PANAMJAS
Pan-American Journal of Aquatic Sciences

Offshore spawning of the Argentine hake (*Merluccius hubbsi*) Patagonian stock

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Abstract: The spatial variation of the spawning shoals of *M. hubbsi* in Patagonia during its reproductive peak (January) between 2001 and 2008 was analyzed. In 2001 and 2004 spawning of hake in the north-patagonian area was concentrated inshore between 50 m and 80 m depths, in coincidence with a bottom thermal front (9° - 14° C). Since 2005 an expansion of spawning into deeper waters (near the 100 m isobath), where bottom temperature ranged between 6° and 8° C, was observed. This offshore group was characterized by a high proportion of females (0.58 – 0.78), larger (modes 53 – 62 cm TL) than those of the coastal region (modes 40 – 45 cm TL). The relative fecundity and oocyte dry weight values were lower in the offshore spawning area than those obtained for the inshore reproductive ground. This observation could indicate that the offshore group corresponds to hake females at the end of spawning in migration to deeper waters.

Key words: reproduction, post-spawning migration, fecundity, temperature, salinity

Resumen. Desove del efectivo patagónico de merluza común (*Merluccius hubbsi*) en aguas alejadas de la costa. Se analiza la variación espacial de los cardúmenes desovantes de *M. hubbsi* en el área patagónica durante su pico reproductivo (enero) entre 2001 y 2008. En 2001 y 2004 el desove de la merluza en la región nor-patagónica estuvo concentrado en la zona más costera, entre 50 m y 80 m de profundidad, en coincidencia con un frente térmico de fondo (9° - 14° C). A partir de 2005 comienza a observarse una expansión del desove hacia aguas más profundas (cercano a la isobata de 100 m), donde la temperatura de fondo oscila entre 6° y 8° C. Este grupo desovante externo se caracterizó por una alta proporción de hembras (0,58 – 0,78), de mayor tamaño (modos 53 – 62 cm LT) que las muestreadas en la región costera (modos 40 – 45 cm LT). La fecundidad relativa y el peso seco ovocitario fueron más bajos en los desovantes del sector externo que los estimados para los reproductores del área más costera. Esto podría indicar que el grupo externo corresponde a hembras de merluza en el final de la estación reproductiva, en migración hacia aguas más profundas.

Palabras clave: reproducción, migración post-desove, fecundidad, temperatura, salinidad

Introduction

The Argentine hake (*Merluccius hubbsi*) is a demersal species distributed in waters of the Southwest Atlantic Ocean from 22° to 55° S, at depths ranging between 50 and 500 m (Cousseau & Perrota 1998). This species is one of the most abundant fish resources in the Argentine Sea, where its biomass has reached annual values between one and two million metric tons during the early 90´s (Aubone *et al*. 2004). In this area, two main stocks were identified: the northern group (between 34° and 41° S) and the southern group (between 41° and 55° S). The last one, known also as the Patagonian stock, economically is the most important, with a spawning biomass of around 400.000 t estimated from Virtual Population Analysis (VPA) during

2007 (Renzi & Irusta 2007).

Spawning of *M. hubbsi* of the Patagonian stock occurs in waters off the Chubut province during (austral) spring and summer, with a main peak between December and January (Macchi *et al*. 2007). These authors described the traditional reproductive cycle of this stock, characterized by a movement of pre-spawning aggregations in October from deeper waters (more than 100 m depths) toward the coast (close to the 50 m isobath), where reproduction takes place. Spawning begins in November-December in the area known as Isla Escondida (43°30' - 44° S), and one month later the most abundant reproductive shoals move toward the south following the 50 m isobath to Camarones Bay (44°30' - 45° S). In this area, during January, it takes place the main reproductive activity of the hake, but in February the density of the shoals begins to decrease as consequence of displacements of this species offshore after spawning. Macchi *et al*. (2007) suggested that latitudinal variations of the main hake schools during the breeding season would be associated with the optimal temperature range for reproduction and survival of the early life stages.

During the 1980's, spawning of Argentine hake in Isla Escondida were characterized by large and dense schools sited near the coast (Aubone *et al*. 2004), but since the middle of the 1990's a decrease in fish abundance and variations in the spatial pattern of hake spawning aggregations were observed (Macchi *et al*. 2005). These changes were described as displacements of spawning females offshore with a more scattered distribution.

Recent studies suggest a strengthening of this pattern of reproductive behavior of the Argentine hake Patagonian stock, showing a wide spatial dispersion of spawning females during the last years, mainly towards deeper waters (Macchi *et al*. 2008). Being the reproduction of these individuals successful, this process and the larval development would occur at temperatures much lower than those previously reported for *M. hubbsi*. If so, growing and survival of the early life stages could be affected, increasing pre-recruitment mortality of this species

In this paper spatial variations of the spawning shoals of *M. hubbsi* in Patagonia during its reproductive peak in January between 2001 and 2008 was analyzed. Annual changes in frequency and density of ripe females and its association with environmental variables were studied.

Materials and Methods

Samples of *Merluccius hubbsi* were collected from bottom trawl performed during six research surveys carried out in the northern-Patagonian area during January between 2001 and 2008 (Table I). Extension of the sampling area and position of the trawl stations were similar during all analyzed years, except for 2004 when no data was collected southwards of 45°30' S, in the San Jorge Gulf (Fig. 1). However, in this area during January scarce or null reproductive activity of Argentine hake has been observed (Macchi *et al*. 2004).

Table I. Number of trawls stations, Argentine hake individuals sampled and ovaries collected during January in the different years analyzed.

