles s⁻¹ along Chilean Patagonia (Landaeta *et al.* 2011). Therefore, the presence of sharp

pycnoclines may increase the biophysical coupling between physical and ecological processes in early life stages of fishes.

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