Assessing the atmospheric oscillations effects on the biology of the bullet tuna (*Auxis rochei*) and its possible linkage with global warming

Pedro Muñoz Expósito

Tese para Obtenção do Grau de Mestre em Biologia Marinha

Trabalho efectuado sob a orientação de José Carlos Báez Barrionuevo (Instituto Espanhol de Oceanografia) e Karim Erzini (Universidade do Algarve)

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Declaração de autoria de trabalho:

Declaro ser autor deste trabalho, que é original e inedito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluida.

If I have seen further, it is by standing on the shoulders of giants.

Isaac Newton (s. XIII)

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To his memory.

LIST OF ACRONYMS

- **AO:** Arctic Oscillation.
- **AOacum:** Arctic Oscillation accumulated.
- **AOpw:** Arctic Oscillation Previous Winter.
- **AOw:** Arctic Oscillation Winter.
- **AOpy:** Arctic Oscillation Previous Year.
- **CMS:** Conservation of Migratory Species of wild animals.
- **ENSO:** El Niño Southern Oscillation.
- **FAO:** Food and Agriculture Organization of the United Nations.
- **FL:** Fork Length.
- **ICCAT:** International Commission for the Conservation of Atlantic Tunas.
- **IEO:** Instituto Español de Oceanografía.
- **IDAPES:** Información de Datos Andaluces de Producción Pesquera
- **IPCC:** Intergovernmental Panel on Climate Change.
- **LWR:** Length-Weight Relationship.
- **NAO:** North Atlantic Oscillation.
- **NAOacum:** North Atlantic Oscillation accumulated.
- **NAOpw:** North Atlantic Oscillation Previous Winter.
- **NAOw:** North Atlantic Oscillation Winter.
- **NAOpy:** North Atlantic Oscillation Previous Year.
- **NMP:** National Monitoring Program.
- **NOAA:** National Oceanic and Atmospheric Administration.
- **PSU:** Practical Salinity Units.
- **UNCLOS:** United Nations Convention on the Law Of the Sea.

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RESUMO

O principal objetivo deste estudo é explorar os possíveis efeitos que as oscilações atmosféricas poderiam ter sobre a condição biológica e desembarques anuais do judeu (*Auxis rochei*). Este estudo também tem como objetivo fornecer mais informações sobre a biologia desta espécie. Num contexto global, onde a exploração de recursos marinhos foi aumentada como conseqüência do desenvolvimento humano, o ecossistema pelágico desempenha um papel importante como fonte de alimento marinho. Mais especificamente, a pesca do atum experimentou um incremento substancial durante as últimas décadas devido ao seu importante valor socioeconômico. Como outras espécies de atum, o judeu é considerado como espécie altamente migratória, que realiza migrações em larga escala para a desova e para as áreas de invernada. No entanto, conforme foi relatado para outras espécies de atum, o comportamento migratório do judeu é susceptível de ser afectado por cambios pontuais no ambiente circundante, numa proporção importante decorrente de variações das condições atmosféricas. No mar Mediterrâneo e Oceano Atlântico, essas oscilações atmosféricas interanuais são indexadas pela oscilação do atlântico Norte (NAO) e a oscilação ártica (AO). As diferentes fases positivas e negativas de ambos os índices estão associadas a um estatuto diferente atmosférico e, portanto, as características oceanográficas das massas de água, bem como os ventos predominantes serão afetadas. Sob esse contexto, este estudo baseia-se no fato de que as oscilações atmosféricas causarão um efeito sobre a condição física de *A. rochei*.