Years	Sampling trawls	Individuals sampled	Ovaries collected
2001	58	19 786	1056
2004	41	13 941	886
2005	56	14 811	977
2006	64	15 176	1138
2007	64	11 455	990
2008	61	12 820	968

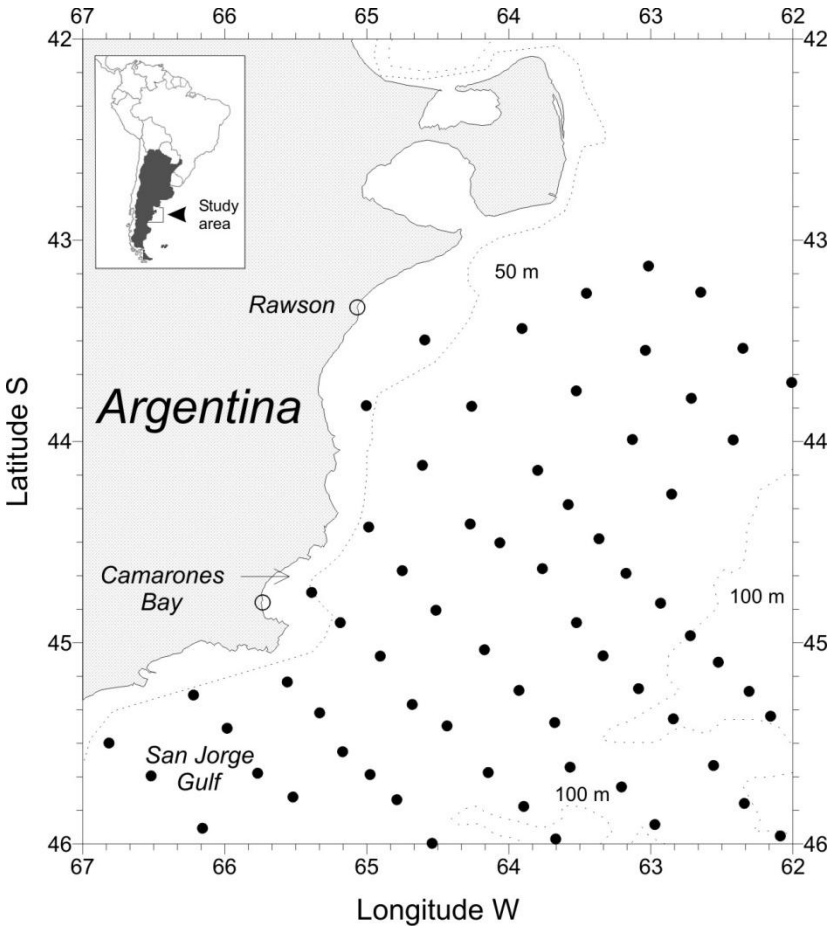

Figure 1. Samples location of *M. hubbsi* collected in the north Patagonian area during January for the years 2001 to 2008.

During each sampling station salinity and temperature data were collected using a Sea-Bird 19 CTD (conductivity–temperature–depth profiler). Data series were filtered and reduced to values of temperature and salinity according to a 1 db interval. Row data from the CTD were calibrated by measuring water samples with a salinometer. Because of *M. hubbsi* is a demersal species that aggregates near the bottom during day-time, we employed only data from this zone to analyze oceanographic information in relation to spawning activity.

Argentine hake specimens were captured at depths between 50 m and 110 m by using a bottom-trawl net with a mouth width of about 20 m, a height of about 4 m, and with a 20 mm mesh at the inner cover of the cod-end. Speed and time of the fishing trawls was about 4 knots and 30 minutes, respectively. Samples were weighed and later total length (TL) in cm, sex and maturity stage were recorded for each fish (Table I). A macroscopic maturity key of five stages designed for biological studies was employed: 1) immature, 2) developing and partially spent, 3) spawning (ripe and running), 4) spent and 5) resting (Macchi & Pájaro 2003a).

In addition, ovaries of adult females were collected from different trawl stations (about 30 females per station) and preserved in 10 % neutral-buffered formalin for histological analysis (Table I). A total of 6 015 ovaries were weighed (GW) to the nearest 0.1 g and a portion of sample (about 2.0 g) was removed from each gonad, dehydrated in ethanol, cleared in xylol and embedded in paraffin. Sections were cut at 5-µm thickness and stained with Harris's hematoxylin followed by eosin counterstain. Histological diagnosis was used to validate the macroscopic stage, mainly in the case of spawning and post-spawning individuals. Ripe females were characterized by ovaries with abundant hydrated oocytes, which are evidence of imminent spawning, while specimens with new (day-0) postovulatory follicles (POF) and hydrated oocytes were considered spawning females. Both histological diagnostics correspond to the stage 3 of the macrospic maturity key, characterized by the presence of hydrated oocytes. Macchi *et al*. (2004), based on the criteria suggested by Hunter & Macewicz (1985), classified as post-spawning

females those individuals with more than 50% of yolked oocytes in atresia, which correspond to the macroscopic stage 4 (spent).

Spatial distribution of the histological maturity stages, expressed as a simple percentage, and the proportion of spawning females (macroscopic stage 3) weighed by the fish density were used as indices to define the hake spawning areas. Fish density, expressed as hake tons per surface unit (t/nautical mile^2), was obtained from catch values per swept area estimated from each sampling station.

According to the abundance of females in macroscopic stage 3 (with hydrated oocytes) two main spawning aggregations were identified: the inshore group (IS) sited in front of Camarones Bay and the offshore group (OS), between 45° S and 46° S near the 100 m isobath. With the aim to compare both spawning aggregations, two mini-areas composed by the same sampling stations performed every year were defined (Fig. 5). Because offshore spawning began to be evident from 2005 on, the comparison was carried out only with data collected from that year to 2008. Sex ratio estimated from adult fish (macroscopic maturity stages 2 to 5) and female length distribution for each reproductive group were analyzed during these years. This analysis was performed with samples collected in 12 trawl stations (6 from each spawning area); in total 25,725 individuals were used (Table II). To differentiate adult and juvenile hake females within size distributions the length limit was established as 33 cm TL, because it is the mean length at first maturity estimated for the Patagonian hake stock during the spawning peak (Macchi *et al*., 2007).

