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Original article

Large-scale migration of a school shark, *Galeorhinus galeus*, in the Southwestern Atlantic

Andrés J. Jaureguizar[1,2], Federico Argemi[3], Gastón Trobbiani[4], Elbio D. Palma[5,6] and Alejo J. Irigoyen[4]

Knowledge of the spatial and temporal distribution patterns of chondrichthyans is critical for their effective management. In this study we report and analyze a large-scale latitudinal migration (~ 1,425 km) of a female school shark in the Southwestern Atlantic shelf where it is currently classified as Critically Endangered. During the austral summer (February 15, 2015), ninety-four school sharks were captured (75 females and 19 males) and tagged with fin tags in Nuevo Gulf (~ 42°43'S, 64°53'W, Argentina). A female of 112 cm total length was recaptured in Uruguayan shelf waters in the austral winter (August 17, 2015). This long displacement represents the first direct evidence to support Vooren and Lucifora's hypothesis of a single transnational population of *Galeorhinus galeus* in the Southwestern Atlantic. The good agreement found between the school shark habitat conditions (salinity 33-34, temperature 12-17°C) and the warmer member of Subantarctic Shelf Waters suggests that the seasonal variation in school shark abundance within this region could be related to water masses movements.

Keywords: Argentina-Brazil, Distribution pattern, Habitat preference, Migration, Shelf water.

El conocimiento sobre los patrones de distribución espacio-temporal de los condrictios es crítico para su manejo efectivo. En este trabajo presentamos y analizamos una migración latitudinal de gran escala (~ 1.425 km) de una hembra de cazón en la plataforma del Océano Atlántico Sudoccidental, donde está actualmente clasificada como Críticamente en Peligro. Durante el verano austral (15 de Febrero de 2015), 94 cazones fueron capturados (75 hembras y 19 machos) y señalados con marcas "rotatag" en el Golfo Nuevo (~ 42°43'S, 64°53'W, Argentina). Una hembra de 112 cm de longitud total fue recapturada en aguas de la plataforma uruguaya durante el invierno austral (17 de Agosto de 2015). Este gran desplazamiento representa la primera evidencia directa para apoyar la hipótesis de Vooren y Lucifora sobre una única población transnacional de *Galeorhinus galeus* en el Océano Atlántico Sudoccidental. La gran coincidencia encontrada entre las condiciones de hábitat para el cazón (salinidad 33-34, temperatura 12-17° C) y el integrante más cálido del Agua de Plataforma Subantártica sugiere que la variación estacional en la abundancia del cazón dentro de esta región podría estar relacionada con el movimiento de las masas de agua.

Palabras claves: Aguas de plataforma, Argentina-Brazil, Patrón de distribución, Preferencia de hábitat, Migración.

Introduction

Galeorhinus galeus (Linnaeus, 1758) is a medium-sized shark that occurs in coastal and shelf temperate waters (Compagno *et al*., 2005; Ebert *et al*., 2013). A recent study (Chabot *et al*., 2015) has shown that there are at least five genetically differentiated populations (Africa, Australia, North and South America and Western Europe), with no genetic interconnectivity among them, possibly due to the long distances between different ocean basins and barriers related to temperature. In the Southwestern Atlantic (SWA), it inhabits in the Bonaerensean Biogeographic District,

[1]Comisión de Investigaciones Científicas de la Provincia de Buenos Aires (CIC), Calle 526 e/ 10- 11, CP 1900, La Plata, Argentina.
[2]Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP), Paseo Victoria Ocampo N° 1, B7600EEP, Mar del Plata, República Argentina. ajj@inidep.edu.ar, https://orcid.org/0000-0003-1916-8682 (corresponding author)
[3]Fundación Temaiken, Ruta 25, Km. 1, Escobar, Argentina. fargemi@temaiken.org.ar
[4]Centro para el Estudio de Sistemas Marinos (CESIMAR), Consejo Nacional de Investigaciones Científicas y Técnicas (CCT CENPAT – CONICET). Boulevard Brown 2915, (U9120ACD) Puerto Madryn, Chubut, Argentina. (GT) trobbiani@cenpat-conicet.gob.ar, (AJI) alejo@cenpat-conicet.gob.ar
[5]Instituto Argentino de Oceanografía, CONICET, Bahía Blanca, Argentina. uspalma@criba.edu.ar
[6]Departamento de Física, Universidad Nacional del Sur, Av. Alem 1253, B8000CPB, Bahía Blanca, Argentina. uspalma@criba.edu.ar

within the Western Temperate South Atlantic Province (Menni *et al*., 2010), from 30°S (Brazil, Vooren, 1997) to 49°S (Argentina, Chiaramonte, 2015) and from the coastline to 400 m in the northern waters (Brazil, Klippel *et al*., 2016; Peres, Vooren, 1991) and up to 200 m in the southern area (Uruguay-Argentina, Menni *et al*., 2010) (Fig. 1A). Globally, this species is currently classified as Vulnerable, but in the SWA it is categorized as Critically Endangered and without major and urgent management measures its conservation status could become even worse (Walker *et al*., 2006).