Um total de 2381 indivíduos de *A. rochei* foram capturados utilizando diferentes artes de pesca entre os períodos de tempo comprendidos entre 1983 e 1984, e 2003 e 2015 ao longo da costa do Mediterrâneo espanhol, onde esta espécie tem tanto as áreas de desova como as áreas de alimentação pós-desova. Isto é favorecido pelas características oceanográficas do Mediterrâneo e o mar de Alboran. Entre todos os indivíduos, 152 indivíduos foram encontrados numa fase pós-desova, enquanto o resto foram capturados durante a migração antes da desova que eles executam em direção as areas da desova, relatadas para ser perto das Ilhas Baleares (entre outros). Cada indivíduo foi medido até (comprimento furcal em cm) é pesado até a grama mais próxmo e sexado por meio de determinação visual da gônada. Finalmente cada um foi atribuído a uma classe de idade (1,2 ou 3+). Posteriormente, a relação peso-comprimento anual foi ajustado para uma curva de regressão potêncial, cujos

coeficientes de regressão foram usados para calcular ambos os índices de condição (Kmean e LeCren) individualmente. Além disso, os valores de dados de pesca foram obtidos do website do ICCAT. Finalmente, os valores medios dos indices de oscilações atmosféricas (NAO e AO), obtidos a partir do site do NOAA (National Oceanic and Atmospheric Administration), foram correlacionados com os índices de condição e desembarques anuais por meio do teste não paramétrico de Spearman. Este teste estatístico foi realizado para todo o conjunto de dados, para ambos os sexos e para as três classes de idade; assim como para os indivíduos pre-desova e pós-desova. Além disso, um teste de Mann-Whitney foi utilizado para testar a existência de diferenças significativas entre os períodos reprodutivos e a condição física de ambos os sexos.

Os resultados obtidos neste estudo revelam uma variabilidade não periódica das oscilações atmosféricas, bem como uma independência dos desembarques anuais de judeu em relação com os índices atmosféricos propostos anteriormente. Tendo em conta estes resultados, confirma-se o efeito das oscilações atmosféricas sobre a condição física do judeu. Além disso, o índice de condição física, Kmean, é reforçado durante a fase positiva do NAO, desde que o reforço de ventos ocidentais poderia favorecer a migração para a desova no mar Mediterrâneo. Por outro lado, o índice de condição de LeCren foi significativamente correlacionado com as fases positivas da AO. A perda de peso durante a desova, bem como o reforço dos ventos alísios e disponibilidade de nutrientes durante períodos com AO positivo podem ser as explicações mais plausíveis para este resultado. Além disso, diferenças significativas foram encontradas entre a condição física de machos e fêmeas de *A. rochei*, o que sugere um desenvolvimento gonadal diferencial entre ambos os sexos, onde a condição física em fêmeas era significativamente mais elevada; bem como uma correlação estatística direta entre a condição física de ambos os sexos e os índices de oscilação atmosférica. Isto também confirma que as fases do índice NAO favorecem a migração de *A. rochei* para o mar Mediterraneo.

Relativamente à estrutura de idade, foi dominada por indivíduos de classe de idade 1; fortemente correlacionada com os índices de oscilação atmosférica, onde nos indivíduos em pre-desova, melhor condição foi obtida durante fases positivas de NAO; enquanto as fases positivas da AO foram encontradas para ser associado a um incremento do índice LeCren para machos e fêmeas, em cujos casos apresentam uma condição fisica mais elevada. No caso de espécimes em estadp de pós-desova, apenas o

índice Kmean para a classe de idade 3+ era correlacionado com as fases positivas do índice AO, desde que o reforço dos ventos alísios favorecem a migração para o Oceano Atlântico para as áreas de invernada. Estes resultados confirmam um maior investimento energético efectuado por indivíduos de maior idade durante o período de desova. Em todos os casos, obteve-se um intervalo de tempo que varia entre seis meses e um ano entre a prevalência das condições ambientais e as consequências biológicas observadas nos indivíduos analisados. Estes resultados confirmam que as condições ambientais do ano anterior e na temporada anterior são factores importantes para a variabilidade da condição fisica de *A. rochei* no mar Mediterrâneo sem diferenciação das fases reprodutivas. Finalmente, um crescimento allometrico positivo foi reportado para esta espécie com nenhuma diferenciação de classe de sexo ou idade. No entanto, um crescimento alométrico negativo foi obtido para indivíduos da classe de idade 3+ após o período de desova. Isto sugere um maior investimento energético efectuado por indivíduos de mais idade, que está associado a uma maior perda de peso. No entanto, ainda há vários aspectos da biologia do judeu, como o comportamento migratório completo, que ainda não é completamente compreendido.

