Analysis of the effect of atmospheric oscillations on physical condition of pre–reproductive bluefin tuna from the Strait of Gibraltar

J. C. Báez, D. Macías, M. de Castro,
M. Gómez–Gesteira, L. Gimeno & R. Real

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Abstract

Analysis of the effect of atmospheric oscillations on physical condition of pre–reproductive bluefin tuna from the Strait of Gibraltar.— The aim of this study was to explore the possible effects of atmospheric oscillations: North Atlantic Oscillation (NAO) and Arctic Oscillation (AO), on the physical condition of bluefin tuna (*Thunnus thynnus*). We estimated a fitness ratio from 3,501 pairs of length–weight data based on bluefin tuna caught in bait–boat fisheries before the spawning season (January, February and March), for each length class and year. In order to obtain a single fitness ratio (K–mean) per year we determined the average for all length classes. We also evaluated Le Cren's condition index (K_{LC}). We observed significant positive correlations between the atmospheric oscillations and both physical condition indexes. In the case of K–mean, the AO explained 75% of the observed variability. Regarding K_{LC}, the NAO explained approximately 73% of the observed variability, while the AO explained 70% of the observed variability. The increase in physical conditions of bluefin tuna in association with positive atmospheric oscillations could be mediated by the increase in the prevalence of strong trade winds. We concluded that the increase in the prevalence of strong westerly winds, mediated by a positive AO or NAO, favours the trip from the Atlantic to the Mediterranean by reducing energy costs due to migration and by increasing the supply of nutrients at the surface by the mixing of deep water and surface water in local areas such as the Strait of Gibraltar.

Key words: Arctic Oscillation, Atmospheric Oscillations, Clime, North Atlantic Oscillation, Fisheries, Tuna.

Resumen

Análisis del efecto de las oscilaciones atmosféricas en la condición física del atún rojo del estrecho de Gibraltar antes de su reproducción.— El objetivo de este estudio fue explorar los posibles efectos de las oscilaciones atmosféricas, la oscilación del Atlántico Norte (NAO) y la oscilación del Ártico (AO), en la condición física del atún rojo (*Thunnus thynnus*). Para ello, estimamos un índice de condición física para cada clase de talla y año a partir de 3.501 pares de datos de talla–peso de atunes capturados en la pesca de cebo vivo antes de la temporada de desove (enero, febrero y marzo). Con el fin de obtener un valor único del índice de condición física (K–mean) por año calculamos el promedio de todas las clases de talla. Además, calculamos el índice de condición física de Le Cren (K_{LC}). Observamos correlaciones positivas significativas entre las oscilaciones atmosféricas y los dos índices decondición física. En el caso del K–mean, la AO explicó un 75% de la variabilidad observada. En relación con el K_{LC}, la NAO explicó aproximadamente un 73% de la variabilidad observada, mientras que la AO explicó un 70% de la variabilidad observada. El aumento de la prevalencia de fuertes vientos de componente oeste podría intervenir en la mejora de la condición física del atún rojo asociada con una fase positiva de las oscilaciones atmosféricas. Llegamos a la conclusión de que el aumento de la prevalencia de fuertes vientos de componente oeste, ya sea por una AO o una NAO positiva, favorece el viaje de los atunes que llegan desde el Atlántico hasta el Mediterráneo porque, por un lado, reduce los costes energéticos de la migración y, por otro, aumenta la cantidad de nutrientes en superficie al mezclar las capas de agua profundas y superficiales en zonas locales como el estrecho de Gibraltar.

Palabras clave: Oscilación ártica, Oscilaciones atmosféricas, Clima, Oscilación del Atlántico Norte, Pesca, Atún.

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José C. Báez, David Macías & Raimundo Real, Depto. de Biología Animal, Fac. de Ciencias, Univ. de Málaga, E–29071 Málaga, España (Spain).– Maite De Castro, Moncho Gómez–Gesteira & Luis Gimeno, EphysLab, Univ. de Vigo, Fac. de Ciencias de Ourense, Ourense, España (Spain).

