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The spatio-temporal distribution of juvenile hake (*Merluccius gayi gayi*) off central southern Chile (1997–2006)

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Abstract – The Chilean hake (*Merluccius gayi gayi*) is the predominant groundfish species inhabiting the southern Humboldt, mainly from Coquimbo (29° S) to Puerto Montt (42° S). At present there is only limited knowledge on the spatial distribution of juveniles of this species, particularly concerning its dependence on key physical characteristics. On the basis of annual surveys carried out during austral winters from 1997 to 2006, changes in the presence of juveniles were studied using Generalized Additive Model techniques. Temporal factors and spatial effects were more important than single physical variables in explaining the presence of juvenile hake (<34 cm total length). Juvenile hake had a preference for shallower waters. Although salinity and oxygen were significant, their contribution was marginal. Juvenile hake seem to prefer shallow oxygenated waters, but the nonlinear relationships and partial secondary peaks detected in salinity and oxygen probably only reflected the influence of three water masses found in the winter habitat. Endogenous factors could be more important in determining temporal and spatial changes in the proportion of juvenile hake. An important change in the presence of juveniles has occurred since 2004, coinciding with a significant decline in biomass of adult hake. It is postulated that cannibalism pressure from adults has probably declined and that spatial and temporal changes in the presence of juvenile hake seem to be more associated with fishery-induced demographic effects.

Key words: Acoustic survey / Fish distribution / Midwater trawl / Presence-absence / Hake / GAM

1 Introduction

Spatial distribution of fish is influenced by physical external factors and is also driven by endogenous factors such as those associated with individual development and/or effects of interaction with conspecifics (Shima et al. 2002). Although these factors interact, the identification of significant factors or habitats can lead to a better understanding of how the environment influences affect marine fish populations and fisheries and can, therefore, help to support their management and conservation. The connectivity from juvenile to adult habitats can result in an important transfer of biomass, nutrients and energy (Gillanders et al. 2003).

Spatial distributions can also be inhibited by ecological interactions between juveniles and adults. Indeed, juveniles are usually segregated from adult fish (Abella et al. 2005; Bartolino et al. 2008; Gillanders et al. 2003), and this should be more evident in species where the incidence of cannibalism is high. Indeed, species of the genus *Merluccius* are considered important predators in the ecosystems they inhabit, and cannibalism of younger conspecifics is common (Alheit and Pitcher 1995). This is the case of the Chilean hake (*Merluccius gayi gayi*), which is the predominant groundfish species inhabiting the southern Humboldt, mainly from Coquimbo (29° S) to Puerto Montt (42° S). This species is a predator that impacts euphausiids, commercial foraging small pelagic fish, benthic crustaceans and conspecifics. Indeed, adult hake are able to cannibalize younger conspecifics at an incidence of close to 26% by weight (Cubillos et al. 2003), mainly concerning ages 0, 1 and 2 (Jurado-Molina et al. 2006). If a significant fraction of adults were removed by fishing mortality, changes in the distribution and incidence of juveniles might be shown immediately in the population.

Chilean hake is one of the most important groundfish resources for small-scale fishermen and for an industrial bottom trawl fleet operating off central southern Chile (33° S–42° S), with Valparaíso and Talcahuano as the main ports for landings. It is know that adult hake is distributed on the continental shelf environment, extending between 50 and 400 m depth (Lillo et al. 2007), and is associated with cold, salty, nutrient-rich, oxygen-poor equatorial subsurface waters