In the SWA, the school shark has been proposed as a migratory species travelling seasonally between the Southern Brazilian Shelf and the Northern Argentine Shelf (Vooren, 1997; Fig. 1A). Off southern Brazil (30°- 34°S), it is abundant at depths of 40-350 m, and the seasonal pattern is characterized by a fall immigration with peaks during winter (June–September) and a spring emigration (October-November), being absent during the summer months (January and February) (Peres, Vooren, 1991). On this basis, Vooren (1997) hypothesized that the school sharks spend the austral winter in the northern region of their latitudinal range (off southern Brazil), and then migrate southwards to the Northern Argentine Shelf (35°- 45°S) in the austral summer. This migration could be related to reproductive habits (giving birth in nursery areas) that putatively occur in the south (Vooren, 1997; Nion, 1999; Walker, 1999; Lucifora *et al*., 2004).

Lucifora *et al*. (2004) found that the patterns of occurrence, reproductive condition, and embryonic growth in the Northern Argentine Shelf waters (San Blas Bay, Fig. 1A) are complementary to those from the Southern Brazilian Shelf, supporting the hypothesis that there is a single large population of school sharks in the SWA. Recently, some evidence collected within the southern part of the SWA shelf sustains the north/south migration pattern. Two specimens tagged near Nuevo Gulf (42°43’S) were recaptured, one off Anegada Bay (40°12’S) and the other one near Mar del Plata (~38ºS). The latter one is the longest northward travel registered so far (~ 847 km) in the SWA, and occurred from late austral summer (March) to late austral spring (December) (Irigoyen *et al*., 2015, Fig. 1A).

In this study, we provide new evidence on the large-scale latitudinal migration of school sharks along the SWA shelves, and discuss the relationship between the observational data and the distribution and circulation of water masses in this area.

Material and Methods

Study area. The region of interest extends from Nuevo Gulf (~ 42°30’S, Argentina) to the northern sector of the Southern Brazilian Shelf (~30°S, Fig. 1A). The offshore circulation in this region is dominated by two intense western boundary currents flowing in opposite directions: the Malvinas Current (MC), a northward flowing cold and relatively fresh detachment of the Antarctic Circumpolar Current, and the Brazil Current (BC), a southward flowing warm and salty wind-driven current (Piola, Matano, 2001). The MC and the BC collide at approximately 38°S creating a region of intense mesoscale variability known as the Brazil/Malvinas Confluence (BMC) (Matano *et al*., 1993). The circulation over the shelf reflects the influence of the western boundary currents, which contribute to the formation of a northward flow of cold and fresher waters in the south and a southward flow of warm and saltier waters in the north (Palma *et al*., 2008; Matano *et al*., 2010). Interestingly, the northward shelf flow of Northern Argentine Shelf waters (mainly Subantarctic Shelf Waters) overshoots the BMC location and meet the southward flowing subtropical waters near 33°S, well inside the Southern Brazilian Shelf, generating a density compensated front, known as the Subtropical Shelf Front (Piola *et al*., 2000, Fig. 1A).

Sampling procedure. A diurnal fishing cruise was developed in Nuevo Gulf waters on February 15, 2015 to tag school sharks. This cruise was within the project “Habitat use and migration patterns of large sharks in coastal waters of the Southwest Atlantic Ocean (SWA)”, initiated jointly by researchers from the CIC-INIDEP (Comisión de Investigaciones Científicas; Instituto Nacional de Investigación y Desarrollo Pesquero), CONICET-CENPAT (Consejo Nacional de Investigaciones Científicas y Técnicas; Centro Nacional Patagónico), and Temaiken Foundation. The study area is part of Valdés Península, a World Heritage site in terms of their relevance from the point of view of conservation, and in particular for the large concentrations of birds and marine mammals.