Corresponding author: J. C. Báez, Inst. Español de Oceanografia (IEO), Centro Oceanográfico de Málaga, Puerto pesquero de Fuengirola s/n., 29640 Málaga, Spain.

E–mail: jcarlos.baez@ma.ieo.es

Introduction

Many studies have described the response of tuna regarding factors such as distribution and recruitment to climatic variability (Fromentin et al., 2000; Fromentin, 2001, 2002a, 2002b, 2002c, 2003, 2009; Ravier–Mailly, 2003; Ravier & Fromentin, 2001a, 2001b, 2001c, 2002, 2003, 2004; Borja & Santiago, 2002; Mejuto, 2003; Caballero–Alfonso et al., 2012; Di Natale & Idrissi, 2012) and the cumulative influence of climate variability during the life history of fish (Báez et al., 2011b). Studies on the effect of climatic variability on the physical condition of tuna, however, are scarce (Golet et al., 2007; Báez et al., 2011b).

The bluefin tuna (*Thunnus thynnus*), an economically important fish, is a highly pelagic migratory species and the largest member of the Scombridae family. According to the International Commission for the Conservation of Atlantic Tunas, this species is managed considering two stocks in the Atlantic Ocean: one that spawns in the Gulf of Mexico, and the other that spawns in the Mediterranean Sea. In the Mediterranean Sea, bluefin tuna are currently commercially caught mainly by purse seiners and tuna traps; catches by other gears are minor. Most catches occur just before, during and just after the spawning season —mainly from March to August, with a peak in June—, taking advantage of the massive influx of bluefin tuna from the Atlantic through the Strait of Gibraltar to the spawning grounds in the Mediterranean. In addition, some small–scale fishery is carried out by bait–boat and hand lines in the Strait of Gibraltar throughout the year (fig. 1). Commercial bait–boats in this area mainly target adult bluefin tunas.

The North Atlantic Oscillation (NAO) is a dominant pattern of coupled ocean–climate variability in the North Atlantic and Mediterranean basin (Hurrell, 1995). However, this atmospheric oscillation is closely correlated with Arctic Oscillation (AO). Nevertheless, the dominant mode of atmospheric circulation variability in the Northern Hemisphere is determined by the Arctic Oscillation (AO). The AO is characterized by a meridional dipole in atmospheric sea level pressure between the northern polar regions and mid–latitudes (Thompson & Wallace, 1998). The AO has been attributed to stratosphere–troposphere coupling. According to Thompson et al. (2000), this includes the NAO, which may be considered a different view of the same phenomenon. Thus, the AO and the NAO both tend to be in a positive phase during winters when the stratospheric vortex is strong (Douville, 2009). Few studies have analyzed the possible effect of the AO on fish ecology; for example, Yatsu et al. (2005) studied this effect in the Pacific Ocean, and Gancedo (2005) in the Atlantic Ocean.

The aim of this study was to explore the possible effects of the NAO and AO on the physical condition of bluefin tuna.

