



Influence of estuarine and continental shelf water advection on the coastal movements of apron ray *Discopyge tschudii* in the Southwestern Atlantic

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Summary

Evaluated was the seasonal and inter-annual association between habitat variables and distribution pattern of the apron ray (*Discopyge tschudii*) and its relationship, with the main force on the environmental condition to understand the influence of estuarine and continental shelf processes in the coastal fishes of the Southwestern Atlantic Coastal System (34°–41°S). Two winter and five spring research surveys in the SACS were analyzed and the Perry and Smith methodology applied to determine the seasonal association of depth, temperature and salinity and the abundance of apron ray. The season with the highest inter-annual spatial distribution variation was related to the main external force on environmental conditions (e.g. wind, atmospheric temperature, and Río de la Plata discharge and shelf water intrusion). Apron ray showed persistent habitat selection, with the water temperature (<16°C) and salinity (higher than 31.8) being environmental factors most influencing its spatial distribution. In the spring, the apron ray spatial distribution showed higher inter-annual variation than in winter. The persistence of the spring habitat selection of *D. tschudii* suggests that its onshore-offshore as well as north-south movements are influenced by water mass movements forced by a combination of local conditions (wind) and regional-scale weather patterns (e.g. strength of the Malvinas Current). This study provides evidence on the importance of considering environmental conditions on the spatial distribution of apron ray and improves the knowledge on interactions between estuarine and shelf water dynamics as determinants of the spatial distribution of a coastal fish species in the Southwest Atlantic Coastal System.

Introduction

In temperate coastal systems, which are characterized by the wide variability in their oceanographic conditions, interactions of the water masses between adjacent systems (estuaries-coastal, coastal-shelf) influence the seasonal and inter-annual fish composition in each system. The incursion of marine fish species into estuaries has been related to the penetration of coastal waters (e.g. Lagoa dos Patos – Chao et al., 1982; Garcia et al., 2001; Río de la Plata – Jaureguizar et al., 2004, 2007; Western Australia – Chuwen et al., 2009); incursions of estuarine species into coastal marine waters areas have been attributed to large freshwater discharges (e.g. inner shelf off New Jersey – Milstein, 1981; Gulf of México – Yañez-Arancibia et al., 1985; Río de la Plata – Jaureguizar et al., 2007).

Although considerable work has been undertaken to determine the influence of water movements on fish community structures in estuaries and their adjacent coastal waters, less effort has focused on how the estuarine and continental shelf processes influence coastal fish communities. Movements of estuarine and continental shelf water masses could also influence temporal changes in the composition of coastal fish species.

The Southwestern Atlantic Ocean (SWAO) is considered one of the most active regions of the world's oceans (Chelton et al., 1990), and the dynamics of the coastal environment of the Southwestern Atlantic Coastal System (SACS, 34°–41°S) are determined by the interaction between different oceanographic systems (Lucas et al., 2005). This region comprises a system mainly controlled by local freshwater input (Río de la Plata), a coastal system with intermediate salinity, and a shelf/slope system defined by sub-Antarctic shelf waters advected from the south (Guerrero and Piola, 1997) and subtropical shelf waters coming from the north (Piola et al., 2000). The wind mainly drives the water mass circulation (Palma et al., 2004; Simionato et al., 2004, 2006) and greatly influences the spread of the Río de la Plata plume (Guerrero et al., 1997; Piola et al., 2005) and its velocity profile. The estuary responds with vertically decaying currents for winds with a dominant component perpendicular to the estuary axis, and with currents that reverse their direction from surface to bottom for winds with a prevailing direction parallel to the estuary axis (Simionato et al., 2007). Southeasterly (north-westerly) winds push surface waters upstream (downstream) towards (from) the upper part of the estuary (Simionato et al., 2004, 2007). This mass transport must be compensated by a net outflow (inflow) of bottom waters downstream (upstream) the estuary, which gives rise to the observed inversion in current directions (Simionato et al., 2007).

The shark, skate, ray and chimaera shelf fauna in the SWA correspond to the Western Temperate South Atlantic Province (WTSAP), which extends from Río de Janeiro to just south of Valdes' Peninsula (Menni et al., 2010). *Discopyge tschudii* (apron ray) is a characteristic species of the WTSAP, and occurs in deep and cold shelf waters, i.e. at depths between 38 m and 110 m and water temperatures between 7.1°C and 16.05°C (Menni et al., 2010). In the coastal system (<50 m depth), *D. tschudii* is a discriminator species of the spring offshore coastal shelf fish assemblage (mean depth, 28.9–49.6 m, mean bottom salinity 33.6–33.9, and mean bottom temperature 10.6–14.9°C; Jaureguizar et al., 2006), and migrates to the inshore coastal system in winter, i.e. into the

Río de la Plata (Jaureguizar et al., 2004). The environmental gradient between shelf/slope and freshwater of the SACS (36–41°S) and the habitats used by this species, has allowed us to consider the apron ray as a tracer to study the bio-physical interaction between these systems. This study thus intended to (i) determine the seasonal and temporal distribution patterns of apron ray (*Discopyge tschudii*) at a regional scale (over 1000 km) on the SACS (34–41°S) and their relationships with environmental variables, and (ii) analyze the influence of the estuarine and shelf water mass dynamics on the inter-annual geographic variations in the spatial distribution of apron ray. We thus provide information that contributes to an improved understanding of the physical mechanisms and processes that influence fish distributions in coastal marine environments.