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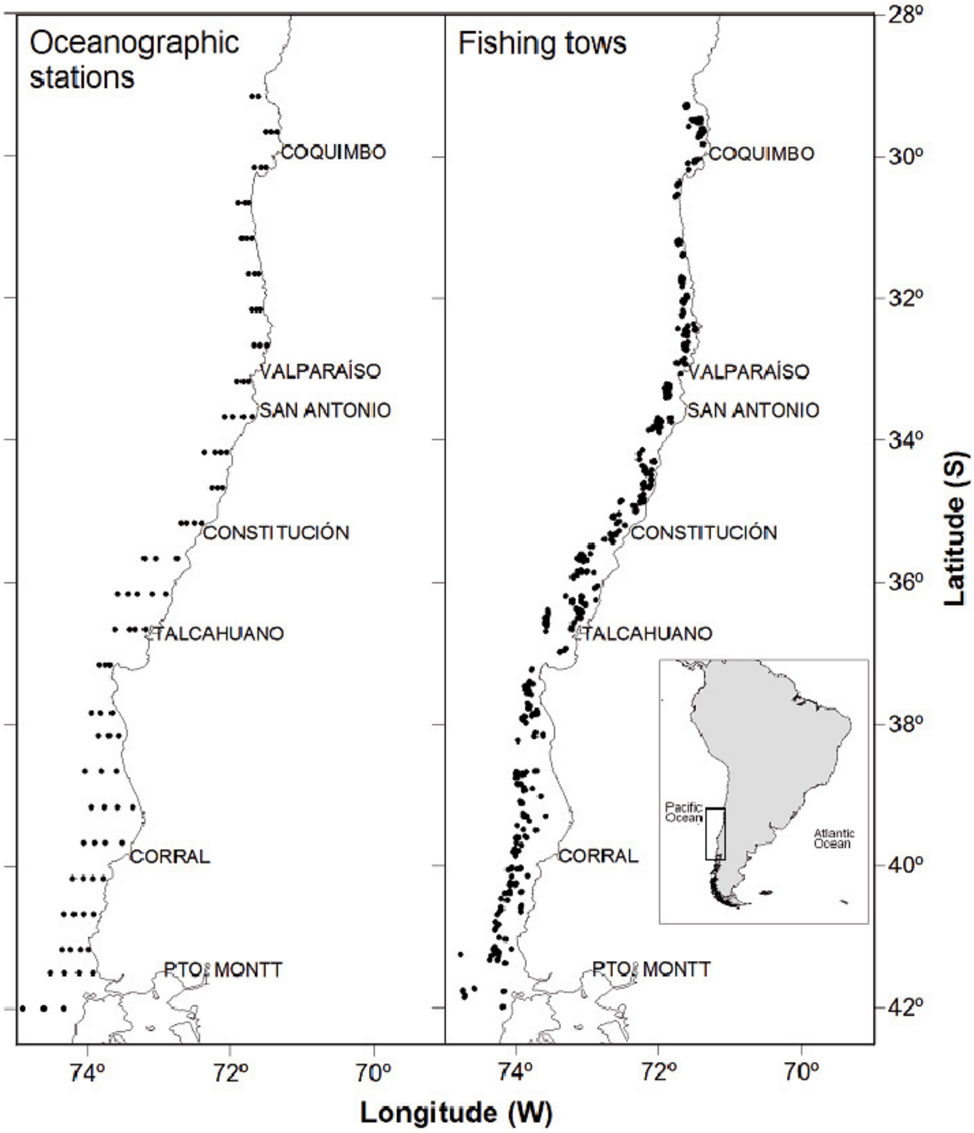

Fig. 1. Study area showing the distribution of oceanographyc stations and fishing tows, period 1997–2006.

(ESSW) flowing southward along the Peru-Chile undercurrent (Silva and Neshyba 1979). Usually, the ESSW occupies the bottom of the continental shelf, and is characterized by low oxygen content (less than 3 ml per L), high salinity (34.7 to 34.9 psu), and temperatures between 11 to 12 °C. Near the continental slope and deeper, waters are influenced by cold (~7 °C) and fresh (34.4 psu) Antarctic intermediate water (AAIW), while shallow and southward waters are usually influenced by cool (~12 °C), fresh (34.25 psu), and oxygenated subantarctic waters (SAW) (Strub et al. 1998). In this way, the environment of the hake's habitat is influenced by the interacting conditions imposed by three water masses, poleward circulation of the Peru-Chile undercurrent, and wind-driven upwelling events that are stronger during summertime. Nevertheless, knowledge of the spatial distribution of juvenile hake is limited, particularly its dependence of key physical characteristics. In this paper, the spatial dependence of juveniles was studied with the aim of identifying which physical factors determine the spatial distribution of the species during winter, based on acoustic surveys carried out between 1997 and 2006.

2 Material and methods

2.1 Study area and data sources

The study area extended from northern Coquimbo (28° 30′ S) to southern Chile (41° S), following the 500 m depth isobath that extends on average 20 nautical miles in the E-W direction (Fig. 1). This is the main distribution area of stocks of

Table 1. Number of tows obtained and used (nearest oceanographic stations), length range and average length of hake in the used tows in each winter acoustic survey.