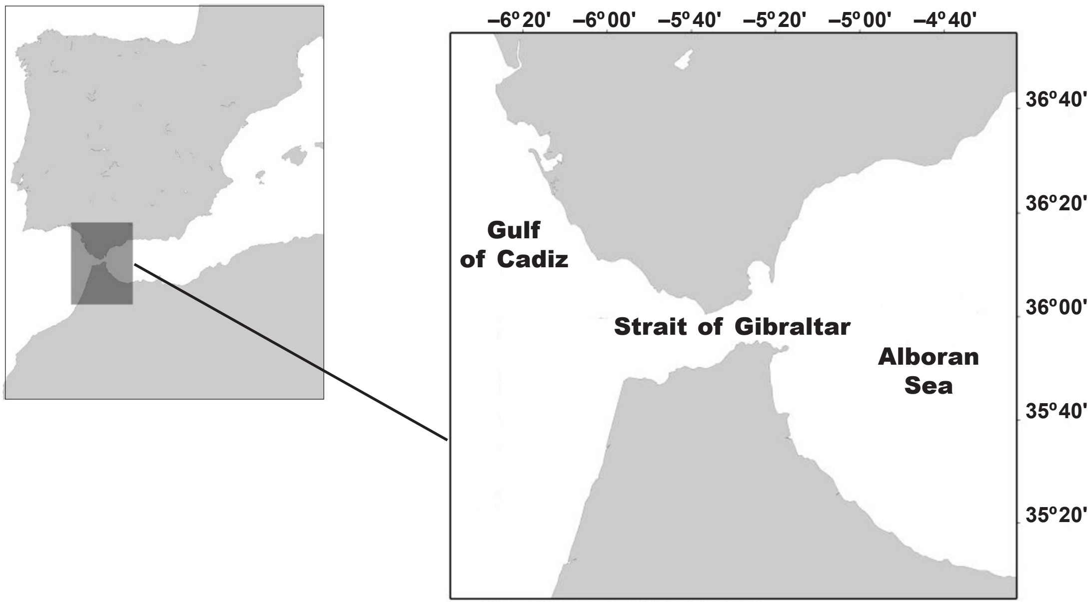

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Fig. 1. The study area was centred on the Strait of Gibraltar. The Strait of Gibraltar separates two regions: the Gulf of Cadiz (in the Atlantic Ocean) and the Alboran Sea (within the Mediterranean Sea).

Fig. 1. La zona del estudio tiene en su centro el estrecho de Gibraltar. El estrecho de Gibraltar separa dos regiones: el golfo de Cádiz (en el océano Atlántico) y el mar de Alborán (en el mar Mediterráneo).

Table 1. Length–weight relationship parameters per year for the bluefin tuna (*Thunnus thynnus*) longer than 130 cm FL, and caught in bait–boat between January and March in the Strait of Gibraltar: Year. Year of harvest; n. Number of tunas sampled per year; R^2. Regression coefficient from each adjust the length–weight relationships, according to the function: $W = a \cdot FL^b$ (i), where W is the weight and FL is fork length; *P*. Significance observed per function; *a*. Constant parameter of the function; *b*. Power parameter of the function.

*Tabla 1. Parámetros que relacionan la talla y el peso por año para los ejemplares de atún rojo (*Thunnus thynnus*) cuya longitud furcal supere los 130 cm y se hayan capturado en la pesca de cebo vivo entre enero y marzo en el estrecho de Gibraltar: Year. Año de la captura; n. Número de atunes muestreados por año;* R^2. *Coeficiente de regresión de cada ajuste de las relaciones talla–peso, de acuerdo con la función:* $W = a \cdot FL^b$ *(i), donde W es el peso y FL es la longitud furcal;* P. *Significancia observada por función;* a. *Parámetro constante de la función;* b. *Potencia de la función.*

Year	n	R^2	*P*	*F*	*a*	*b*
2001	681	0.969	< 0.001	20888.4	0.0485	2.808
2002	482	0.977	< 0.001	20298.9	0.0332	2.8894
2003	683	0.969	< 0.001	18868.9	0.0892	2.6961
2004	170	0.956	< 0.001	3691.77	0.0476	2.8221
2005	401	0.95	< 0.001	7608.74	0.0581	2.7841
2006	139	0.981	< 0.001	7089.96	0.0338	2.885
2007	582	0.95	< 0.001	11087	0.0608	2.772
2008	308	0.931	< 0.001	4109.96	0.1155	2.6539
2009	35	0.886	< 0.001	256.58	0.0249	2.949
2010	20	0.951	< 0.001	348.38	0.1625	2.5771

Material and methods

The study area coincides with the the fishing ground located in Spanish waters of the Strait of Gibraltar between the Rock of Gibraltar and Cape Trafalgar (fig. 1).