Material and methods

Specimens of *Discopyge tschudii* and oceanographic data were obtained between 34°S and 41°S, in early winter (1993 and 2004) and spring (1994, 1998, 1999, 2003 and 2005) (Table 1; Fig. 1) during fishery evaluation cruises from the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP). The specimens were collected from 323 sampling stations (Stns.) in early winter and 769 Stns. in spring (Table 1). Sampling was conducted with an Engel bottom trawl net (200 mm stretched mesh in the wings, 120 mm stretched mesh in the cod ends; 4 m high, 15 m wide opening) that was towed at four knots for 15 min per set. *Discopyge tschudii* abundance (number of individuals per unit area) was calculated for each station using the swept area method (Alverson and Pereyra, 1969). The swept area, *a*, was estimated from:

$$a = D \times hr \times X2$$

Where *D* is the distance covered, *hr* is the length of the head-rope. *X2* is that fraction of the head-rope length, *hr*, which is equal to the width of the path swept by the trawl, the ‘wing spread’, *hr***X2*. *D* was estimated in units of nautical miles (nm), by:

$$D = 60 \times \sqrt{(\text{Lat}_1 - \text{Lat}_2)^2 + (\text{Lon}_1 - \text{Lon}_2)^2 \times \cos^2(0.5 \times (\text{Lat}_1 + \text{Lat}_2))}$$

where *Lat*₁ = latitude at start of haul (degrees), *Lat*₂ = latitude at end of haul (degrees), *Lon*₁ = longitude at start of haul (degrees), *Lon*₂ = longitude at end of haul (degrees).

Oceanographic data (depth, water temperature and salinity) at each sampling station were obtained using a Conductivity-Temperature-Depth (CTD) profiler (Sea-Bird Electronics Inc., Bellevue, WA, USA). Data were calibrated and reduced to a

1 m vertical resolution, with a final precision of ±0.03°C for water temperature and ±0.05 for salinity.

The *D. tschudii* abundance was mapped to examine its seasonal and inter-annual spatial distribution. For each year, the identification of associations between environmental conditions (depth, water temperature and salinity) and the distribution of *D. tschudii* was evaluated using the method developed by Perry and Smith (1994) without the stratification scheme. This method tests statistically the null hypothesis of a random association between fish distribution and habitat conditions across the cumulative distribution function through randomization procedures.

First, we estimate the general frequency distribution of the habitat variable (depth, temperature, or salinity) by constructing its empirical cumulative distribution function as:

$$f(t) = \sum_i \frac{1}{n} \times I(x_i) \quad \text{where} \quad I(x_i) = \begin{cases} 1, & \text{if } x_i \leq t \\ 0, & \text{otherwise} \end{cases}$$

Here, *t* represents an index, ranging from the lowest to the highest value of the habitat variable at a step size appropriate for the desired resolution (1 m to depth, 0.2°C to temperature, and 0.2 to salinity), *n* represents the total number of sampling stations in the survey and *x_i* is the value of the habitat variable in sampling station *i*.

Second, we associated the abundance of apron ray in each sampling station with the habitat conditions at that sampling station.

$$g(t) = \sum_i \frac{1}{n} \times \frac{y_i}{Y} \times I(x_i)$$

where *y_i* represents the apron ray abundance obtained in sampling station *i*, and *Y* denotes the estimated mean apron ray abundance of all sampling stations. If large values of *y_i*/*Y* are consistently associated with particular habitat conditions, then this suggests a strong association between the apron ray abundance and those habitat conditions. The cumulative distribution functions calculated from *g(t)* illustrate the range of conditions at which the species occurred and can be compared with the habitat conditions available in the sampled area. If there was no particular association between apron ray distributions and the habitat variable within the area surveyed, for example if the apron ray were randomly distributed with respect to the habitat variable, then *g(t)* and *f(t)* would be almost identical.

Finally, the maximum absolute value of vertical difference between *f(t)* and *g(t)* curves was calculated (*D*_{max}) to determine the strength of the association between catch and habitat variable. A randomization procedure was developed to evaluate the significance of the test statistic. This was done by randomizing the pairings of *y_i* and *x_i* over all *i* for the data within a survey and then calculating the *D*_{max} for the new pairs. We repeated this procedure 2000 times and calculated the probability of observing a value of *D*_{max} equal to or greater than that of the observed data (*P*) under the null hypothesis that apron ray are randomly distributed in relation to habitat conditions. We assumed significant differences when *P* value was lower than 0.05.

To illustrate the association between apron ray distribution and environmental variables, the horizontal distribution of abundance and the environmental value where 90% of the population occurred were mapped. The bottom water temperature and salinity isolines were obtained by krigging interpolation onto a 0.5°lat. × 0.5°long. grid.

