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RESEARCH NOTE

Permeable frontiers in the open sea: The case of Swordfish in the Atlantic Ocean

Fronteras permeables en mar abierto: El caso del pez espada en el océano Atlántico

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Abstract.- There is a vivid debate about the border location between North and South Atlantic swordfish stocks. Climate oscillations, East Atlantic (EA) and North Atlantic Oscillation (NAO), have a major impact on the Northern Hemisphere climate and weather conditions. The initial hypothesis of present study was that if it is considering the southern frontier, each stock will be differentially affected by both climatic oscillations, which would imply the existence of a strong border. However, a similar effect on both sides of the border would result in a permeable barrier. The results suggest that the combined effects of EA and NAO affect both the North and the South Atlantic swordfish stocks in similar ways, and consequently, the location of the border may reside farther north than the current management boundary at 5°N.

Key words: Climatic oscillations, Atlantic Ocean, North Atlantic Oscillation, East Atlantic pattern

INTRODUCTION

Swordfish *Xiphias gladius* Linnaeus, 1758 is the monotypic member of the family Xiphiidae, suborder Scombroidei. This species is globally distributed in tropical and temperate marine pelagic waters between 45°N and 45°S, including the Mediterranean Sea, the Black Sea and the Marmara Sea (Palko *et al*. 1981). In the Atlantic, swordfish has a great economic value both for its market demand and for its volume of catches, reaching in 2016 a total of 20,998 t (ICCAT 2017). The largest proportion of the Atlantic catches is made using surface-drifting longline (ICCAT 2006-2016).

Swordfish is known to large scale movements (*e.g.,* Witzell & Scott 1990) and this highly migratory behavior complicates the definition of population boundaries. In the Atlantic-Mediterranean region three separate stocks have been recognized: Mediterranean, North Atlantic and South Atlantic, on the basis of fisheries data and genetic evidence that include both mitochondrial and nuclear DNA markers (see Smith *et al*. 2015). Currently there is a vivid debate about the location of the boundary separating the North and South Atlantic (Braun *et al.* 2019). For stock assessment purposes, this boundary was placed by ICCAT at 5°N (Abid & Idrissi 2006). Nevertheless, ICCAT recently noted that the stock boundaries are approximations and that the possible impacts of seasonal changes and oceanographic processes in resource distribution need to be fully understood (ICCAT 2017). Chow & Nohara (2003) consider that the current management boundary between the North and South Atlantic swordfish stocks should be reconsidered to be established between 10°N and 20°N. Smith *et al*. (2015) supported the separation between the three stocks and concluded that the boundaries that separate the South Atlantic population extend beyond the 5°N management boundary to 20°N-25°N from 45°W (Smith *et al*. 2015).

The North Atlantic stock has reduced its catches by 48.6%, from the maximum of 20,238 t in 1987 to 10,404 t in 2016, with an average of 12,000 t per year. This decrease could be due to ICCAT regulations, changes in several fleets, and/or socioeconomic factors (ICCAT 2018). The South Atlantic stock reached 5,000 t before 1980, and from this year it increased to levels comparable to those of the North Atlantic stock, reaching its maximum in 1995 with 21,930 t. At present, it has been reduced by 65% with a catch of 7,725 t declared in 2016 (ICCAT 2018). The reduction of catches of swordfish has been reflected in FAO's State of the world fisheries and aquaculture reports (FAO 2016).

The North Atlantic Oscillation (NAO) is considered the main source of seasonal and annual variability of atmospheric conditions in the North Atlantic Basin (Hurrell 1995, Hurrell *et al*. 2001). The NAO effects are more significant in winter, especially from November to March (Hurrell 1996). The NAO is a fluctuation in the difference of atmospheric pressure between the Azores' high and the Icelandic's low, affecting the climate from the Arctic to the subtropical Atlantic (Hurrell *et al*. 2001). The positive phase of the NAO increases the pressure difference between these two cores and is associated with above-normal precipitation and intensity of the westerly winds over Northern Europe and below-normal precipitation over Southern and Central Europe. In the negative phase of the NAO, with the decrease in the pressure differences between the two cores, opposite patterns of temperature and precipitation anomalies, in addition to the arrival of storms in Southern Europe and the Mediterranean are observed.