We hypothesized that the physical condition of bluefin tuna before the spawning season could be associated with atmospheric oscillations. Under this hypothesis, the accumulation of fat by adult bluefin tuna during the pre–spawning period could have reproductive benefits during the spawning season and be a crucial factor in spawning success.

The length–weight relationship (LWR) in fishes is a widely used tool in fisheries biology and has several applications in population dynamics and stock assessment. Moreover, the LWR in fishes from a specific geographic region during a specific season could be useful to estimate their physical condition. We used 3501 pairs of length–weight data based on bluefin tuna caught in bait–boat fisheries before the spawning season (January, February and March) from 2001 to 2010 (see Macías et al., 2011) (table 1).

To adjust the length–weight relationships, a power curve regression was used according to the function:

$$W = a \cdot FL^b \qquad \text{(i)}$$

where W is the weight, FL is fork length, and *a* and *b* are parameters of the function. According to Froese (2006), based on the length–weight relationship, it is possible to estimate a fitness ratio or K–mean for each length class and year:

$$K\text{–mean} = a \cdot FL^{(b-3)}$$

to obtain a single value of K–mean per year we obtained the average for all length classes, because K–mean could be affected by changes in length (Le Cren, 1951; Nath Saha et al., 2009). According to Le Cren (1951), the effect of length could be eliminated using Le Cren's condition index (K_{LC}, hereafter): Wo/We; where Wo is the weight observed per fish, and We is the weight estimated from the formula (i).

Atmospheric data

Monthly values of the NAO index and AO index during the study period were taken from the website (from 2000 to 2010) of the National Oceanic and Atmospheric Administration: http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao_index.html and http://www.esrl.noaa.gov/psd/data/correlation/ao.data, respectively.

Table 2. The physical condition indexes (K–means and K_{LC}) obtained per year according to Froese (2006) and Le Cren (1951), respectively: NAOsm. Average of the monthly North Atlantic Oscillation index between September of the year prior to capture, to March; AOsm. Average of the monthly Arctic Oscillation index between September of the year prior to capture, to March (AOsm).

Tabla 2. Los índices de condición física (K–means y K_{LC}) obtenidos por año según Froese (2006) y Le Cren (1951), respectivamente: NAOsm. Promedio del índice mensual de la oscilación del Atlántico Norte entre septiembre del año anterior a la captura y marzo; AOsm. Promedio del índice mensual de la oscilación ártica entre septiembre del año anterior a la captura y marzo (AOsm).

Year	NAOsm	AOsm	K–mean	K_{LC}
2001	–0.1929	–0.927	1.797	0.967
2002	0.1629	0.4406	1.8805	1.00486
2003	–0.429	–0.5657	1.813	0.989
2004	0.12	–0.3131	1.866	1.0249
2005	0.1214	–0.00214	1.844	1.0239
2006	–0.2314	–0.425	1.893	0.991
2007	–0.1271	0.613	1.943	1.00956
2008	0.5414	0.458	1.913	1.0365
2009	0.1429	0.334	1.9044	1.0487
2010	–0.7771	–1.558	1.839	0.986

We expected a delay between the atmospheric fluctuation and the capture and physical condition of bluefin tuna. Since the catches of bluefin tuna in bait–boat occur from January to March, and the feeding season extends from September (end of post–reproductive migration) to March (beginning of reproductive migration), we used the average of the monthly AO and NAO indexes from September of the year prior to capture to March (AOsm and NAOsm, respectively, hereafter).

Data analysis

We initially obtained ten length/weight relationships, one for every year studied. Length and weight frequencies by year can be seen in Macias et al. (2011). The different K–mean and K_{LC} per year (table 2) were estimated from these parameters.

We correlated both parametric variables using Pearson correlations. Normality of the data was tested by means of the Kolmogorov–Smirnov test (Sokal & Rohlf, 1995).