School sharks were captured in waters between 80 and 110 m depth during the diurnal fishing trip (Fig. 1A) and tagged with fin tags (standard Rototag). The Rototag is a two-piece plastic cattle ear tag that is inserted through the first dorsal fin (Fig. 2). To capture the sharks, an 800 m bottom longline with 110 hooks (“Goldfish-Octopus Hook” type 10/0 92553 series) was set from a semi-rigid boat (4.9 m length) for 120 min with hooks baited with chub mackerel (*Scomber colias*). The setting time was established based on previous tests in order to ensure the welfare of captured individuals (Irigoyen *et al*., 2015). Upon capture, sharks were sexed and their total length measured. During the fishing sessions the surface water temperature was measured.

Abbreviations. SWA: Southwestern Atlantic Ocean, BMC: Brazil/Malvinas confluence, MC: Malvinas Current. BC: Brazil Current, SASW: Subantarctic Shelf Water, CIC: Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, INIDEP: Instituto Nacional de Investigación y Desarrollo Pesquero, CONICET-CENPAT: Consejo Nacional de Investigaciones Científicas y Técnicas; Centro Nacional Patagónico, DINARA: Dirección Nacional de Recursos Acuáticos, TL: Total length, SST: Sea Surface Temperature, T: Temperatures, S: salinity.