Table 1
Summary of research surveys, Southwestern Atlantic Coastal System, indicating for each the initial and final Julian day of survey (Date), total survey sampling stations (Stns.), sampling station with apron ray catch (Stns. ar), and total number of apron ray caught (Ar. caught)

Season	Year	Date	Stns.	Stns ar.	Ar. caught
Winter	1993	188–222	166	120	3508
	2004	189–227	157	76	615
Spring	1994	303–326	177	93	1702
	1998	329–353	108	28	850
	1999	313–337	141	57	253
	2003	332–355	152	29	162
	2005	317–354	181	77	775

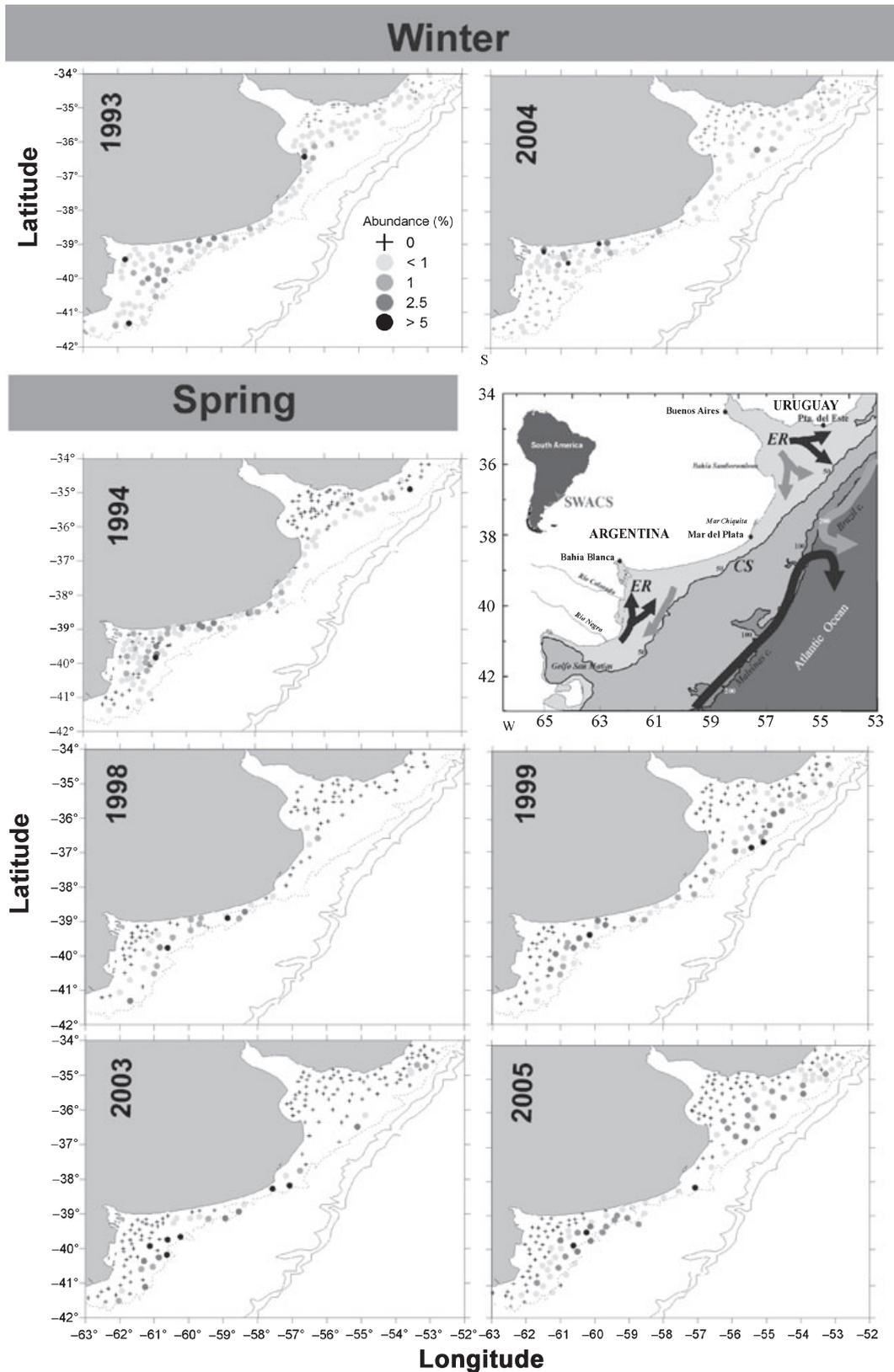


Fig. 1. Seasonal (winter and spring) *Discopyge tschudii* spatial distribution by year, indicating relative abundance (1000 individuals/nm²) by sampling station. Schematic representation of oceanographic regime, Southwestern Atlantic Coastal System (RDP: Río de la Plata; ER: El Rincón; CS: Continental Shelf) and its seasonal drift (black arrows = winter; grey arrows = spring)

The relationship between *D. tschudii* spatial cover and the main external force on environmental conditions (wind, atmospheric temperature, and Río de la Plata discharge and shelf water intrusion) was examined during the season when

the highest inter-annual coverage variation was observed for the whole area. The Río de la Plata (RDP) monthly mean discharges were obtained from the Instituto Nacional del Agua y del Ambiente (INAA). The monthly mean discharge anom-