			Length range (cm)		Average		
Year	Tows obtained	Tows used	Minimum	Maximum	Length (cm)	N° Specimens	Source: Lillo et al.(*)
1997	133	55	12	80	40.6	11 162	1998
1999	136	93	15	88	47.5	9 817	2000
2000	126	87	11	87	40.9	13 905	2001
2001	141	63	12	87	39.3	13 884	2002
2002	151	86	9	91	40.7	17 393	2003
2004	137	75	9	88	31.0	10 377	2005
2005	138	75	7	70	26.9	10 410	2006
2006	135	80	7	73	29.3	11 121	2007

(*) Lillo et al. Evaluaciones hidroacústicas de merluza común from 1998 to 2007, Inf. Téc. FIP-IT, http://www.fip.cl

the hake *Merluccius gayi gayi*, where the presence of southern hake *Merluccius australis* is marginal.

The data used were obtained from eight acoustic surveys carried out in the years from 1997 to 2006, except 1998 and 2003 (Table 1). These acoustic surveys were made in winter (southern hemisphere) on board the Research Vessel Abate Molina. In each survey, oceanographic stations were sampled by CTDO, along E-W transects with a spacing of 30 nautical miles (Fig. 1a). Vertical profiles of temperature (°C), salinity (psu), and dissolved oxygen (ml per L) were registered. To identify the acoustic records, determine the proportion of species, and obtain the length composition of hake that were acoustically registered, a number of fishing tows were conducted in each survey (Fig. 1b), out of which the fishing tows nearest to the oceanographic stations were selected. The total number of tows, selected tows, number of specimens, and range and average lengths of specimens are summarized in Table 1. Fishing tows were obtained with a mid-water trawl net (Engel, circumference with 666 meshes of 90 mm, and 50 mm cod-end), which was trawled at a ground speed of about 3 kt depending on the bottom depth. The operation time for each trawl was 30 min. The starting position of the trawls when the net was at the target depth and the final position at the end of the trawl were recorded to determine the average depth of the trawl.

2.2 Statistical analysis

The generalized additive models (GAM) technique was used to study the spatial dependence of juveniles. We used the "mgcv" package of Wood (2002, 2003, 2006) for the language and software R v. 2.9.2 (Ihaka and Gentleman 1996; http://www.r-project.org) because the "gam" function from the "mgcv" library is very much like the "glm" function of generalized linear models. The presence of juveniles was studied according to the following general model:

$$J = \mu + t + s(x, y) + s(T) + s(S) + s(\mathrm{O}) + s(Z) \sim \text{Binomial} \quad (1)$$

where J is the presence of juveniles (<34 cm total length), μ is the intercept, t is the year effects (as a factor), $s(\bullet)$ is the spline smoother, $s(x, y)$ is a bi-variate spline function that takes into account spatial effects of longitude (x) and latitude (y). T, S, O and Z are temperature (°C), salinity (psu), dissolved oxygen (ml per L), and mean depth of aggregations (m), respectively. Because some environmental variables were correlated, only sub-models based on equation (1) were evaluated. A correlation matrix was obtained to select which combinations of predictor should be incorporated as independent variables. For the dependent variable, a binomial error distribution with a "logit" link was used. To do this, fish shorter than 34 cm total length were assigned to one and the other data were assigned to zero for adults. This choice of size was based on recent estimates of the length at which 50% females are mature (Lillo et al. 2009a, 2009b). We used the "mgcv" library because it implements an automatic selection of the smoothing parameters associated with each smooth term on the basis of generalized cross-validation (GCV). Basically, cross-validation involves leaving one of the data-points out, fitting the model to the remaining data, and then computing the squared difference between those points. This procedure is repeated for all data-points and for several amounts of smoothing, with the smaller squared differences hence indicating a better model (Wood and Augustin 2002; Wood 2006). In this case, unbiased risk estimator (UBRE) score was used (Wood 2006). Also, the explained deviance and the Akaike Information Criterion (AIC) were used to select the best competing GAM model.

3 Results

From 1997 to 2002, the fraction of juvenile hake was restricted to the coast and northward of the study area; in 1997, 2000, and 2002 it was also distributed southward. A virtual absence of juveniles occurred in the central part (33° S–39° S) of the study area from 1997 to 2002, but juveniles were distributed throughout the study area from 2004 to 2006 (Fig. 2).