Many studies have shown that fish stocks are affected by NAO, with changes in their biology and productivity patterns (Báez *et al*. 2011, 2019; Shackell *et al*. 2012). Thus, it has been shown that the NAO affects the distribution, local abundance, and recruitment of tuna and related species such as swordfish. Accordingly, NAO affects the distribution, local abundance, and recruitment of tunas and allies, including swordfish, and these changes are reflected on fishing landings (Rubio *et al.* 2016).

The East Atlantic (EA) pattern is the second most important node of low-frequency variability in the North Atlantic region with NAO (Barnston & Livezey 1987). EA effects, whose pattern is structurally similar to NAO, are detected throughout the year. It consists of a north-south dipole of pressures affecting the North Atlantic and spans from east to west with the centers between 55°N 20-35°W and 25-35°N 0-10°W (Barnston & Livezey 1987). This pattern significantly influences temperature, precipitation, and wind over western and central Europe (Hurrell 1995, Wulff *et al*. 2017). The positive phase of EA pattern is associated with above-average temperatures in Europe and below-average temperatures in the southern United States during January-May, and in the northern United States during July-October. In addition, this phenomenon is also associated with an increase in precipitation in northern Europe and a decrease across southern Europe (NOAA-NWS)[1].

According to Comas-Bru & McDermott (2013), the combined NAO-EA effect is more efficient for explaining the climate variability in the European continent than the effect of the NAO alone, likely because the EA pattern modulates the strength and location of the NAO dipole (Comas-Bru & McDermott 2013).

The initial hypothesis of the present study was that if it the placement of the boundary separating the North and South Atlantic Swordfish stocks is considered at 5ºN as suggested, each stock will be differentially affected by both climatic oscillations (NAO, EA), which would imply the existence of a strong border. However, if a similar effect was observed on both sides of the border, it could indicate the existence of a permeable frontier. The main aim of the present study was testing the permeability of the swordfish stocks border in the Atlantic Ocean.

Materials and methods

Fishing data

Swordfish catch data were obtained from the task I of the ICCAT, the Regional Fisheries Organization responsible for tuna and highly migratory species in Atlantic waters (ICCAT-CICAA-CICTA)[2].

Sixty-five years of records (1950-2017) of the data series were documented. The swordfish catch data include all the fishing gears of the Northern Hemisphere (average of 56,913 t for the whole series) and the Southern Hemisphere (average of 6091 t for the whole series) stocks. A single annual value per stock was estimated for the analysis, as the sum of the reported monthly values per fishing gear (Table 1). Because this period (1950-2017) did not show a normal distribution, and many values are placed below the mean in the first half of the series, the period 1990-2017 was used for the final analyzes.

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[1] National Oceanic and Atmospheric Administration, National Weather Service, National Weather Service Organization, Silver Spring. <www.cpc.ncep.noaa.gov/data/teledoc/ea_tmap.shtml>

[2] The International Commission for the Conservation of Atlantic Tunas <www.iccat.int/en>

Table 1. Data used in the present study. Key: SWO (SH), swordfish landing from South stock; SWO (NH), swordfish landing from South stock; NAOw, mean of the winter months November to March for the North Atlantic Oscillation; NAO, annual mean North Atlantic Oscillation; EA, annual mean East Atlantic pattern / Datos usados en el estudio. Clave: SWO (SH), desembarques de pez espada del stock sur; SWO (NH), desembarques de pez espada del stock norte; NAOw, valor promedio de los meses de invierno de la oscilación del Atlántico norte; NAO, valor anual promedio de la oscilación del Atlántico norte; EA, valor anual promedio oscilación del este