aly was calculated taking into account the mean monthly discharge between 1931 and 2005. Considering that the Río de la Plata responds rapidly to wind variability in synoptic scales (which peaks at periods of around 4 days), in both current and salinity fields, we used the on-board wind data obtained during the cruises. Wind direction is described according to meteorological convention (wind comes). Winds were assembled considering the direction of the resulting flow, based on bottom water circulation forced by local winds as observed by Simionato et al. (2007), i.e. winds forcing an inflow or an outflow of bottom water into or from the estuary. The inflow of bottom waters results when the wind blows from directions between NW (315°) and E (45°); the outflow of bottom waters occurs when the winds blow from between SE (135°) and W (270°). Monthly sea surface temperature (SST) maps obtained by the Advanced Very High-Resolution Radiometer (AVHRR) onboard NOAA satellites and processed by the PATHFINDER PROJECT version 5 (<http://poet.jpl.nasa.gov>) with 4 km resolution and monthly Net Heat Flux (*Qnet*) maps (WHOI OAFflux Project) on a one degree grid (<http://oaf Flux.whoiedu>) were used to infer a more global description of shelf water intrusion to northern SACS. Anomalies were calculated by subtracting the climatological mean value of the entire data available for each month. To determine to what extent the inter-annual variability in SST in the SACS was related to the advection of water or to variations in air-sea net heat transfer, the average net heat flux (*Qnet*), sea surface temperature (SST), and their anomalies (*Qneta* and *SSTa*, respectively) were extracted from a region limited by 36°–37°S and 55°–56°W for each month (Fig. 3e). Considering that the wind has a differential effect on the water mass distribution in the water column in the Río de la Plata (Simionato et al., 2007), we also included into this analysis the vertical profiles of temperature (*T*) and salinity (*S*) in the northern SACS region area (box 1° × 1° grid, 110 km × 92.5 km averaged for the study region, centered at 36°S–55.5°W).

Results

Spatial distribution

Discopyge tschudii were widely distributed in the SACS (Fig. 1). The winter distribution showed a persistent pattern,

with *D. tschudii* covering the total coastal area of El Rincón (ER) and also occurring in the Río de la Plata (RDP). In both areas, the abundance of this species was higher in nearshore waters. The spring distribution showed a lower spatial coverage and higher inter-annual variability than winter. *D. tschudii* occupied mainly offshore waters, where the higher abundances were found. In spring, ER and RDP showed different inter-annual variation in the spatial distribution. The ER showed a persistent pattern where *D. tschudii* mainly covered the offshore area, except during 1994 when it also occupied the inshore coastal area. In the RDP the distribution pattern was more variable, with *D. tschudii* showing a wide distribution in the coastal system in 1994, 1999, and 2005 and a narrow distribution in 1998 and 2003 (Fig. 1).

Environmental influence on *Discopyge tschudii* distribution

Associations between *D. tschudii* and environmental variables changed with the season (within the sampled range); during winter, the distribution was not associated with bottom depth within the sampled depth range (5–65 m) (Table 2). While *D. tschudii* distribution was related to water temperature and salinity, these patterns were not consistent. Thus, in 1993 there was a strong association with both variables, but during 2004 the distribution was not related to water salinity or temperature ($P > 0.1$, Table 2). During spring, the distribution of *D. tschudii* was strongly associated with all environmental variables and distributed at the greatest depths of the total range available, with 90% of the population occurring at bottom depths between 16.5 m and 51.5 m, which represented 25 (1998) to 60.5% (1994) of the survey area (Table 2). This species had a cumulative frequency distribution that reflected very strong associations with particular salinities ($P < 0.01$, Table 2); 90% of the population was associated with a salinity average higher than 31.8 and lower than 33.8, which covered 39.8 (1998) to 82.3% (1999) of the survey area. *Discopyge tschudii* was associated with cold waters, with 90% of the population on SACS occurring at average water temperatures between 11.4°C and 15.4°C, representing 25.9 (1998) to 63.8% (1994) of the survey area (Table 2).

Table 2

Test results for statistical differences in *Discopyge tschudii* cumulative frequency distributions (CFD) compared with habitat cumulative frequency distributions of depth, temperature, and salinity

	Depth						Temperature					Salinity							
	<i>D</i>	P	Percentile			<i>H</i>	<i>D</i>	P	Percentile			<i>D</i>	P	Percentile			<i>H</i>		
			5%	50%	95%				5%	50%	95%			5%	50%	95%			
Winter																			
1993	0.268	0.469	13.0	36.0	53.0	0.819	0.334	<0.001	7	9.6	11.8	0.819	0.214	0.036	32	33.8	34	0.753	
2004	0.185	0.837	13.5	32.5	45.5	0.739	0.312	0.122	8.4	9.6	12.8	0.936	0.278	0.127	32.8	33.8	34	0.707	
Average	0.268	0.405	13.0	35.0	53.0	0.814	0.353	0	7	9.6	12	0.811	0.21	0.016	32.2	33.8	34	0.755	
Spring																			
1994	0.435	0.001	16.5	35.5	42.5	0.605	0.315	0.002	11.4	13.4	15	0.638	0.346	0	31.2	33.6	33.8	0.661	
1998	0.706	0	28.0	42.0	51.0	0.250	0.702	0	12.6	14.2	15.4	0.259	0.552	<0.001	33.2	33.6	33.8	0.398	
1999	0.435	0	23.5	41.5	51.5	0.511	0.36	0	10.4	13.8	15.6	0.631	0.273	0.001	31.6	33.6	34.2	0.823	
2003	0.605	<0.001	28.5	44.5	50.5	0.355	0.605	0	11.6	14	16	0.375	0.521	0	33	33.4	33.8	0.401	
2005	0.475	<0.001	20.0	42.0	51.0	0.575	0.379	0	12.2	14	15.4	0.519	0.409	0	32.4	33.6	34	0.724	
Average	0.487	0	19.0	39.0	50.0	0.599	0.477	0	11.4	13.6	15.4	0.472	0.369	0	31.8	33.6	33.8	0.613	

Entries = maximum difference between CFD (*D*), significance test values (*P*), habitat values where 0.05, 0.5 and 0.95 percentiles of *D. tschudii* abundance occurred, and percentage of sampled habitat occupied by 90% of *D. tschudii* total abundance (*H*).