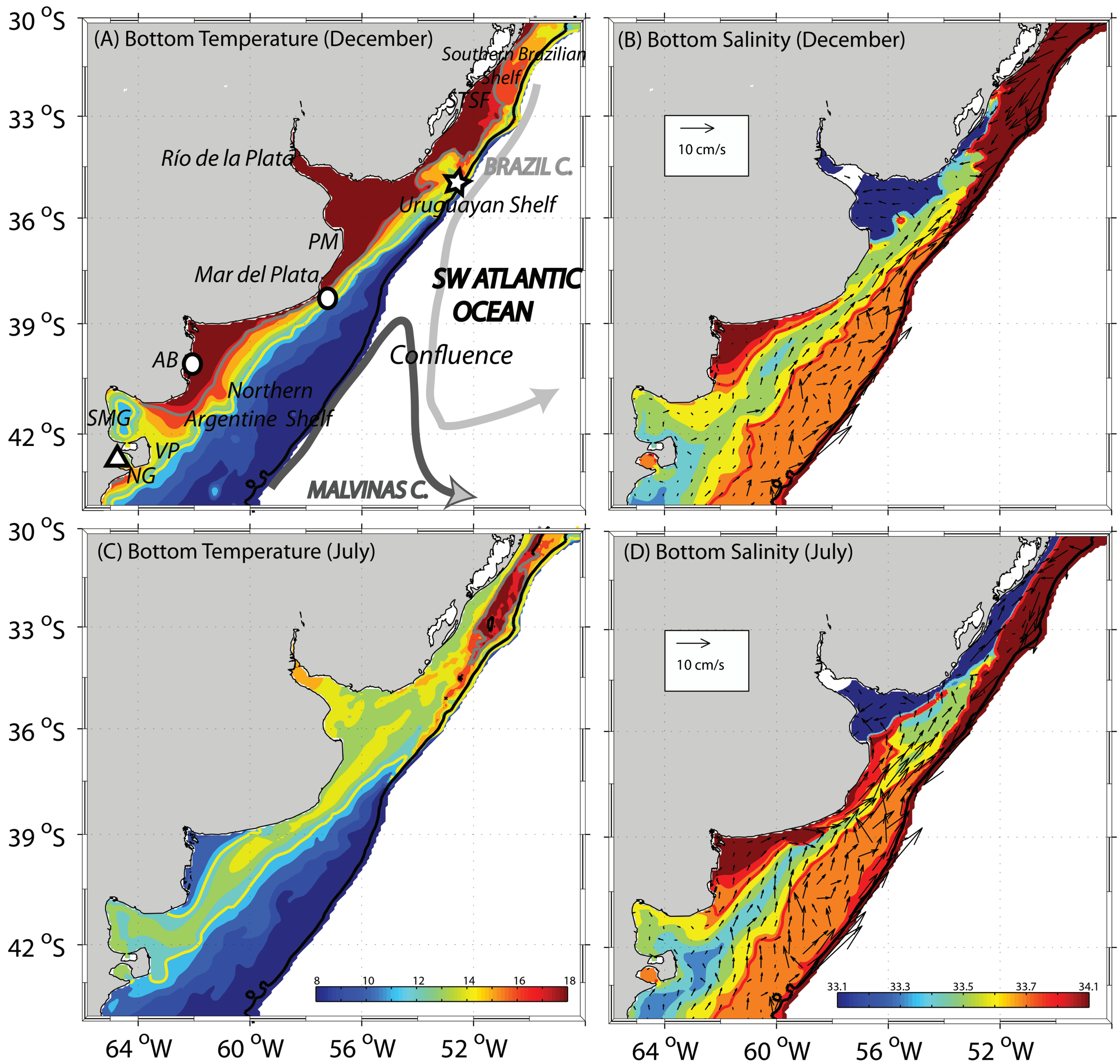

Fig. 1. Schematic representation of the depth-averaged ocean circulation in the Southwestern Atlantic Ocean (adapted from Matano *et al*., 2010) showing the geographical locations of tagging of *Galeorhinus galeus* [Triangle, Nuevo Gulf (NG), 42°30'S, 65°55'W, depth 100 m], newest recapture in Uruguayan shelf waters (Star, 35°30'S, 51°48'W – depth 290 m) and the two old recapture sites (Circle, Mar del Plata, 38°24'S, 57°18'W, depth 40 m and Canal Culebra, 40°24'S, 62°06'W - depth 15 m, Irigoyen *et al*., 2015). Additional geographical locations are indicated with acronyms: SMG = San Matías Gulf, VP = Valdés Peninsula, AB = Anegada Bay, PM = Punta Médanos, STSF = Subtropical Shelf Front. The thick curved lines represent the path of the major ocean currents. The black line is the 200m isobath. Colours indicate bottom temperature (a, c) and bottom salinity (b, d) and black arrows indicate the bottom shelf circulation extracted from a numerical model (Palma *et al*., 2008). The yellow and gray lines in the left panels indicate the 11 and 17 °C isotherms respectively. The red and cyan lines in the right panels indicate the 33.93 and 33.5 isohalines.

Results

Ninety-four school sharks (Fig. 2C) were captured, 75 females and 19 males. The size length distribution was unimodal in both sexes, the total length (TL) of female ranged from 90 to 150 cm of TL with a peak in 120 cm of TL, and in male, the TL ranged between 100 and 130 cm of TL with a mode in 120 cm TL (Fig. 2C). The surface water temperature was 18°C.

A 112 cm TL female (#tag 4165, Figs. 2A-B) was recaptured in Uruguayan Shelf waters on August 17, 2015 during a bottom longline fishery operation at 140 km off the coast at a depth around 290 m (35°18'S, 52°30'W, near the limit with the Southern Brazilian Shelf). An onboard observer of Dirección Nacional de Recursos Acuáticos (DINARA, Uruguay) reported the recapture. The specimen had been tagged in Nuevo Gulf (~ 42°30'S, Argentina) during February 15, 2015. At the moment of capture, it measured 110 cm TL. After 183 days, the recapture location implied that the shark travelled a minimum distance of approximately 1425 km (Fig. 1A). According to the female maturity curve in the southern area of distribution [juveniles (TL until 118 cm LT), sub-adult (118 cm > TL < 129 cm), adult (TL > 129 cm), Lucifora *et al*., 2004], and size at 50% maturity at ~124 cm TL (Chiaramonte, 2000; Lucifora *et al*., 2004), the recaptured specimen is a sub-adult.

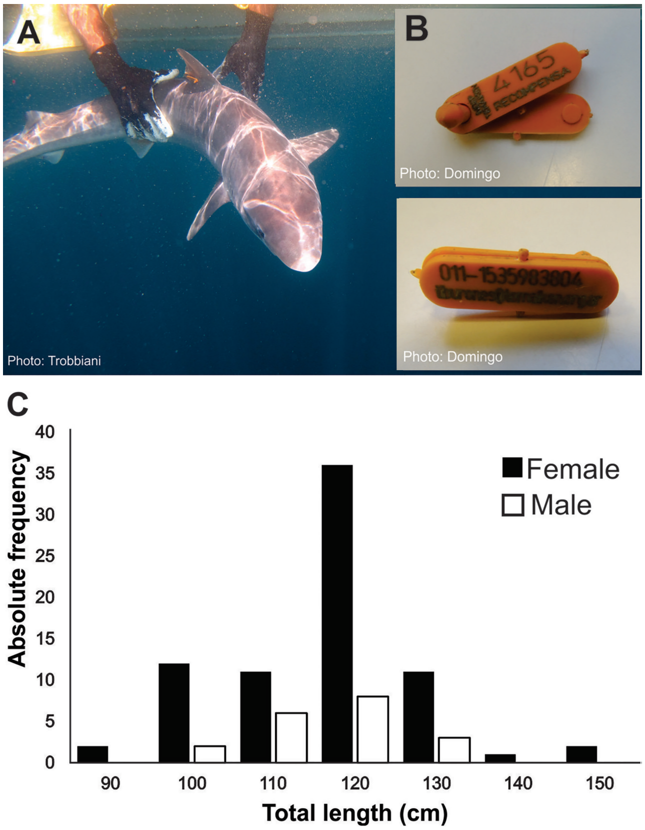

Fig. 2. A) Releasing of a tagged *Galeorhinus galeus*, B) the recaptured tag on August 17, 2015, and C) length size distribution of school sharks captured and tagged in Nuevo Gulf (~ 42°30'S, Argentina) during February 15, 2015.