Year	SWO (SH)	SWO (NH)	NAOw	NAO	EA
1950	100	3546		-0.1208333	-0.3325
1951	200	2681	-0.504	-0.0083333	-0.3716666
1952	200	2793	-0.092	-0.425	-0.6883333
1953	200	3503	-0.352	-0.0175	-0.7266666
1954	100	2934	0.17	0.0025	-0.9116666
1955	100	3602	-0.48	-0.3991666	-0.8241666
1956	1	3358	-0.502	-0.0441666	-1.2866666
1957	224	4578	0.102	-0.1958333	-0.9516666
1958	92	4904	-0.542	-0.5891666	-0.2433333
1959	171	6232	0.12	0.3525	-0.23
1960	459	3828	-0.566	-0.41	-0.4041666
1961	1016	4381	0.192	0.04333333	0.1
1962	769	5342	-0.682	-0.3416666	-0.96
1963	1418	10190	-1.012	-0.4166666	-0.6933333
1964	2030	11258	-1.354	-0.0416666	-0.4825
1965	2578	8152	-0.668	-0.13	-0.9908333
1966	1952	8849	-0.572	-0.3283333	-0.5158333
1967	1577	8607	0.298	0.36666667	-0.8258333
1968	2448	8672	-0.122	-0.94	-0.5025
1969	4481	8503	-1.254	-0.0583333	-0.6008333
1970	5426	8995	-0.612	-0.2533333	-0.1308333
1971	2166	4766	-0.706	0.01	-1.1016666
1972	2580	4065	0.342	0.51	-0.8025
1973	3078	5574	0.384	-0.0866666	-0.36
1974	2743	5872	0.112	0.18083333	-0.755
1975	3062	8326.144	0.062	-0.0741666	-0.885
1976	2812	6153.856	0.368	0.1875	-1.46
1977	2855	5796	-0.754	-0.3358333	0.09583333
1978	2766	11237	-0.382	0.3175	-0.27
1979	3294	11104	0.04	0.135	-0.025
1980	5323	13058	0.104	-0.4125	-0.4041666
1981	3975	9680	0.102	-0.2125	-0.1741666
1982	6447	11943	0.202	0.43	0.02833333
1983	5402	13292	1.078	0.31	0.03416667
1984	9161.6	9340	0.264	0.2475	-0.5841666
1985	9585.7	10254	-0.392	-0.1833333	-0.0366666
1986	5894	14774.4	0.274	0.5033333	0.14166667
1987	6029.89	16240.435	0.308	-0.1225	-0.0508333
1988	13172	15450.4	0.422	-0.0133333	-0.1441666
1989	17055	13190.111	1.058	0.70166667	-0.1366666
1990	17304.21	13776.132	0.584	0.59416667	-0.0608333
1991	13892.57	6201.173	0.336	0.26833333	-0.4975
1992	13813.33	19545.447	0.55	0.58083333	-0.1391666
1993	16130.27	13956.686	0.886	0.17916667	-0.6308333
1994	18958.006	14795.677	1.376	0.57583333	0.40583333
1995	21930.3	12625.114	1.196	-0.0808333	-0.695
1996	18289.16	14731.359	-0.696	-0.2141666	-0.3491666
1997	18542.053	6439.496	0.14	-0.1566666	-0.0608333
1998	14027.225	13569.965	-0.142	-0.4808333	0.59
1999	15501.61	6765.39	0.376	0.39083333	-0.1508333
2000	15727.598	5875.558	1.066	0.20666667	0.21416667
2001	15127.98	5140.548	-0.412	-0.1825	0.365
2002	14103.943	4046.29	0.406	0.03916667	0.47916667
2003	12632.648	3544.995	-0.004	0.0975	0.41083333
2004	13076.581	7301.1735	0.418	0.2425	-0.2583333
2005	13162.354	8951.354	0.314	-0.2675	0.00833333
2006	14245.038	5507.79105	-0.254	-0.2075	0.45083333
2007	15629.5185	5735.34963	0.594	0.17333333	0.06083333
2008	12546.0004	8080.13429	0.524	-0.3783333	-0.0516666
2009	12679.3329	8060.07518	0.004	-0.2433333	0.46166667
2010	12655.3945	9429.75264	-1.184	-1.1525	0.36583333
2011	11455.1564	7902.11553	-0.608	0.29333333	-0.0158333
2012	10679.2637	11827.9117	1.348	-0.4558333	0.0225
2013	8211.78799	10566.2945	-0.424	0.21	0.4975
2014	10884.8706	8815.71616	0.588	0.0875	0.565
2015	10937.4844	8389.73754	1.19	0.3967	0.94
2016	10658.0239	10376.1014	0.508	-0.175	1.1158
2017	10556.2906	10169.4988	0.23	0.1733	0.6733