Table 3. Pearson´s correlation obtained between the physical condition indexes (K–means and K_{LC}), obtained per each year according to Froese (2006) and Le Cren (1951), respectively, and the average of the monthly North Atlantic Oscillation index between September of the year prior to capture, to March (NAOsm); and the average of the monthly Arctic Oscillation index between September of the year prior to capture, to March (AOsm).

Tabla 3. Correlación de Pearson entre los índices de condición física (K–means y K_{LC}) obtenidos por año según Froese (2006) y Le Cren (1951) respectivamente, el promedio del índice mensual de oscilación del Atlántico Norte entre septiembre del año anterior a la captura y marzo (NAOsm) y el promedio del índice mensual de la oscilación ártica entre septiembre del año anterior a la captura y marzo (AOsm).

Atmospherics oscillations	K–mean	K_{LC}
AO	$R^2 = 0.752$	$R^2 = 0.695$
	$p = 0.012$	$p = 0.026$
NAO	Not significant	$R^2 = 0.728$
		$p = 0.017$

Results and discussion

We observed positive significant correlations between the atmospheric oscillations and the two physical condition indexes (table 3). In the case of K–mean, the AO explained 75% of the observed variability, while the relationship with NAOsm was not significant (fig. 2). Regarding K_{LC}, the NAO explained approximately 73% of the observed variability, while the AO explained 70% of the observed variability (fig. 3).

Our results indicate that the physical condition indexes (K–mean and K_{LC}) of bluefin tuna caught from the Strait of Gibraltar are associated with the atmospheric oscillations. The present paper is the first reference about the effect of AO on fisheries located that southerly.

Positive AO phase is characterized by a strong polar vortex (from the surface to the lower stratosphere). In this situation, storms increase in the North Atlantic and drought prevails in the Mediterranean basin. When the AO is in a negative phase, the continental cold air sinks into the Midwestern United States and Western Europe, while storms bring rain to the Mediterranean region (Ambaum et al., 2001; Báez et al., 2013).