Table II. Female proportions (FP) estimated for the inshore and offshore spawning groups of Argentine hake in January during the different years analyzed.

	Inshore	spawning	Offshore	spawning
Years	FP	n	FP	n
2005	0.25	2193	0.47	4360
2006	0.43	3102	0.58	4651
2007	0.44	1686	0.78	4165
2008	0.25	2509	0.71	3059

Females with hydrated oocytes from each reproductive area were collected and the ovaries preserved in 10 % neutral-buffered formalin to estimate relative batch fecundity (RF). After histological diagnosis 160 ovaries without evidence of recent spawning (no POF) were selected from the inshore (n = 93) and offshore (n = 67) spawning areas. The methodology used to estimate RF by the gravimetric method has been developed by Hunter & Goldberg (1980) and described for different species (Macchi 1998, Macchi & Acha, 2000, Macchi *et al*. 2004). A t-test was applied to compare the RF mean values estimated from each spawning area (IS and OS) during the different sampling years, previous to test normality and variance homogeneity by a f-test (Sokal & Rohlf 1969).

During January 2007 and 2008, it was possible to collect samples of hydrated oocytes to estimate the oocyte dry weight of females (DW) as an index of egg quality from the different spawning groups. For this, a sample of 100 hydrated oocytes was removed from the central part of each gonad selected in the inshore (n = 45) and offshore (n = 48) spawning areas. These oocyte samples were rinsed in distilled water, dried for 24 h at 60° C and weighed (± 0.1 mg). Later, a comparison of the DW mean values estimated from each spawning area (IS and OS) during 2007 and 2008 was carried out using the same methodology described for RF.

Results

Spatial distribution of ripe, spawning and post-spawning females

Spatial coincidence between the proportions of ripe and spawning females determined by histological diagnosis was observed, which evidence that both stages may be used as indices of reproductive activity (Fig. 2). In 2001 and 2004 spawning of hake in the north-patagonian area was mainly concentrated close to the 50 m isobath between 43° and 45° S, showing a high proportion of females with hydrated oocytes and day-0 POF in Camarones Bay. During these years spatial distribution of spawning females was more reduced than in the rest of the period analyzed, as was also evidenced by the high proportion of post-spawning females with advanced atresia throughout the sampled region, mainly in deeper waters (Fig. 2).

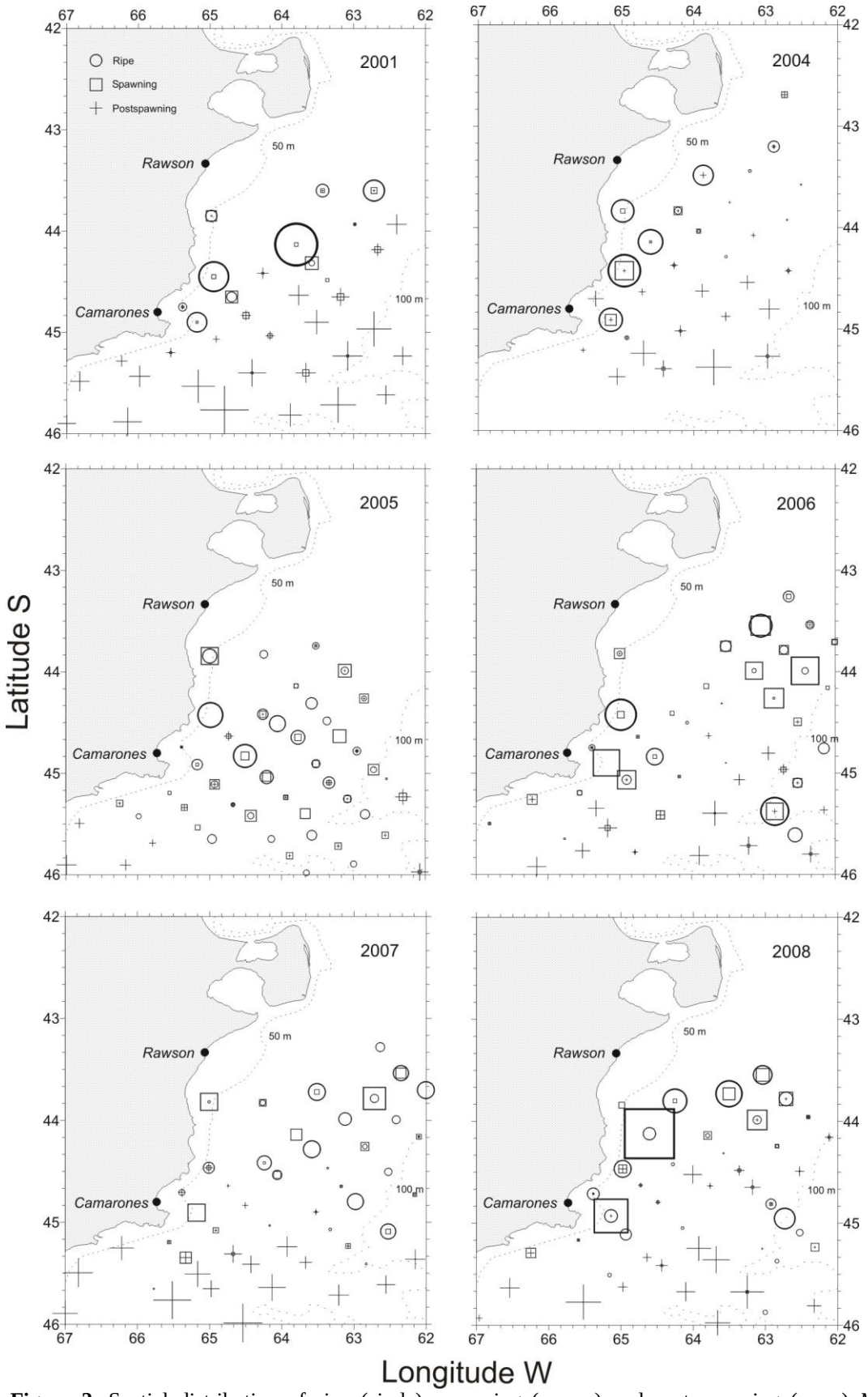

Figure 2. Spatial distribution of ripe (circle), spawning (square) and post-spawning (cross) *M. hubbsi* females, determined by histological analysis, during January for the years 2001 to 2008. The size of the symbols represents the percentage of each maturity stage.