The year factor and latitude-longitude effects were more important predictors explaining inter-annual changes and spatial distribution of the presence of juveniles, with 21.5 and 10.1% of explained deviance (Model 1 and 2, Table 2). Single physical predictors such as temperature (Model 3) and depth of aggregations (Model 6) explained 9.9 and 9.2% of the deviance, respectively (Table 2). The effects of single physical predictors on presence of juvenile were essentially nonlinear. In this way, the presence of juveniles was very low for temperatures <7 °C, and temperatures higher than 7 °C had positive

Table 2. Models evaluated to explain the presence of juvenile hake during the austral winter, J = presence of juvenile hake, t = year factors, x = longitude, y = latitude, T = temperature (°C), S = salinity (psu), O = oxygen (ml per L), Z = depth of aggregations (m), μ = overall mean, and $s(\bullet)$ = spline smoother.

Models	Unbiased risk estimator (UBRE) score	Deviance explained (%)	AIC
M01 $J = \mu + t$	3.2963	21.5	103 385.8
M02 $J = \mu + s(x, y)$	3.9189	10.1	118 368.3
M03 $J = \mu + s(T)$	3.9272	9.9	118 568.0
M04 $J = \mu + s(S)$	4.2848	3.4	127 173.4
M05 $J = \mu + s(\mathrm{O})$	4.3906	1.5	129 720.2
M06 $J = \mu + s(Z)$	3.9658	9.2	119 496.8
M07 $J = \mu + t + s(x, y) + s(T)$	2.3807	38.3	81 354.0
M08 $J = \mu + t + s(x, y) + s(S)$	2.6267	33.8	87 274.0
M09 $J = \mu + t + s(x, y) + s(\mathrm{O})$	2.7044	32.3	89 143.8
M10 $J = \mu + t + s(x, y) + s(Z)$	2.2772	40.1	78 863.6
M11 $J = \mu + t + s(x, y) + s(T) + s(S)$	2.3401	39.0	80 377.2
M12 $J = \mu + t + s(x, y) + s(T) + s(\mathrm{O})$	2.3558	38.7	80 753.8
M13 $J = \mu + t + s(x, y) + s(S) + s(Z)$	2.2493	40.7	78 190.5
M14 $J = \mu + t + s(x, y) + s(\mathrm{O}) + s(Z)$	2.2531	40.6	78 282.8
M15 $J = \mu + t + s(T) + s(S)$	2.7027	32.3	89 101.1
M16 $J = \mu + t + s(T) + s(\mathrm{O})$	2.6944	32.5	88 901.4