Palavras Chave: Mar Mediterrâneo, *Auxis rochei*, ciência das pescas, oscilações atmosféricas.

ABSTRACT

This study aims to explore a possible effect of the atmospheric oscillations on the physical condition and the variability in landings of the bullet tuna (*Auxis rochei*), as well as to provide further information about the biology of this highly migratory species, which is under an increasing commercial pressure. In order to accomplish to accomplish these objectives a total of 2381 individuals of *A. rochei* were collected all over the Spanish Mediterranean coast. Each individual was measured, weight, sexed and aged. The fitness condition indexes (K_{mean} and LeCren) were posteriorly obtained individually after the representation of the length-weight relationships. Additionally, fisheries and atmospheric oscillations data were also obtained. A non-parametric Spearman test (α=0.01) was used to correlate the atmospheric oscillation indexes with both physical condition indexes and annual landings data. Finally, a Mann-Whitney test (α=0.05) was used to test significant differences between the physical condition of males and females for both the pre-spawning and post-spawning individuals.

The results obtained reflect that the atmospheric oscillations, indexed by the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), associated to a time lag (between six months and one year) between the prevalence of the atmospheric conditions and the biological responses in the individuals. Generally, positive phases of the NAO index (negative AO) enhance the migration towards the Mediterranean Sea (higher K_{mean}), and positive phases of AO (negative NAO) favor the exit towards the Atlantic Ocean (higher LeCren index).

These results are explained by the modification of the predominant winds that could favor the migration, as well the nutrients availability after the spawning period. It was also observed that the condition factor in females is significantly larger than in males, which suggests a higher energetic investment in reproduction carried out by females. Finally, a change in growth for older post-spawning individuals was detected, that suggests a higher reproductive investment by older individuals. Nevertheless, despite these findings, further research in this field is needed, since several aspects of the biology of *A. rochei* remain unclear.

Keywords: Mediterranean Sea, *Auxis rochei*, Fisheries Science, Atmospheric Oscillations.

1. INTRODUCTION

1.1. Background.

Historically, the whole Ocean has been widely recognized for being an important source of resources, not only for human consumption, but also for the development of civilizations. Because of this reason, ancient civilizations settled by the coastline; a pattern otherwise followed nowadays (Luebbers, 1978; Veski *et al.*, 2005). Precisely, this tendency allows several coastal regions to benefit from the services provided by marine ecosystems. An important proportion of the food consumed all over the world comes from the sea, either in a direct or indirect way, according to the Food and Agriculture Organization of the United Nations (FAO, 2011). Unfortunately, during the last decades, human developments as well as the increase in the global population have led to overexploited ecosystems (Vitousek *et al.*, 1997; McCauley *et al.*, 2015).

Under this framework, the pelagic ecosystem constitutes an important socioeconomic source for human beings (Würtz, 2010). Several legislations and conventions have attempted to establish legal frameworks for the protection of this ecosystem, by establishing legal frameworks aiming to protect living and non-living pelagic resources (with special attention on the large migratory pelagic species), such as the United Nations Convention on the Law of the Sea (UNCLOS) or the Convention on the Conservation of Migratory Species of Wild Animals (CMS) (also known as the "Convention of Bonn") [1]

In this context, UNCLOS 64th article addresses the rights and liabilities that the signing states have to accomplish in terms of management and conservation, focusing on the so-called "highly migratory species"; a term that indeed makes no reference to any biological definition. The list of these highly migratory species is provided in the Annex 1 of UNCLOS and includes 11 different tuna species (Scombridae), 12 billfish species (Istiophoridae, Xiphiidae), the Genus Trachinotus, 4 species of saurians, dolphinfish (Coryphaena spp.), oceanic sharks and some cetacean species. Moreover, the CMS includes turtles, mammals and marine birds.

In this context, the *International Commission for the Conservation of Atlantic Tunas* (ICCAT) focuses its efforts on the conservation of a group of protected species

[1] see www.fao.org; www.cms.int

(belonging to different families and orders), mainly showing migratory behavior, globally analyzed by the ecosystemic committee of the commission.