In January 2005, an expansion of the hake reproductive area was observed, with ripe and spawning females distributed from the coast to the 100 m isobath and with low proportions of the advanced atresia stage (Fig. 2). However, reproductive activity was most important in the southern area near Camarones Bay, as in January 2001 and 2004.

In 2006 three main spawning groups were detected in the north-patagonian area, one northwards of 44° S far away from the coast, another in Camarones Bay close to the 50 m isobath and the last one offshore between 45° and 46° S, near the 100 m isobath (Fig. 2). During this year the reproductive area was characterized by a low incidence of atresia as in 2005.

During January 2007 distribution of females with hydrated oocytes and day-0 POF was similar to that described for 2006, but no defined spawning groups were observed. Post-spawning individuals were mainly detected south of 45° S (Fig. 2)

In 2008 the highest proportions of females with hydrated oocytes and day-0 POF were observed inshore as in 2001 and 2004, but the offshore spawning group near the 100 m isobath remained in a position similar to that described during 2006 and 2007 (Fig. 2). The incidence of post-spawning females was higher south of 45° S, as in the two previous years.

Frequency and abundance of spawning females in relation to temperature and salinity.

The relationship between frequency of sampling trawls with spawning females (stage 3 of the macroscopic key) and the bottom temperature and salinity was analyzed (Fig. 3). During 2001 and 2004, stations with spawning females dominated in areas with temperatures and salinities between 9 - 14 °C and 33.40 - 33.60, respectively (Fig. 3). Since 2005, with the expansion of the spawning area, frequency of spawning females increased at temperatures lower than 10 °C, and this pattern persisted during the following years sampled.

During January 2005 and 2006 high frequencies of trawl stations with spawning females at salinities lower than 33.40 were observed, while in 2007 and 2008 this pattern changed, showing more stations with females in stage 3 at salinities between 33.40 and 33.55 (Fig. 3).

Abundance of spawning females (stage 3) in relation to temperature and salinity data showed variations during the different years analyzed, with a similar pattern to that described for the frequency of stations with spawning females. In 2001 and 2004 the highest densities were observed at higher temperatures and salinities, in particular during the last year, when spawning females were found mainly between 12 and 14 °C, at salinities higher than 33.40 (Fig. 4). During January 2005 spawning females were observed in a wide temperature range (from 7 to 13 °C), but the most important aggregations were detected between 8 and 10 °C, at salinities lower than 33.40 (Fig. 4). One year later the temperature and salinity ranges were similar than those of 2005, but the most important reproductive aggregation was observed at temperatures higher than 10 °C and a little spawning group was detected between 7 and 8 °C. In January 2007 and 2008 the secondary female group at low temperatures was composed by more dense spawning shoals, but they were observed at salinities higher than in 2006 (Fig. 4).

In spite of the wide temperature range in which was possible to detect spawning females of hake since January 2005, during the last three years analyzed a similar spatial pattern between both variables was observed; it was characterized by two main spawning aggregation: the principal group at temperatures higher than 10 °C, near the coast mainly in front of Camarones Bay (IS), and the secondary group at temperatures between 6 and 8 °C (OS), sited close to the 100 m isobath (Fig. 5).

The IS group in general was coincident with the bottom thermal front of the nor-patagonian area, which is sited parallel to the coastline following the bathimetry and showing a NE –SW alignment between Rawson and Camarones Bay (Fig. 5). It is located offshore in the northern area but approaches shore southwards, showing horizontal temperature gradients ranging between 10 °C and 13 °C.

Comparison between the spawning aggregation of Camarones Bay (IS) and the offshore group (OS)

Sex ratio estimated from samples collected for each mini-area (IS and OS) during January between 2005 and 2008 (Table II), showed always lower female proportion in the reproductive aggregation of Camarones Bay than in the OS area. In contrast, an increase in female proportion was observed in the OS group since 2005.

Length distributions of females from both spawning aggregations in general were dominated by adult individuals (>33 cm TL), although the structure of each group during the different years analyzed showed variations. In 2005 and 2006, the IS and OS areas were characterized by young

spawners with modes between 40 and 42 cm TL (Fig. 6). During January 2007 the length distribution of the IS group was similar than those of the two previous years, with young adult individuals; nevertheless, the OS area was dominated by larger females with modes between 53 cm and 58 cm TL (Fig. 6). In January 2008 the spatial difference in size composition remained as in 2007, with larger females (modes between 56 cm and 62 cm TL) offshore and young spawners inshore. Nevertheless, in contrast to previous years, the coastal spawning area was also characterized by the presence of juvenile groups with modes in 20 cm and 32 cm TL (Fig. 6).