Horizontal distribution of bottom salinity and temperature

The spatial coverage of *Discopyge tschudii* and its inter-annual variation were highly related to environmental conditions, highlighted by its strong association with the salinity and temperature (16°C upper thermal boundary, 32 lower salinity boundary; Table 2). In the RDP region, the winter environmental spatial conditions were more persistent than during spring. In winter, when temperatures below 16°C dominated the region, the salinity (~ 32) restricted the distribution of *D. tschudii* (Fig. 2). During spring, the environment showed higher inter-annual variation, and the north/south or inshore/offshore spatial distribution of *D. tschudii* was related to low water temperature ($< 16^{\circ}\text{C}$) and high salt content (> 32) water mass distribution (Fig. 2). The ER region was always dominated by more-saline waters (> 32), and the seasonal spatial coverage of *D. tschudii* was mainly related to temperature (Fig. 2). During spring when the inshore area was cold ($< 16^{\circ}\text{C}$, 1994), *D. tschudii* was found throughout the system as in winter; when the inshore area was warmer, this species was more abundant in the offshore area (Fig. 2).

Río de la Plata discharge, wind pattern, net heat flux, and shelf water intrusion

The external force on the environmental condition at a regional scale (Río de la Plata discharge, wind, and shelf water intrusion) was analyzed only during the spring season, when *D. tschudii* distribution showed the greatest inter-annual variation. The anomalies of RDP monthly mean discharge showed negative values for most months before the sampling cruises (Fig. 3a). The maximum freshwater discharge was in 1998 and the minimum in 1999 and 2003 (Fig. 3a). The wind patterns showed an inter-spring variation in the wind direction. During 1998 and 2003 the winds were mostly from the S (180°) and SW (225°), forcing an outflow of bottom waters from the estuary (Fig. 3b). In 1994, 1999 and 2005 dominant winds from the N (0°) and E (90°) forced an inflow of bottom continental shelf water into the estuary (Fig. 3b). The vertical profiles showed that in 1994 and 2005 the water column was highly stratified (thermocline/pycnocline at ~ 10 m), but was weakly stratified or quasi homogenous in 1998, 1999 and 2003 (Fig. 3c). During 1994, 1998 and 2005 the surface waters were warmer ($> 18^{\circ}\text{C}$) and fresher (< 28) than in 2003 and 1999. The bottom waters in 1994, 1999 and 2005 were colder ($< 16^{\circ}\text{C}$) and more saline (> 31.5) than in 1998 and 2003