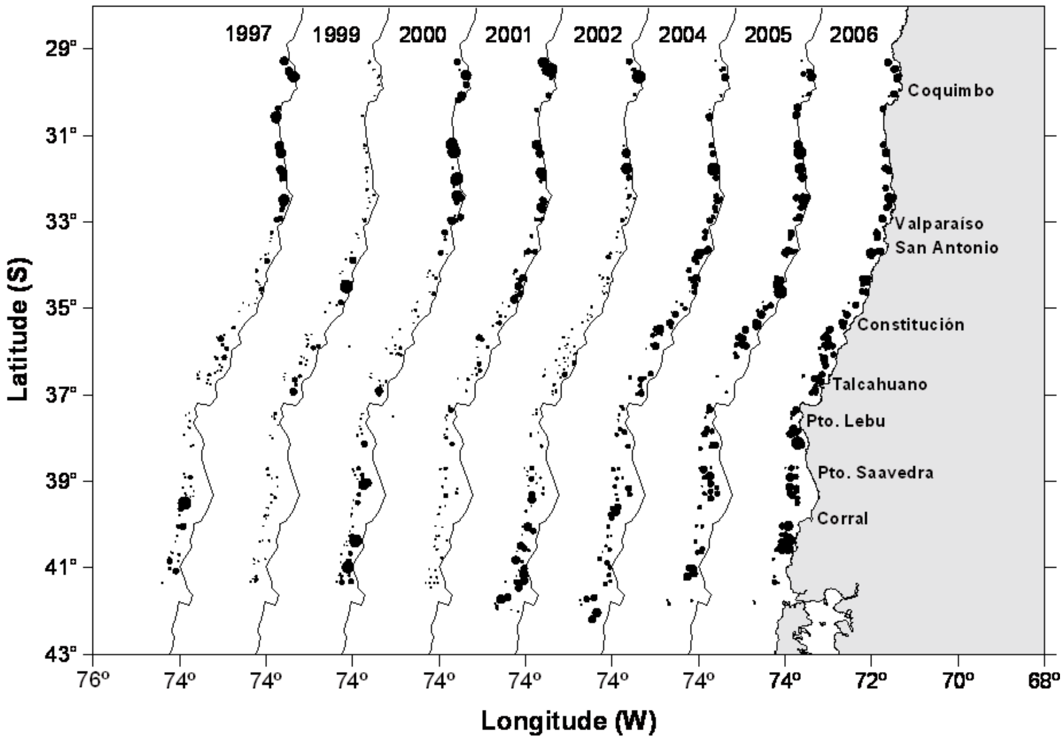

Fig. 2. Spatial distribution of juvenile hake (<34 cm TL) in the fishing tows obtained during each survey. Size of the solid circles is proportional to the presence of juvenile hake in each fishing tow.

effects on juvenile hake presence with a peak close to 12 °C. In contrast, salinity had a "V" shape effect on the presence of juvenile hake, with very low presence in the range between 34.3 to 34.6 psu. Some small secondary peaks in the presence of juveniles were also observed for oxygen levels below 3 ml per L, but presence was positively related to oxygenated waters (O_2 > 3 ml per L). Finally, juveniles were located shallower in the water column (Fig. 3).

The correlation among predictor variables revealed high negative correlations between temperature and depth of aggregations, and between oxygen and salinity (Table 3). Higher positive correlations occurred between latitude and longitude and between salinity and latitude, while a negative correlation was found between oxygen and latitude (Table 3). Southern waters were fresher, colder and more oxygenated than northern waters (Fig. 4). The models with more than one environmental