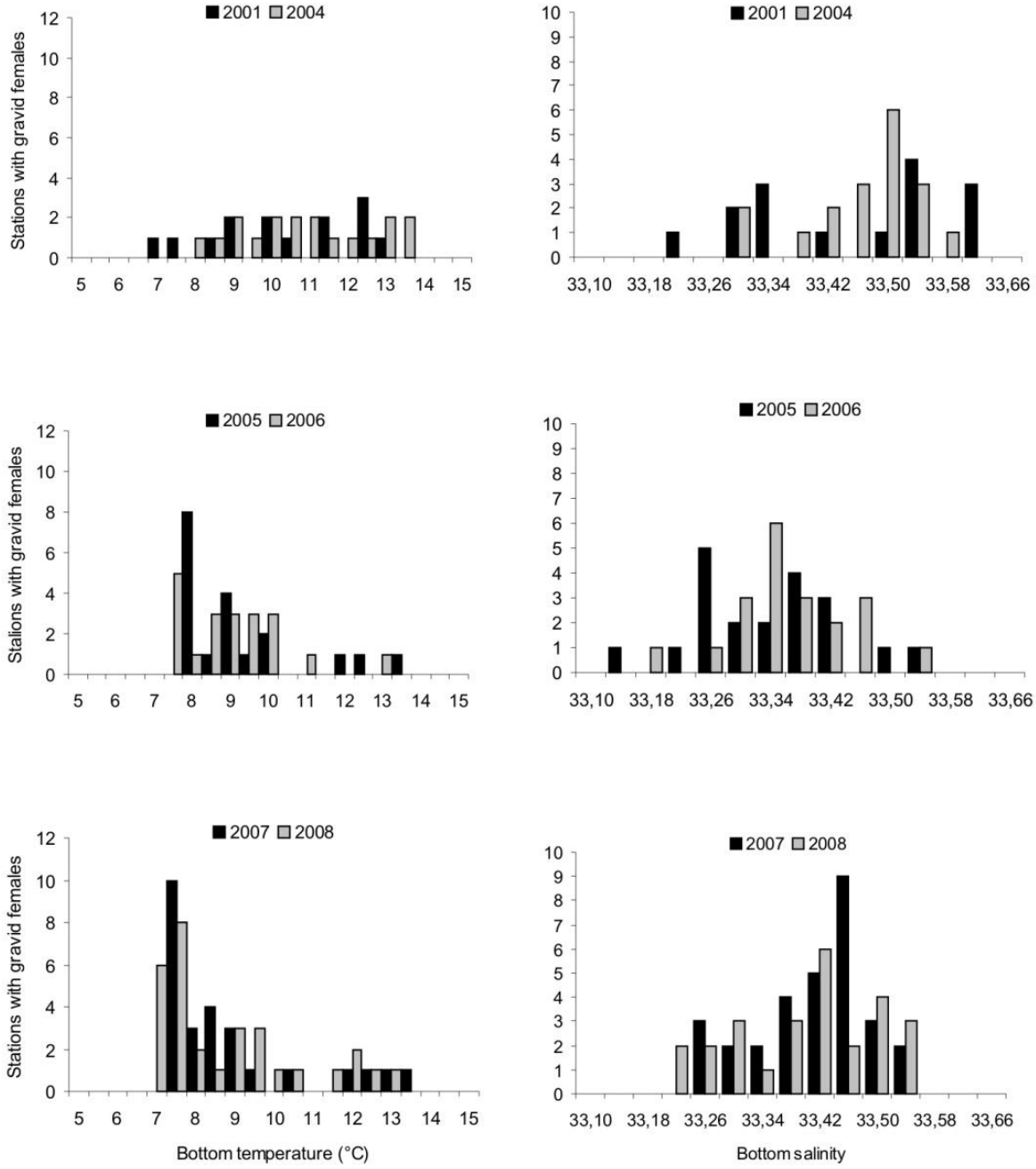

Figure 3. Absolute frequency distribution of sampling trawls with presence of *M. hubbsi* spawning females (macroscopic stage 3) in function of bottom temperature and salinity during January for the years 2001 to 2008.