Discussion

There is substantial evidence elsewhere that *G. galeus* is capable of migrating over significant distances across the open ocean. In the Southwestern Pacific several long distance displacements (> 500 km) have been observed including one reaching 4940 km (Hurst *et al*., 1999). In the Northeast Atlantic, specimens tagged off England and Ireland have been recaptured as far away as off northern Iceland, a 2,641 km journey (Stevens, 1990). In SWA waters, the spatial and temporal distribution patterns of this species are not well known, but the migration recorded in this study (~1,425 km) is within the range observed in other temperate shelves, and confirm the possibility of a long seasonal migration of a single population of the species as posited by Vooren (1997) and Lucifora *et al*. (2004). These results concur with genetic analyses that revealed no significant population structure among individuals from San Matías Gulf, Anegada Bay, and Punta Médanos (Fig. 1A; Cuevas *et al*., 2016).

At large scale, the school shark distribution within the SWA extends from coast of Rio Grande do Sul State (28°S, Brazil; Bellisio *et al*., 1979) to Península San Julián (49°S, Argentina, Chiaramonte, 2015), mainly associated to Bonaerensean Biogeographic District (Menni *et al*., 2010). In the Southern Brazilian Shelf waters the school shark occurs during austral winter months (from June to September) mainly between 100 and 350 m deep on the continental slope and it is absent in spring and summer months (Ferreira, Vooren, 1991; Peres, Vooren, 1991; Klippel *et al*., 2016). In that region, the sea surface temperature (SST) is a better predictor for *G. galeus* occurrence than depth, salinity or chlorophyll, it prefers SST below 17°C with maximum occurrence around 12.5-15°C (Klippel *et al*., 2016). After or during the end of winter, G. galeus starts a southward migration to Uruguayan and Northern Argentine Shelf waters (Marín, Puig, 1987). In the inner shelf (depth < 50 m), under the influence of the Río de la Plata freshwater discharge, its spring occurrence is associated with higher salinities (33.1-34.1) and intermediate temperatures (T from 11.7 to16.5°C) (Jaureguizar *et al*., 2006, 2015). On the Northern Argentine Shelf, the school shark occurs during spring (October-December, T from 12 to 13°C, mainly males) and early autumn (mainly females), and is absent during summer (T > 16 - 17°C) and winter (Lucifora *et al*., 2004).

These early studies indicate that the T and S ranges that the school shark inhabits coincide with the warmest water mass of the Subantarctic Shelf Waters (Fig. 1), also called Mid Continental Shelf Water (Piola *et al*., 2000; Lucas *et al*., 2005, with 33.5 < S < 33.7; Palma *et al*., 2008). The mean salinity (Figs. 1B-C) and temperature (Figs. 1A-C) distribution patterns at the bottom during summer (January) and winter (July) generated by a numerical model are in good agreement with school shark early observations within the SWA shelf waters. The school shark migration could be explained by predominance of salty (33-34) and warm (12° - 17°C) waters in the inner-middle shelf related to a physiological response as a function of salinity and thermal tolerance. In this sense, the southward migration from Southern Brazil Shelf waters during late spring could be related to warm–salty intrusions (T > 16° C; S > 34.72) derived from Subtropical and Subantarctic shelf waters mixtures. Similarly, the summer emigration from Anegada Bay to southern and deeper waters of Northern Argentine Shelf (Elias *et al*., 2005; Irigoyen *et al*., 2015) can be ascribed to the excessive heating of the shallow coastal waters. The subsequent northward migration could be associated to excessive cooling of the southern shelf waters during fall and winter. Consequently, the seasonal variation in school shark abundance along the SWA shelf might be related to movements of the species within a specific range of T and S that in turn is associated with the seasonal variability of the water masses over the shelf. This may allow individuals to keep, within the saline tolerance, a specific range of temperatures within the shelf water as adaptive strategy to reduce the gestation period in adult females, as suggested for other chondrichthyans (Economakis, Lobel, 1998; Robbins, 2007; Hight *et al*., 2012; Elisio *et al*., 2016). The long northward migration (1,425 km) of a female from February to August reported in this study seems to support the above hypothesis.

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