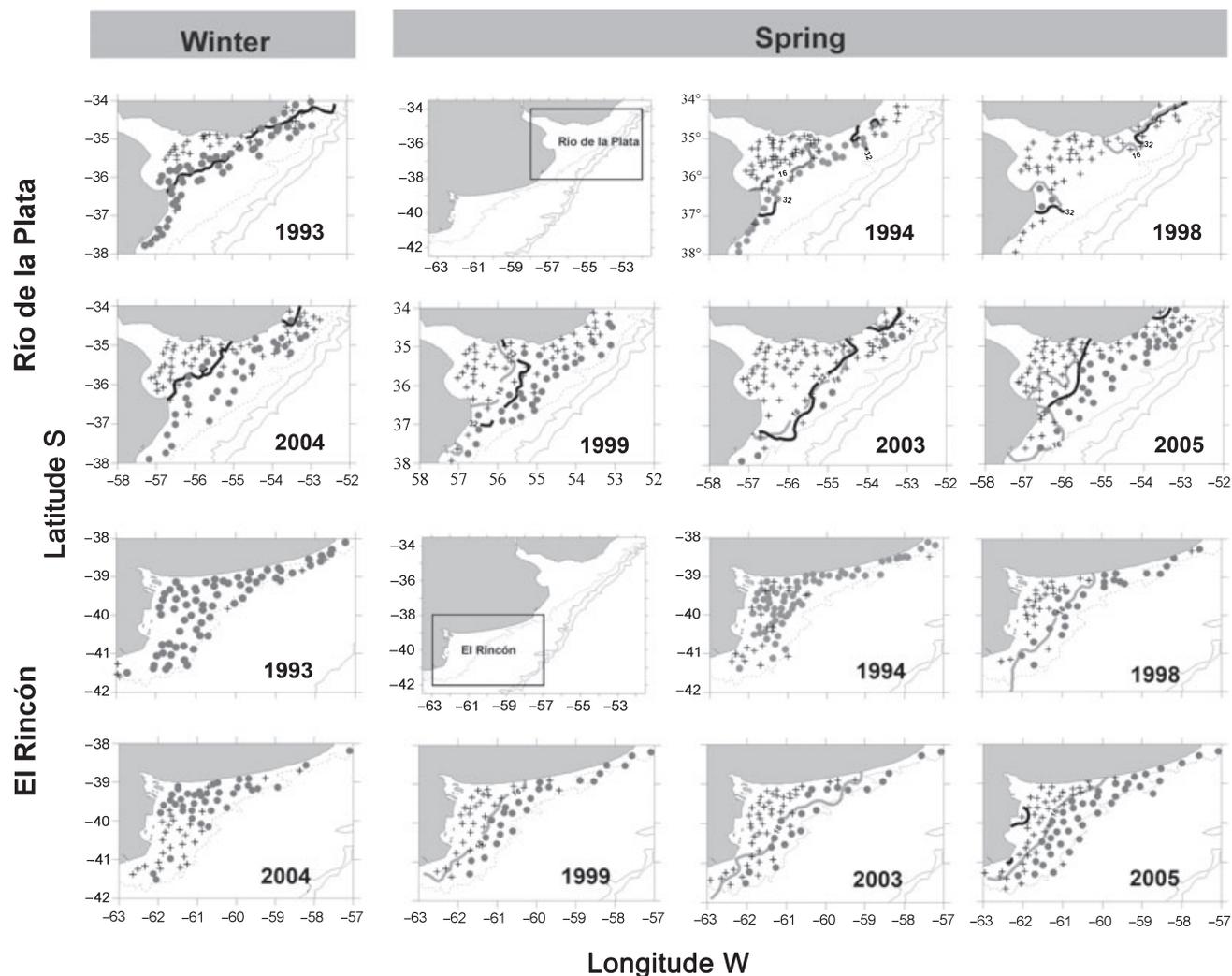


Fig. 2. Seasonal and inter-annual *Discopyge tschudii* spatial coverage and relations with spatial distribution of upper thermal (grey line: 16°C isoline) and lower salinity (black line: 32 isoline) boundary (Perry and Smith (1994) method), Río de la Plata and El Rincón area