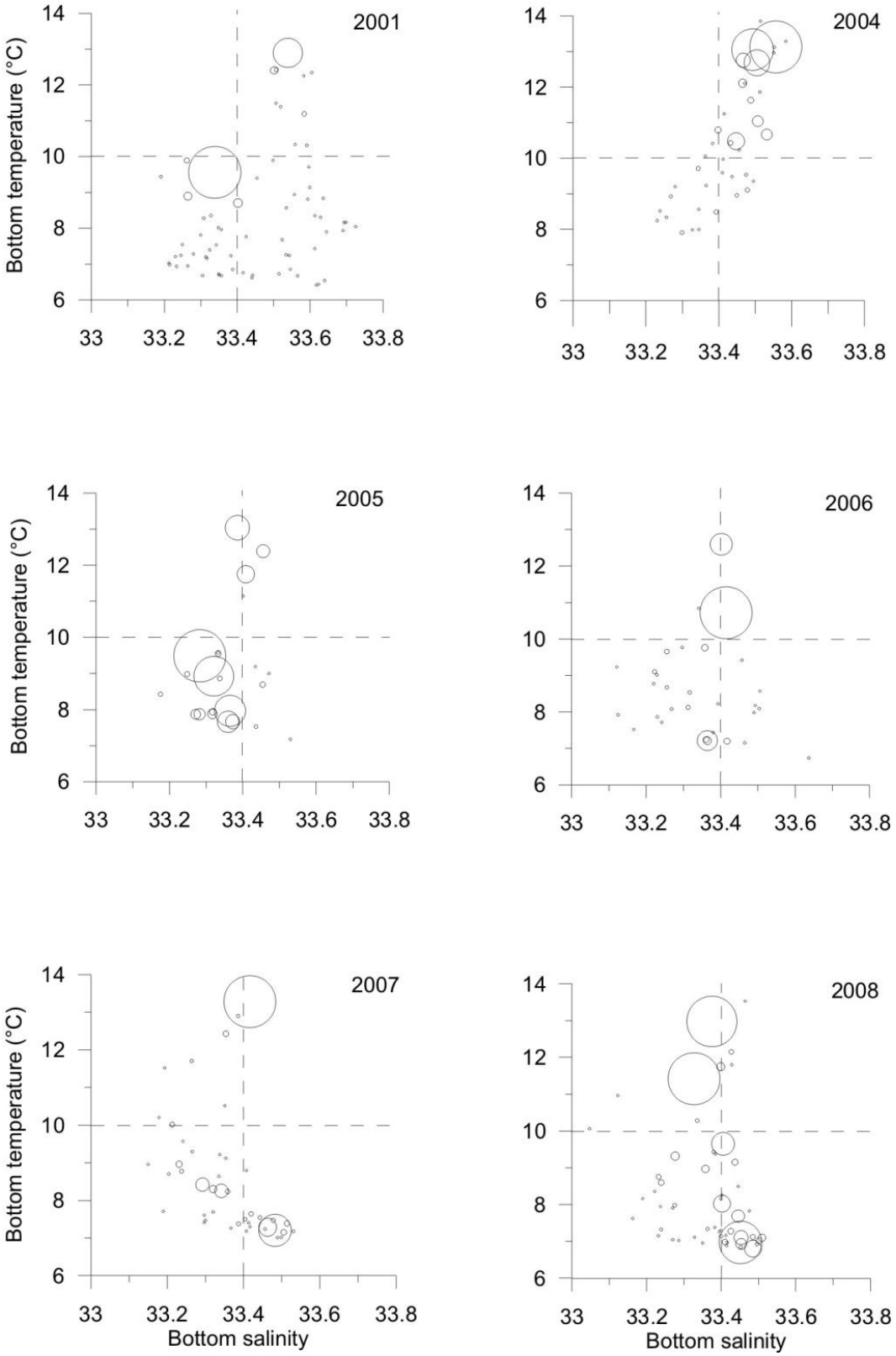

Figure 4. Abundance of *M. hubbsi* spawning females (macroscopic stage 3) in function of bottom temperature and salinity ranges during January for the years 2001 to 2008. The size of the circles is proportional to the density (t/mn^2) of females with hydrated oocytes.

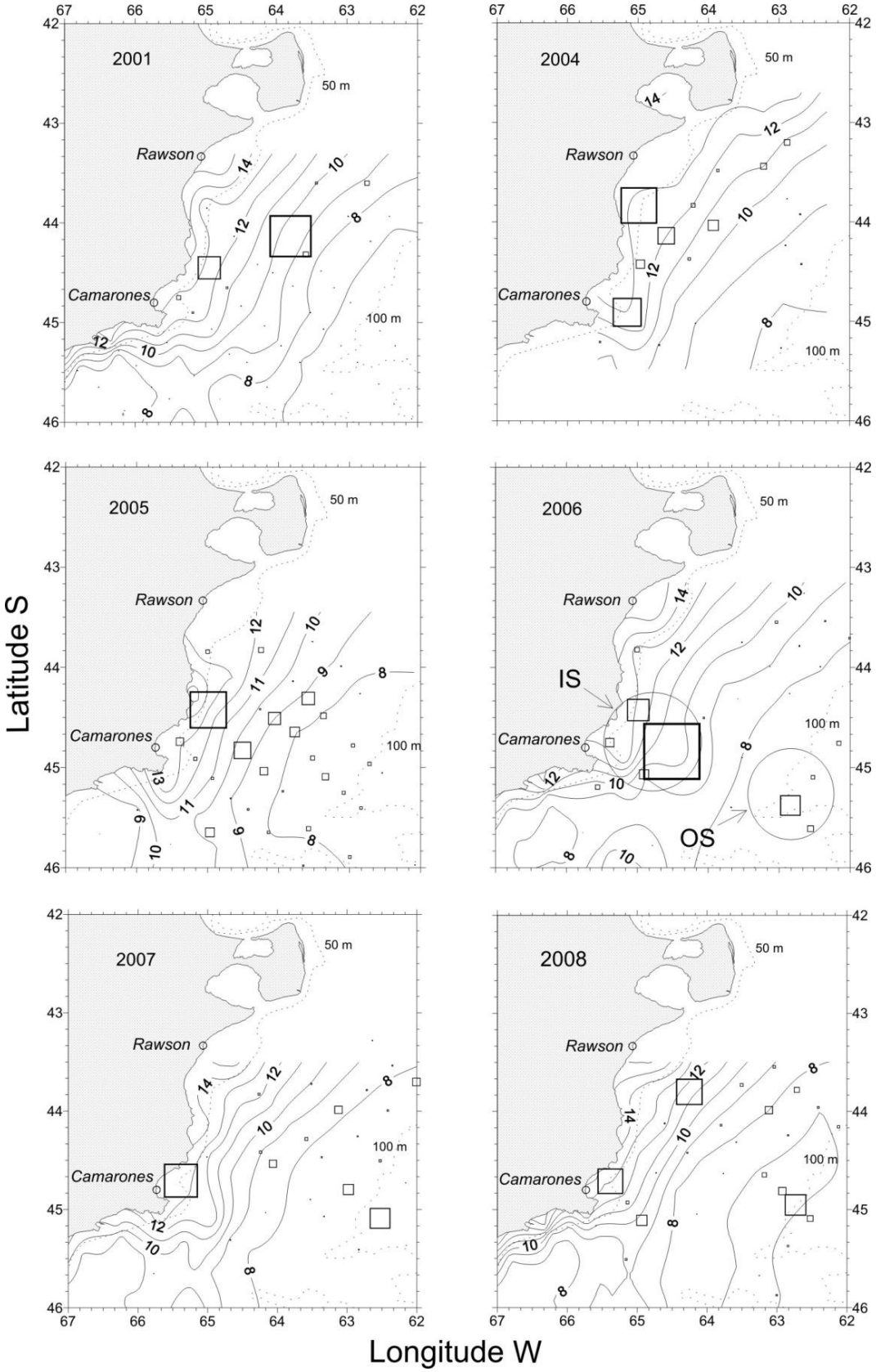

Figure 5. Spatial distribution of *M. hubbsi* spawning females (macroscopic stage 3) in relation to bottom isotherms during January for the years 2001 to 2008. The size of the squares is proportional to the abundance (t/mn^2) of females with hydrated oocytes. The circles in 2006 indicate the inshore (IS) and offshore (OS) spawning areas.