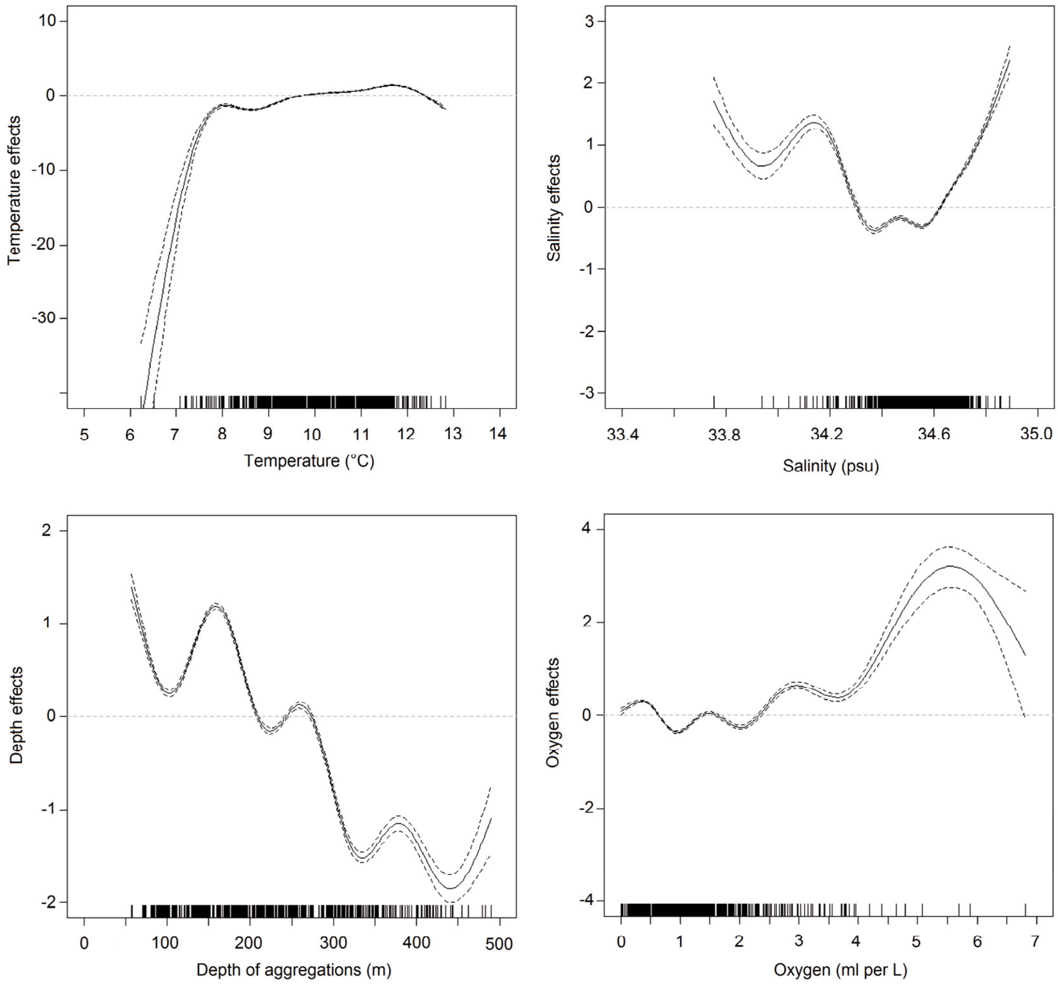

Fig. 3. Relationships between presence of juvenile hake and single physical variables: temperature, salinity, depth of aggregations and oxygen (1997–2006).

Table 3. Coefficients of correlation obtained for pairs of predictor variables available to study the spatial distribution of juvenile hake.

	x (°W)	y (°S)	Z (m)	T (°C)	S (psu)	O (ml per L)
t	–0.090	–0.081	–0.021	–0.055	0.054	–0.068
x		**0.958**	0.166	0.263	**0.489**	**–0.369**
y			0.270	0.200	**0.520**	**–0.428**
Z				**–0.756**	0.137	–0.308
T					0.236	–0.008
S						**–0.762**

variable were evaluated by avoiding the correlation between predictors and according with the explained deviance and AIC. Model 13 was the best for explaining the presence of juveniles, i.e., yearly factors, spatial location, depth of aggregations, and salinity (Table 2). The temporal changes in the presence of juveniles showed an important change in presence of juvenile hake since 2004 (Fig. 5). In general, juveniles tend to be distributed northward (29° S–32° S), southward (39° S–41° S) and in the shallower water during winter in the study area (Fig. 6). Model 14 had similar explained deviance and AIC (Table 2); it also considered depth of aggregations and oxygen (Table 2), although oxygen was negatively correlated with salinity. The contribution of additional physical variables (salinity or oxygen) to year factors and spatial interaction was marginal but noticeable.

4 Discussion

An important change has occurred in the presence of juveniles in the Chilean hake stock since 2004. This change coincided with a dramatic decline in the biomass of adults (Lillo et al. 2007). The acoustic biomass declined from 0.9–1.5 million tons in the period 2000–2002 to 0.27 million tons in 2004, and then fluctuated around 0.3 million tons between 2005 and 2006 (Lillo et al. 2007). The length composition of hake has also changed since 2004, as reflected in the average length and in the length ranges. This was also evident in abundance in terms of age composition: while ages 1 to 3 have dominated in abundance since 2004, ages 4–6 were dominant in the population before 2004 (Lillo et al. 2007). This is probably the reason why temporal and spatial changes were more important in explaining the presence of juveniles than a single