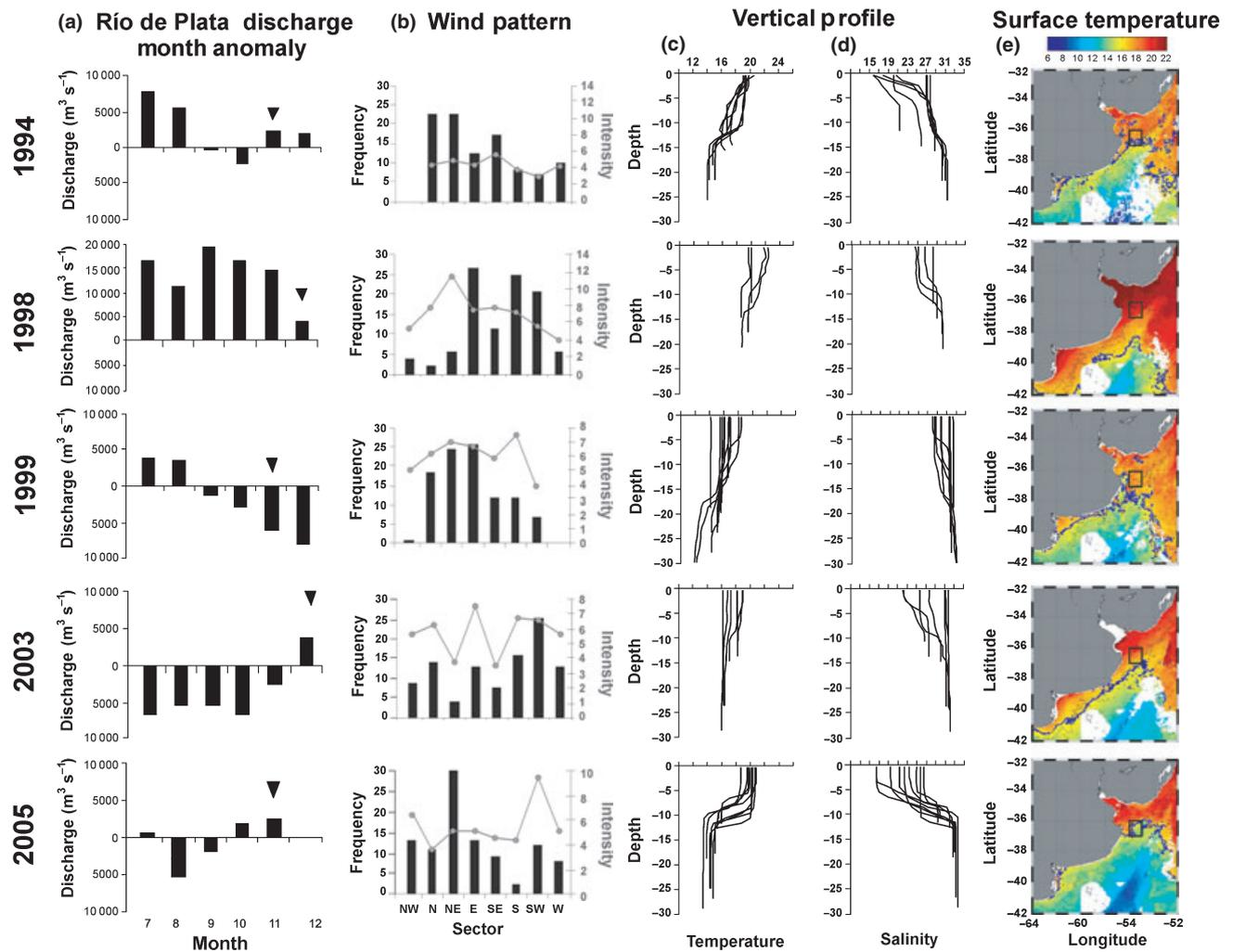


Fig. 3. (a) RDP freshwater monthly mean discharge anomaly, (b) surface wind pattern (mean intensity and frequency by sector) during the cruise, (c) profiles of temperature (*T*) and (d) salinity (*S*) in northern SACS from a limited region (36°–37°S and 55.5°–56.5°W), (e) monthly sea surface temperature (*SST*) maps obtained by Advanced Very High-Resolution Radiometer (AVHRR), where the 16°C (*Discopyge tschudii* upper thermal boundary) isoline is indicated (blue line)

(Fig. 3c,d). Negative *SSTa* were found in 1994 and 2005 (Table 3), demonstrating the presence of waters colder than the mean value for that month for the period 1990–2006, while the net heat flux through the sea-surface was positive (downward into the ocean) in all years. Moreover, negative *Q_{net}* values were also observed in almost all years, particularly in 1994 and 2005 (–4.3 and –10.5°W m^{–2}, respectively). The continental shelf water mass (indicated by the 16°C isotherm) showed a north/south and inshore/offshore inter-annual variation in the SACS region (Fig. 3e). The highest northern extension was in 2005, reaching 36°S, in marked contrast to

1998, reaching only 39°S. During 1994, 1999, and 2005, the continental shelf waters covered the coastal region (< 50 m depth) of the SACS, while during 1998 and 2003 it was mainly associated with the offshore SACS region (> 50 m depth) (Fig. 3e).

Discussion

Our results provide critical information on the spatial and temporal distribution, and habitat selection of *Discopyge tschudii* in the SACS. Water temperature, followed by salinity, was the environmental factor that mostly influenced the spatial distribution of *D. tschudii*, and was consistent among years. The physiological constraint, at water temperatures higher than 16°C and salinities lower than 31.8, restricted the spatial distribution of *D. tschudii*. The seasonal and inter-annual persistence in the habitat selection of this species revealed that the onshore-offshore movements, as well as north-south movements, are likely to be related to water mass movements forced by a combination of local (wind) conditions and regional-scale weather patterns. The seasonal pattern in the spatial distribution of *D. tschudii* could be related to the regional-scale processes, while that of the inter-annual spring

Table 3
Average net heat flux (*Q_{net}*), sea surface temperature (*SST*), and their anomalies (*Q_{neta}* and *SSTa*, respectively) for northern SACS from a limited region (36°–37°S and 55°–56°W)

Year	<i>Q_{net}</i>	<i>Q_{neta}</i>	<i>SST</i>	<i>SSTa</i>
1994	149.3	–4.3	16.9	–1.2
1998	125.3	–23.4	20.2	–0.63
1999	157.7	4.1	20.5	2.4
2003	130.1	–18.6	21.5	0.67
2005	143.1	–10.5	15.7	–2.4

spatial pattern is related to both regional-scale and local processes.

The SACS has a pronounced seasonal water temperature cycle, typical of temperate regions, with a maximum in January–March (T_{mean} : 17–23°C) and minimum from June to August (T_{mean} : 8–12°C) (Lucas et al., 2005), the water movements (Guerrero et al., 1997; Palma et al., 2004; Lucas et al., 2005) being the regional-scale processes related to the seasonal spatial distribution of *D. tschudii*. During winter, under a near-balance of onshore and offshore winds in the northern area (34°–38°S), the surface waters of the Río de la Plata present a north-northeast drift along the Uruguayan and southern Brazil coasts, with a southern penetration of shelf waters into the estuary (Guerrero et al., 1997). In concordance in the southern area (38°–42°S), the high salinity waters from El Rincon basin and shelf waters show their maximum northward extension (Lucas et al., 2005). This environmental condition, where cool and high salinity waters cover a greater area of the SACS, allows a northern and wider distribution of *D. tschudii*, forcing even a winter intrusion of this species into the Río de la Plata estuary (Figs 1 and 2).

After the winter and as the warm season progresses in the SACS, the shallow coastal waters warm faster than deeper shelf waters and coincide with a movement of *D. tschudii* from onshore (5 m) to offshore waters (deeper than 17 m), as is clearly observed in the El Rincon basin (Fig. 2). At the same time, the Río de la Plata coastal system begins to be under the influence of the most frequent northeast and easterly winds that force a southward drift of coastal waters, generating a freshwater flow along the Argentine coast (Guerrero et al., 1997; Simionato et al., 2001), while on a regional scale, the relaxation of the Patagonian gyre generates the formation of a southward coastal flow of shelf waters (Palma et al., 2004). Low salinity conditions in the adjacent Río de la Plata waters forced by a combination of the two processes, produces a reduction in the northern flow of cool and highly saline waters, thus restricting the northern distribution of *D. tschudii* and its intrusion into the Río de la Plata estuary during spring. The high abundance of this species observed in the Río de la Plata during winter (Jaureguizar et al., 2004) therefore appears to be associated with regional-scale processes that favor the northward movement of cold and saline water.