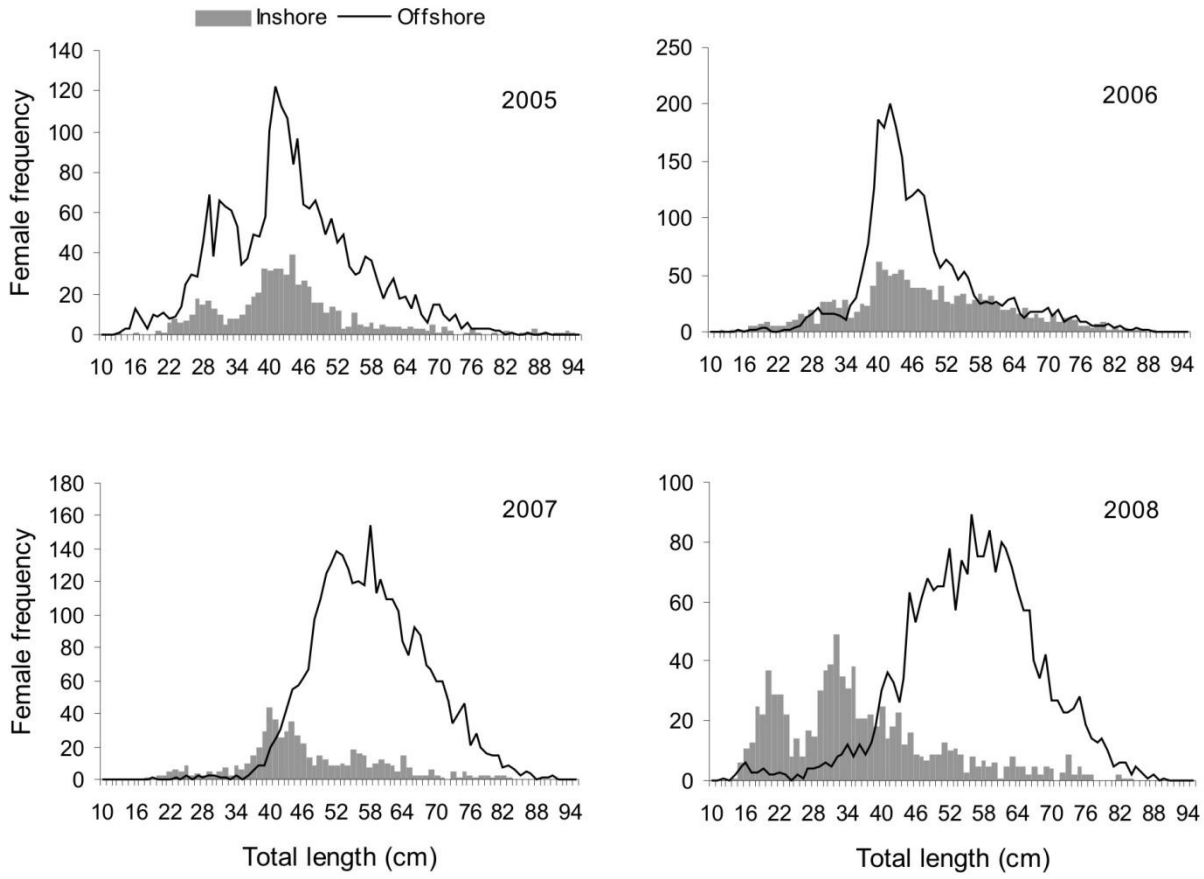

Figure 6. Number of *M. hubbsi* females by length class obtained for the inshore and offshore spawning areas during January for the years 2005 to 2008.

During all years analyzed, RF values from females collected in the OS area were lower than those estimated for the coastal spawning area (Table III). However, comparison of the RF mean values between each spawning group showed no significant differences (P>0.05) for any year.

Table III. Mean relative fecundity values (RF) and standard deviation (SD) estimated for the inshore and offshore spawning groups of Argentine hake in January during the different years analyzed.

	Inshore spawning			Offshore spawning		
Years	RF	SD	n	RF	SD	n
2005	516	178	12	483	197	6
2006	571	248	35	455	141	13
2007	599	126	25	497	213	16
2008	596	132	21	542	167	32

The dry weight of 100 hydrated oocytes (DW) estimated from females collected in January 2007 and 2008 ranged from 2.25 to 3.85 mg. For both years, as was observed with the RF values, DW of females sampled in the OS area were lower than those of the coastal reproductive area of Camarones Bay (Table IV). Nevertheless, the statistical comparison between areas showed high significant differences (P<0.01) only with data from 2007.

Table IV. Mean dry weight of 100 hydrated oocytes (DW) and standard deviation (SD) estimated for the inshore and offshore spawning groups of Argentine hake in January during 2007 and 2008.