ATMOSPHERIC DATA

Data from climatic oscillations were organized monthly, so the annual average was calculated to have a single value per year for the EA and NAO patterns. The winter NAO value (NAOw) was calculated using the mean of the NAO values of the winter months (November-March), during which the oscillation reaches its greatest effects. These data were collected from the National Oceanic and Atmospheric Administration of the United States (NOAA)[3] (Table 1).

STATISTICAL ANALYSIS

Pearson correlation and multiple linear models were adjusted in steps forward between the stock catches variable and the independent variables: EA and NAO patterns, and winter NAO value (NAOw).

RESULTS AND DISCUSSION

The Figure 1 shows the catch trend of swordfish for both North and South Atlantic stocks recorded by ICCAT (period 1950-2017). In both cases, for the period 1990-2017 the most important variable correlated with swordfish catches was the EA pattern (for the north swordfish stock r= -0.649, $P < 0.001$, N= 28; and for south swordfish stock r= -0.414, $P < 0.028$, N= 28).

The combined model for swordfish landings from the Northern Hemisphere (NH) during 1990-2017 is as follows:

Landings SWO NH= 10665.967 – 2681.831 × EA + 997.439 × NAOw

Where NAOw is the average NAO values of the extended winter months (December to March). The model was significant (F= 13.837, $P < 0.001$), explaining almost 50% of the variance (R^2adjusted= 0.487). The EA pattern has a greater explanatory capacity within the combined model (EA beta coefficient= -0.611; NAOw beta coefficient= 0.325).

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[3] <www.esrl.noaa.gov/psd/data/climateindices/list/>

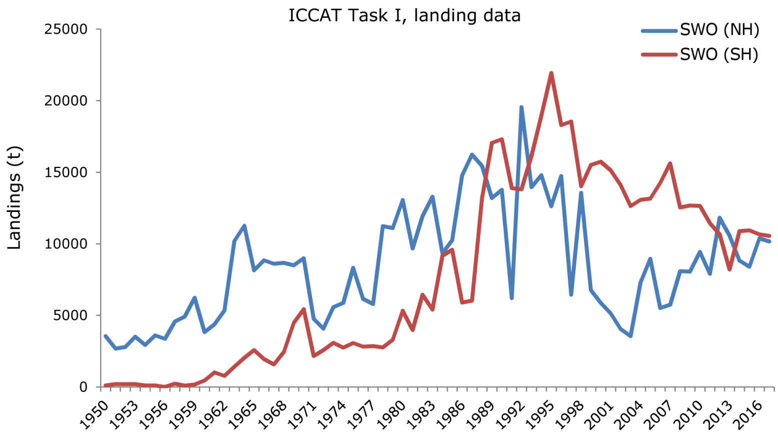

Figure 1. Annual landing data from task I of the ICCAT separated in the two SWO stocks. Key: SWO (NH) North Hemisphere stock, SWO (SH) South Hemisphere stock / Separación de los desembarques anuales de ambos stocks sacado de los datos de la Tarea I de ICCAT. Clave: SWO (NH) Stock del hemisferio norte, SWO (SH) Stock del hemisferio sur

The best model for swordfish landings from the Southern Hemisphere (SH) is as follows:

Landings SWO SH= 11485.195 – 2248.814× EA

The model was significant (F= 5.382, P = 0.028), R^2adjusted= 0.14. The EA pattern has a greater explanatory capacity within the combined model (EA beta coefficient= -0.417).

In order to test the most extreme limits of the border, as well as eliminate noise, the landings northern 20ºN *versus* the landings southern 5ºN were tested, for the period 1990-2017. The results for the northernmost landings showed a multiple lineal relationship with EA and NAOw, according to the expression:

Landings SWO North limit NH= 10658.941– 2894.208 × EA + 967.842 × NAOw

The model was significant (F= 14.263, P < 0.001), explaining almost 50% of the variance (R^2adjusted= 0.496).