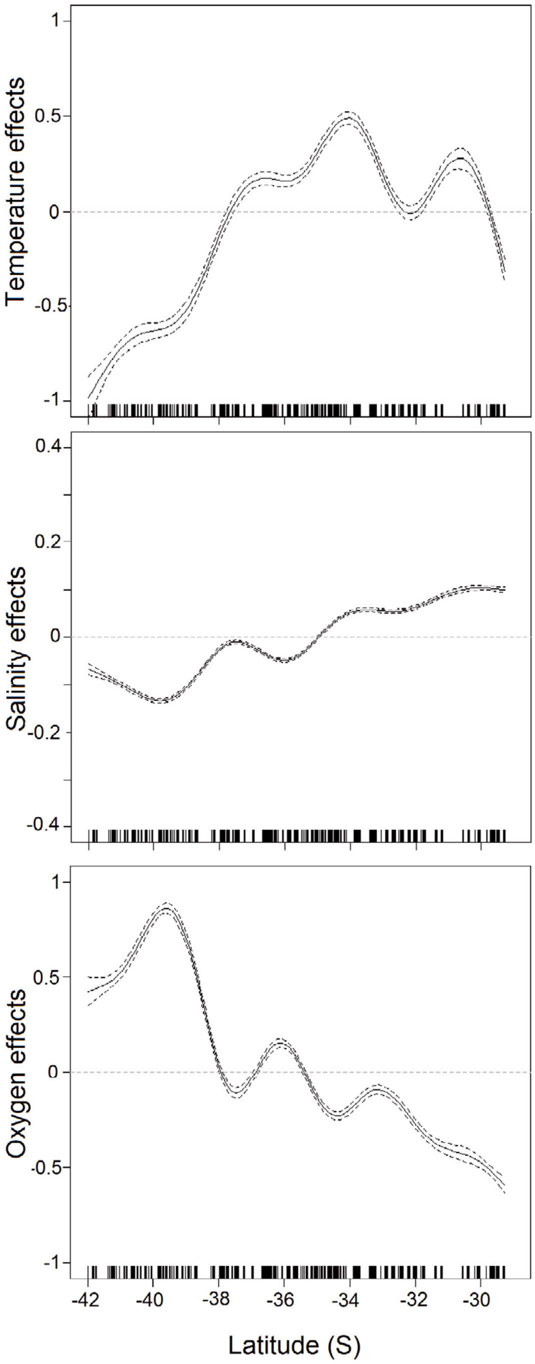

Fig. 4. Latitudinal trends for temperature, salinity, and oxygen (1997–2006).

physical variable. Depth of aggregations was secondary in importance, and contributed significantly to explain presence of juveniles. Clearly, juvenile hake prefer shallow waters, from 50 to 225 m. This preference for lower depth is in agreement with other species such as the European hake *Merluccius merluccius* (Bartolino et al. 2008). Of course, adults prefer deeper waters since they represent the complement of the metric here used, and some ontogenetic migration might occur from the upper shelf to the lower shelf, and to the upper slope of the shelf.

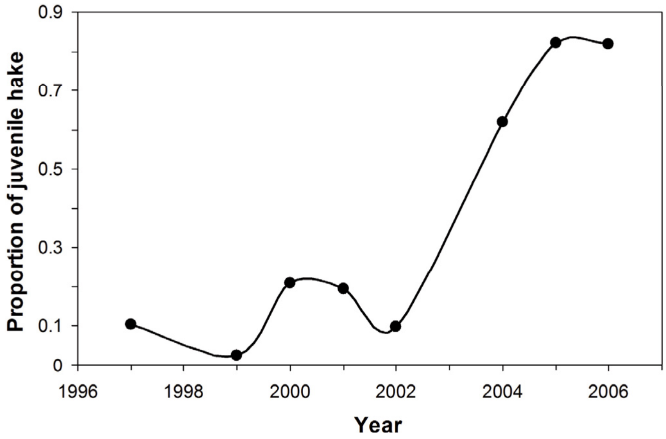

Fig. 5. Proportion of juvenile hake in the surveys, as estimated for the year factor with Model 13 (Table 4).

The spatial pattern obtained represents an average probability map of fish shorter than 34 cm total length. Zones with high probability of juveniles can be recognized and located in both northern (29° S–32° S) and southern (39° S–41° S) parts of the study area, and those with low probability in the centre (33° S−37° S). The physical conditions in these extreme zones are different, as evidenced through the correlations between salinity and latitude ($r = 0.520$) and between oxygen and latitude ($r = -0.428$). Salty waters tend to be distributed northward, and fresh waters tend to be found southward. This gradient is consistent with heavy precipitation and river runoff during winter in the southern zone (Faúndez-Báez et al. 2001; Quiñones and Montes 2001), and also with stronger influence of subantarctic waters (SAW). The continental shelf is also wider in the central part, particularly between 34° S and 36° S (Escribano et al. 2004), where larger adult fish can predate on benthic decapod crustacea, mainly Galatheids such as squat-lobsters *Pleurodes monodon* and *Cervimunida johni*, the stomatopod *Pterygosqilla armata*, and clupeoids *Strangomera bentincki* and *Engraulis ringens* (Arancibia and Fuentealba 1993; Cubillos et al. 2003). In contrast, in the northern part of the study area (29° S–33° S), the continental shelf is virtually absent and juvenile hake can probably find refuge from cannibalism by adults, which had preference for the central part of the study area.