	Inshore spawning			Offshore spawning		
Years	DW (mg)	SD	n	DW (mg)	SD	n
2007	3.054	0.313	24	2.750	0.301	16
2008	3.057	0.365	21	2.893	0.261	32

Discussion

Previous studies based on information collected during different reproductive seasons of the *Merluccius hubbsi* Patagonian stock showed that in January the spawning of this species takes place mainly in costal waters of Camarones Bay, between 44°30'and 45° S (Macchi *et al*. 2004, Macchi *et al*. 2007). The location of the hake's main spawning shoals in the north-Patagonian area during January from 2001 to 2008 agrees with this general pattern, but differences in the spatial distribution of the reproductive females were observed along this period. For example, in January 2001 and 2004 spawning was mainly concentrated near the coast at depths lower than 80 m, following the general pattern reported for previous years (Macchi *et al*. 2005). This observation was corroborated by the spatial distribution of post-spawning females, which increases at deeper waters pinpointing the limit of the reproductive area. Nevertheless, during January 2005 a big spatial dispersion of ripe (with hydrated oocytes) and spawning females (with day-0 POF) was observed. This pattern showed an expansion of the hake spawning area toward deeper waters, with a low proportion of post-spawning individuals in comparison to that observed for 2001 and 2004. This observation in general was similar during January 2006, 2007 and 2008, but these years were also characterized by the presence of a little and conspicuous nucleus of ripe and spawning females near the 100 m isobath, between 44°40' and 45°20' S.

It is possible that expansion of the reproductive area of hake observed in January 2005 may have derived in a secondary spawning group in deeper waters, which has increased in density during the last years. This observation suggests spawning at temperatures lower than those previously reported for *M. hubbsi*, whose inferior limit for detection of hydrated and spawning females had been established in 9 °C (Pájaro *et al*. 2005). In fact, spawning at temperatures between 10 and 13 °C has been the general pattern reported for the northern stock of Argentine hake (Macchi & Pájaro 2003b) and for other species of the Merluccidae family, as *M. merluccius* (Alvarez *et al*. 2001) and *M. australis* (Bustos *et al*. 2007).

During January, the most important aggregations of spawning females of the hake Patagonian stock were observed in a bottom temperature range between 9 and 14 °C, in coincidence with a thermal front, sited parallel to the coast line from 43°S to 45°30'S at depths lower than 80 m. This oceanographic characteristic is part of the tidal frontal system of Peninsula Valdés, formed by the high tidal energy and the seasonal thermal stratification characteristics of this area (Glorioso 1987, Glorioso & Flather 1995, Sabatini & Martos 2002). This frontal system is associated with a highly productive ecosystem and therefore its importance as reproductive and nursery ground for different organisms (Acha *et al*. 2004).

Since 2005, the frequency of sampling stations with spawning females and the density of these individuals increased at temperatures lower than 10 °C, showing annual variation in the salinity range. It is possible that annual differences in the oceanographic condition of the main spawning aggregations could be associated with the recruitment variations observed for the Argentine hake Patagonian stock (Macchi *et al*. 2008). These authors reported that in recent years little spawning biomasses of this species resulted in strong recruitment one year later and vice versa, suggesting that at the higher levels of fishing exploitation of Argentine hake, recruitment variation would depend mainly on environmental conditions. These results show the need to study the interactions between physical and biological process and their influence on recruitment, as was suggested by different fish populations (Francis *et al*. 1989, Gilbert 1997).

The appearance of an offshore spawning group of *M. hubbsi* near the 100 m isobath during the last three years analyzed is a novel fact for this species, mainly because the temperature range in that place (6 - 8 °C) was about half of that estimated for the Camarones Bay (11 - 13 °C). Information obtained from research cruises carried out in the north-Patagonian area during February and June 2005, showed the presence of argentine hake post-

larvae offshore near the 100 m isobath, which indicated that spawning in deeper waters during this year might have been successful (Machinandiarena *et al*. 2006). However, it is possible that growth and nutritional condition of larvae and post-larvae of this group is different to those estimated for individuals of the traditional nursery ground of hake. Hollowed & Bailey 1989 mentioned that larvae of *M. productus* advected offshore would be trapped in an unfavorable environment and will eventually die. In case of *M. merluccius*, Alvarez *et al*. (2001) suggested that if hake larvae are not transported onto the continental shelf before they reach 8 mm in length, it is likely that they will eventually die. These authors reported that oceanographic conditions prevailing during the early life stages will be of primary importance concerning the transport of eggs and larvae onto the nursery grounds, in order to ensure survival success for the egg and larval cohorts, and hence, recruitment success.

Other differences between the inshore and offshore spawning areas of *M. hubbsi* were observed, for example in sex ratio and female size structure. The coastal group of Camarones Bay showed a high proportion of males during all analyzed years, and females of this zone were mainly young adult individuals, with a length range between 40 and 45 cm TL. These observations correspond to the traditional pattern described for spawning aggregations of hake in previous studies (Pájaro *et al*. 2005). On the other hand, the offshore group was characterized by a low proportion of males in the samples and larger females, mainly during 2007 and 2008 when the size modes ranged between 53 and 62 cm TL. These females correspond to individuals older than 5 years old (Otero *et al*. 1986).

Moreover, differences in some aspects of the reproductive potential of each group were observed. Relative fecundity values and oocyte dry weight estimated for females of the offshore spawning area were lower than those obtained for the inshore reproductive ground, although high significant differences were only observed with data of January 2007. These results could indicate that the offshore group corresponds to hake females spawning the last egg batches, taking into account that the number and dry weight of hydrated oocytes of *M. hubbsi* decrease at the end of the spawning season (Macchi *et al*. 2006) as was also reported for other species (Kjesbu *et al*. 1992, Chambers & Waiwood 1996, Mairteinsdottir & Steirnarsson 1998). If so, these individuals may be hake females close to the post-spawning stage in migration toward deeper waters, where they usually concentrate for feeding after reproduction, as was observed by Angelescu & Prenski (1987). This hypothesis could explain the higher proportion of females in the offshore spawning area in comparison to that observed inshore, as suggested by Macchi *et al*. (2007) for the same stock.

Acknowledgements

We acknowledge M. Estrada, E. Christiansen and H. Brachetta for preparation of the histological sections, and for counting the oocyte samples. We also thank N. Scarlatto for reading and making suggestions to improve the manuscript. This work was supported by INIDEP and CONICET (PIP 112-200801-00815). This is a INIDEP contribution N° 1586.

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Received March 2009
Accepted March 2010
Published online June 2010