The inter-annual spring spatial distribution of *Discopyge tschudii* demonstrated migrations on a regional scale (200 km), producing on average a 35% variation in the coastal system distribution (from ~25% in 1998 to ~60.45% in 1994). The main distribution variation occurred in the area influenced by the Río de la Plata (north of 39°S). This finding and its relationship with external forcing trends (water temperature, wind, freshwater discharge and net heat flux) allow us to suggest that the migration could be associated with both regional-scale (Malvinas current) and local scale (wind) forces. The Malvinas Current (MC) flows northward along the western edge of the Argentine Basin, carrying cold, salty (> 33.9) and nutrient-rich sub-Antarctic waters derived from the northern Drake Passage to about 38°S (Piola and Gordon, 1989; Peterson, 1992). Near 38°S, along the shelf break, the MC collides with the southward-flowing Brazil Current, creating a region of strong mesoscale variability (Chelton et al., 1990; Goni and Wainer, 2001), referred to as the Brazil/Malvinas Confluence (Gordon and Greengrove, 1986) with a thermal front between 15°C and 18°C. The confluence location appears to be forced by wind stress (Piola et al., 2010). The negative *SSTa* in the northern SACS (1994 and

2005; Table 3) demonstrates the presence of waters colder than the mean value for that month for the period 1990–2006, while the net heat flux through the sea-surface was positive (downward into the ocean) in all years. Negative *Q_{net}* were also observed in almost all years, with *Q_{net}* maximum values in 1994, 1999 and 2005. The *SSTa*, *Q_{net}*, and the presence of cold water (< 16°C) under the thermocline suggest that the colder water temperatures found in these years were most likely due to advection of continental shelf waters than to a difference in net heat exchange with the atmosphere. Thus, the inter-annual variation observed in the isoline of high thermal tolerance (16°C) of *D. tschudii* (Fig. 3) suggests that its northward extension observed in 1994, 1999, and 2005 is forced by the advection of cold waters over the coastal area which may be modulated by the strength and location of the Malvinas Current. Recently, Piola et al. (2010) presented evidence that intense slope water intrusions onto the Argentina continental shelf only occur between 40°S and 41°S; a plausible explanation is the relaxing of the steep shelf break bottom slope near 41°S due to the inshore deflection of the 100 m isobath. This result suggests that regional-scale processes affect the abundance of species within the fish assemblages of SACS. A northward extension of cold and salty water leads to a greater biomass of *D. tschudii* in the Inner and Central Coastal Shelf (1994, 1999), while a retraction of that northward extension was accompanied by a higher biomass of this species in the Outer Coastal Shelf (Jaureguizar et al., 2006).

As was observed for a demersal teleost fish species (*Prionotus* spp.; Jaureguizar et al., 2007), the intrusion of *D. tschudii* in the Río de la Plata is more likely the result of the most frequent wind conditions during the sampling period than trends in river discharge. The estuary rapidly responds to wind variability at a synoptic scale (which peaks at periods of around 4 days) in both currents and salinity fields. From the composites of current profiles in the Río de la Plata as a function of wind direction from Simionato et al. (2007) and the observed vertical profiles (Fig. 3c,d), there is evidence that the most frequent wind conditions (Fig. 3b) during the spring are the main force behind *D. tschudii* intrusion in the Río de la Plata along the bottom layer. When the spring dominant wind direction is from N-NE-E (1994, 1999, and 2005), warm and low saline (< 28) surface waters (up to 10 m) are pushed downstream from the upper part of the estuary, and the mass transport is compensated by a net inflow of cold and saline (> 30) bottom waters upstream the estuary (Fig. 3). This forcing of *D. tschudii* bottom intrusion in the Río de la Plata is stopped by the progression of adverse wind conditions, as was observed in 1998 and 2003. In these spring periods, the dominance of S and SW winds pushed surface waters (up to 10 m) upstream towards the upper part of the Río de la Plata; the net outflow of warm and fresh bottom water downstream the estuary restricted the progression of *D. tschudii* intrusion, even forcing them back into the coastal system.

General springtime conditions and environment gradients are therefore likely to influence the onshore and northern boundaries of spatial distribution of *D. tschudii*. Their distribution within the northern area (RPD) appears to be based on a combination of species specific factors, including its physiological tolerance to water temperature and salinity, and the environmental conditions produced by local winds and regional-scale processes (Malvinas current) that produce cold water advection into the coastal system. While in the southern area (ER), the weather conditions at the regional scale that define the water temperature, also control the inshore pro-

gression of *D. tschudii*. The coastal fishery evaluation cruises do not conform to a continuous time data series and there is an uneven season sampling intensity, however, the fact that the winter environmental pattern variability is lower than in spring (Guerrero et al., 1997; Jaureguizar et al., 2007), and the physical pattern is more clear and persistent in the El Rincon than Rio de la Plata (Lucas et al., 2005; Jaureguizar et al., 2006), the sampling intensity could be considered representative of the environmental variability in the SCAS. Therefore, the *D. tschudii* distribution pattern found improves the understanding of the seasonal variation in the distribution of a demersal fish species and its inter-annual spatial differences in response to environmental conditions, and provides a basis for understanding how demersal fish movements may respond to climate change, information that is critical for effective conservation planning and the design of future fishery programs. Also, these results demonstrate the importance of considering environmental conditions on the evaluation cruise results, which have implications for management regulations of fished populations. Effective fisheries management relies on knowledge of the spatial-temporal distribution of fish populations.

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