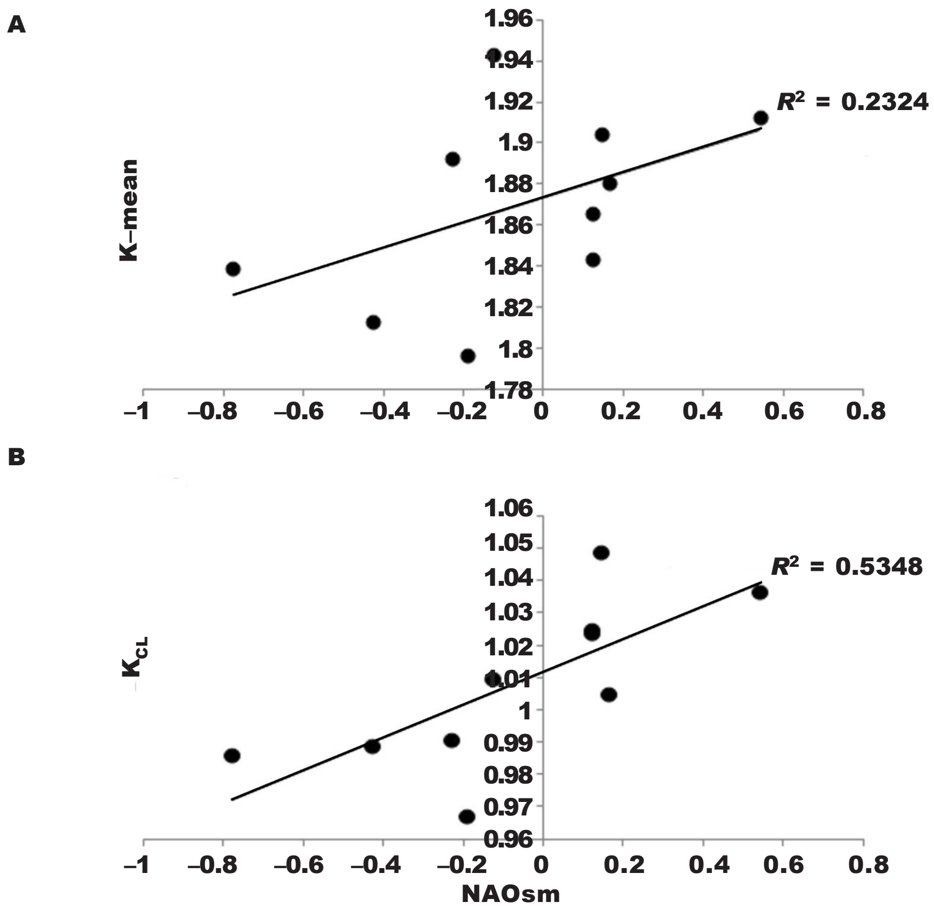

Fig. 2. Plots showing the correlation between the bluefin tuna physical condition indexes and the average of NAO for the period from September (previous year of the capture) to March (NAOsm): A. Relationship between K–mean *vs.* NAOsm; B. Relationship between K_{CL} *vs.* NAOsm. The linear regression coefficient (R^2) is shown in both plots.

*Fig. 2. Gráficos en los que se muestra la correlación existente entre los índices de condición física del atún rojo y el promedio de la NAO en el período comprendido entre septiembre (año anterior a la captura) y marzo (NAOsm): A. Relación entre el K-mean y el NAOsm; B. Relación entre el K_{LC} y el NAOsm. En ambos gráficos se muestra el coeficiente de regresión lineal (*R^2*).*

As Visbeck et al. (2001) reported, a positive NAO phase results in stronger–than–average westerly winds across northern mid–latitudes, which affect both marine and terrestrial ecosystems.

Therefore, the increase in bluefin tuna physical condition in association with a positive AO or NAO could be mediated by the increase in the prevalence of strong westerly winds, in the geographical area delimited between the parallels 40 N and 60 N (Greatbatch, 2000). Strong winds agitate the water, favouring the mixing of deep water and surface water, and thus increasing the supply of nutrients at the surface. Studies from the stomach contents of 595 specimens of bluefin tuna caught from Gibraltar area indicated the opportunistic character of this species in terms of feeding strategy (Serna et al., 2012). Changes in the nutrient concentration in the local area could therefore affect the bluefin tuna in the short term.

Golet et al. (2007) observed a significant decline in the fat and oil content and shape of northern bluefin tuna landed in the Gulf of Maine over a period of 14 years. They suggested this decline was due to an increase in the number of bluefin tuna migrating to the Gulf of Maine from the eastern Atlantic. Thus, according to Golet et al. (2007) both increases in bluefin tuna migration distance and travel through unproductive waters imply a major cost in stored energy.

Similarly, in the case of migrant loggerhead sea turtles, Báez et al. (2011a) observed that prevailing westerly winds during positive NAO phases and the subsequent delayed decrease in SST may lead to