The results for the southernmost landings showed a simple lineal relationship with EA, according to the expression:

Landings SWO South limit SH= 15028.935 – 3868.979 × EA

Moreover, for both cases, a significant negative correlation was observed between the landings and the winter NAO value (North of the northern limit, r= -0.377; P = 0.048. South of the southern limit, r= -0.769; P < 0.001). This could be due to excluding the landings between 20ºN and 5ºN, for the second analysis.

The results of this study highlight the importance of the combined effects of both EA pattern and winter NAO value oscillations to explain interannual variability of swordfish landings in the Atlantic Ocean (close to 50% of the variability, in both cases). Thus, EA and NAO patterns are the main patterns regulating the intensity and effects of storms on the eastern margin of the North Atlantic, especially in winter. These storms have a double effect on the fertilization of the ocean, due to terrestrial inputs of coastal systems (Drinkwater *et al*. 2003) and facilitation of the thermohaline circulation of oceanic waters, which increases the primary production (Báez *et al*. 2014), consequently creating favorable conditions for the swordfish to find a greater amount of potential prey as it moves across the ocean. Moreover, the increase in chlorophyll-*a*, have been previously suggested to impact on swordfish distribution by concentrating possible preys (Lan *et al*. 2015).

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[6] SENAMHI. 2020. Temperatura promedio Piura. Servicio Nacional de Meteorología e Hidrología, Ministerio del Ambiente, Lima. <https://www.senamhi.gob.pe/main.php?dp=piura&p=pronostico-detalle>

Chang *et al*. (2013) suggested in their study that factors such as sea surface temperature and mixing layer depth have an effect on swordfish distribution. These factors are also affected by NAO and other atmospheric oscillations. Schirripa *et al*. (2016) observed a potential AMO (Atlantic Multi-decadal Oscillation) effect on swordfish distribution from the North Atlantic area. Faillettaz *et al*. (2019) concluded that, in the case of bluefin tuna (*Thunnus thynnus*), AMO drives its basin-scale distribution. They also found a relationship between tuna population and NAO. Thus, within the North Atlantic might be a connection between NAO and AMO, perhaps mediated by the sea surface temperature.

Present results suggest that, together, the EA and the winter NAO value affect both swordfish stocks in a similar way. The influence on the climate, which both the EA pattern and the winter NAO value have at the regional level in the North Atlantic, could explain the effects on the landings of the northern swordfish stock. However, the similar effect observed on the landings of the southern swordfish stock, according to the initial scenario, implies the existence of a permeable border between both stocks of swordfish.

A plausible explanation is that there is an important exchange between individuals of both stocks. However, the results of the different tagging programs suggest that there are no significant trans-equatorial migrations across the Atlantic Ocean (García-Cortes *et al*. 2003). Varghese *et al*. (2013) concluded that swordfish performed north-south latitudinal movements but had no evidence of trans-oceanic movements. Although Rosel & Block (1996) and Neilson *et al.* (2006) suggest that the available tagging data are inconclusive due to variable rates of communication of recaptures, the unequal distribution of releases in the Atlantic, and the insufficient recaptures to detail such movements. In this context, recent electronic tagging studies from the Eastern Pacific Ocean (Sepulveda *et al*. 2020) showed that swordfish performed substantial long-distance movement, but no trans-hemispheric crossings. While a high percentage of fishes exhibited regional affiliation towards the eastern Pacific Ocean, a pool of individuals migrated out of that region towards the Central North Pacific, suggesting that borders could also be permeable in Pacific swordfish.

There are many studies showing possible relationships between the NAO and biological-fishery variables (Solow 2002, Rubio *et al*. 2016, Leitão *et al*. 2018). Despite the influence of EA pattern shown in our results, not many references that relate the EA pattern to biological-fishing variables were found. For this reason, it is suggested that further investigation of the species would be needed as it has already been done in other fields (Bastos *et al*. 2016) giving a new point of view to the previously mentioned genetic work of stock differentiation in the case of swordfish.

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