The presence of juveniles is associated with three peaks of salinity. Juveniles in the southern part of the study area (39° S–41° S) are associated with shallow, fresh (peak in 34 psu) oxygenated waters (3.5 to 5.5 ml per L). This pelagic environment contrasts with the central (33° S–37° S) and northern zones. In the central zone, the presence of juveniles is lower and distributed on the continental shelf, where a mix between SAW and Equatorial subsurface waters (ESSW) prevails that could explain the second marginal peak observed in salinity (i.e., at 34.5 psu). The third peak in presence of juveniles tends to be associated with salty waters (<34.8 psu), reflecting the influences of the ESSW, probably due to the high presence of juveniles in the northern zone. Nevertheless, due to the low deviance explained by salinity and oxygen, those nonlinear relationships between presence of juvenile and these parameters could only reflect the collapsing influence of the three water

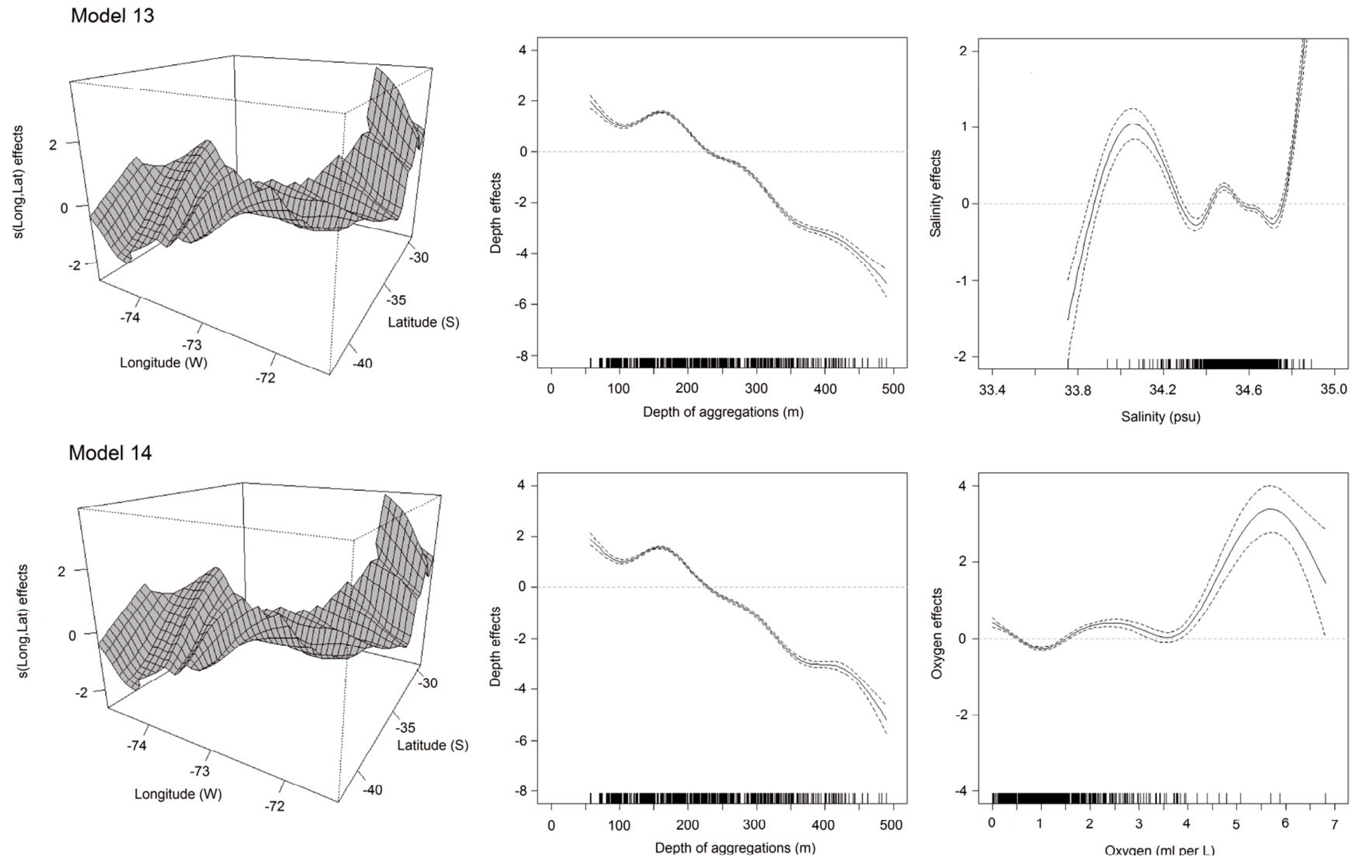

Fig. 6. Relationships between presence of juvenile hake and predictors used in Model 13 and Model 14 (1997–2006).

masses present on the continental shelf and in the water column during the austral winter. Thus, it is hypothesized that changes detected in the presence of juvenile hake could be a response associated with less cannibalism by adults, which could be a fishery-induced demographic impact on the population.

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