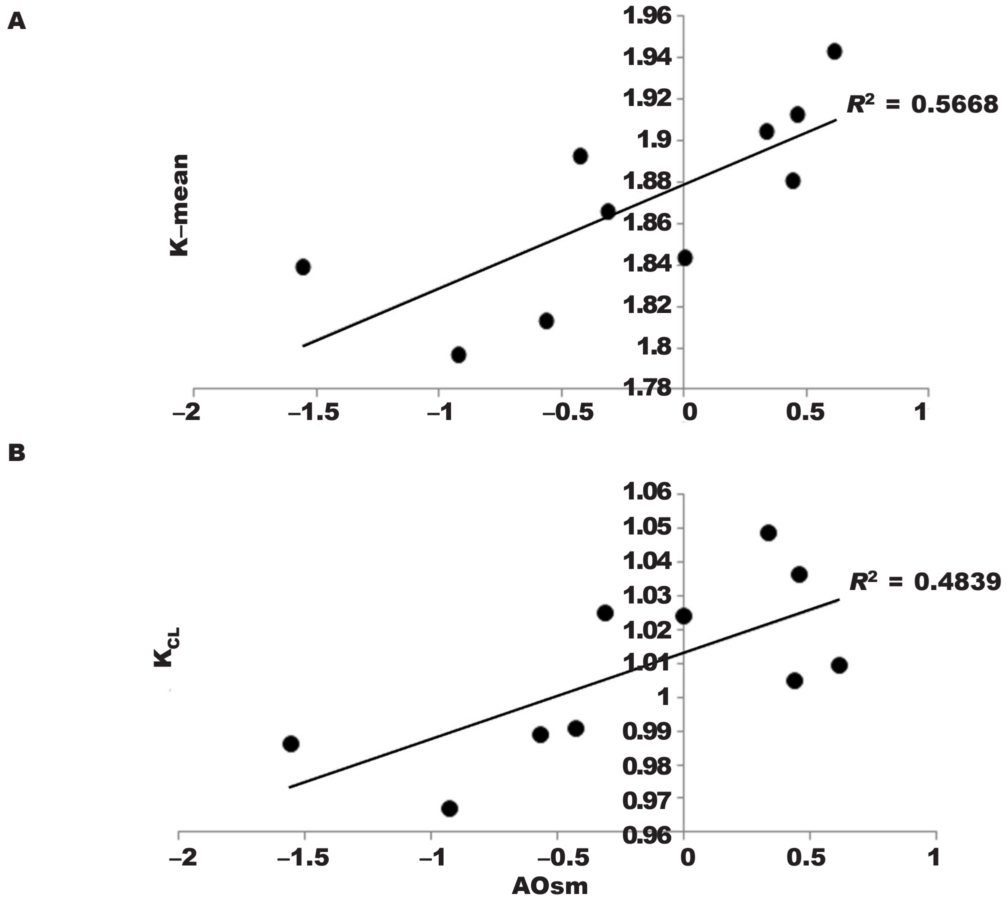

Fig. 3. Plots showing the correlation between the bluefin tuna physical condition indexes and the average of AO from September (previous year of the capture) to March (AOsm): A. The relationship between K–mean *vs.* AOsm; B. The relationship between K_{CL} *vs.* AOsm. The linear regression coefficient (R^2) is shown in both plots.

Fig. 3. Gráficos en los que se muestra la correlación existente entre los índices de condición física del atún rojo y el promedio de la AO entre septiembre (año anterior a la captura) y marzo (AOsm): A. Relación entre el K–mean y el AOsm; B. Relación entre el K_{CL} *y el AOsm. En ambos gráficos se muestra el coeficiente de regresión lineal (*R^2*).*

turtles from the West Atlantic accumulating in the Gulf of Cadiz and Mediterranean Sea.

We concluded that the increase in the prevalence of strong trade winds, mediated by a positive AO or NAO, can improve the physical condition of bluefin tuna in their journey from the Atlantic to the Mediterranean. These strong winds reduce energy costs due to migration and increase the supply of nutrients at the surface by mixing deep water and surface water in local areas such as the Strait of Gibraltar.

Our results indicate that the positive phases of the main atmospheric oscillation in the North Atlantic Ocean (AO and NAO) could favour good physical condition pre–spawning individuals being in. This better physical condition could improve the spawning season (the spawners may lay more and better–quality eggs, and the spawning season could last longer). The better quality of eggs could produce offspring that have higher survival and growth rates, having an effect on subsequent recruitment (Berkeley et al., 2004a, 2004b; Birkeland & Dayton, 2005). In addition, a longer spawning season could improve the survival rate of larvae (Cushing, 1995). More studies are needed to determine further possible relationships between atmospheric oscillations and bluefin tuna recruitment.

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