Large migratory pelagic species share oceanic phases during their lifetime, performing feeding and reproductive migrations and are also being exposed to be fished either by direct or unintentional fisheries (Southall *et al.,* 2006; Robinson *et al.,* 2009). The ICCAT includes most of the aforementioned species, globally analyzed by the ecosystemic committee of this commission, aiming at species conservation and stocks recovery.

Several authors highlight the fact that marine migratory species may respond to climate oscillations, altering their phenology (Chaloupka *et al*., 2008; Mazaris *et al*., 2008), abundance (Báez *et al.,* 2011a), distribution and recruitment (Borja & Santiago, 2002; Mejuto, 2003; Kell et al., 2005; Goñi & Arrizabalaga, 2005; Graham & Harrold, 2009). Despite these progresses, the effects of the climate on the life of these specimens remain unclear, as well as the alterations that current global warming predictions can cause in natural environments (Robinson *et al.,* 2009). For that reason, the ICCAT recommends the study and analysis of the possible relationships between climatic conditions and large migratory species biology.

1.2. Marine Biological Migration Context versus Global Change.

Migration can be defined as a movement (either individual or massive) among different habitats, aiming to take advantage of better environmental conditions for a certain biological target. Migratory movements may occur either at a local scale or at a transoceanic scale. Moreover, these movements can be classified according to the biological target.

Reproductive migrations take place towards areas where the oceanographic features allow the reproductive process as well as the breeding and larvae maintenance, that will allow holding recruitment levels. In this context, the Mediterranean Sea represents an important migratory ground, chosen by a substantial number of species for spawning purposes. On the contrary, feeding migrations occur towards areas where the food supply is enough to ensure either the recovery from the spawning season in case of mature individuals, or nutrients supply in case of non-mature specimens.

The Mediterranean Sea is one the largest oligotrophic areas within the worldwide seas, whose temperature regimes allow the reproduction and breeding for many migratory species with a special focus on tuna species (Würtz, 2010). For instance, high-valued species such as Bluefin tuna *Thunnus thynnus* (Linnaeus, 1758), albacore *Thunnus alalunga* (Bonnaterre, 1788), or bullet tuna *Auxis rochei* (Risso, 1810) (among others) perform annual migrations towards the spawning areas, at temperatures greater than 24ºC (Schaefer, 2001). Posteriorly, on the way back to the Atlantic Ocean they feed in the Alboran Sea, where the up-welling events provide great amounts of nutrients (Parrilla & Kinder, 1987; Würtz, 2010). In this context, the Strait of Gibraltar is the only entrance and exit for migratory routes from the Atlantic Ocean, not only for tuna species but also for marine mammals and cetaceans. Thus, this area has been widely studied by the scientific community in pursuit of management policies.

Although each species presents its own migratory behavior, it has been postulated by many authors that the surrounding environmental conditions affect those organisms by modifying their phenology in response to climate oscillations. In this context, Global Change is generally presented as a long-term process. Keller (2007) defines this concept as a dual process with a natural component otherwise enhanced by human activity. The natural component of Global Change is characterized by a series of natural events that will make the environmental dynamics of the water bodies less predictable and mistimed, with the subsequent effect on the marine migratory species (Robinson *et al.*, 2009). Because of this, Global Change has focused the interest of the scientific communities during the last decades. In the field of the fisheries research, forecasting future processes would also determine the availability of fisheries resources.

According to the Intergovernmental Panel on Climate Change (IPCC, 2014), the globe will continue experiencing an eventual increase on sea surface temperatures (that can have an effect on the biology of these species) whose magnitude and consequences are hard to predict.

1.3. Tuna fisheries

Tuna species constitute an important socioeconomic resource for many coastal regions, not only because of the volume of landings but also because of the high commercial value that some species attain. Subsequently, the exploitation of these valued species has been intensified during many decades leading to a severe reduction in the abundance (Myers & Worm, 2003). This situation caused the establishment of different management policies depending on the stock like temporary closures, annual catch rates or recovery plans in case of the bluefin tuna.

All these tuna species perform large-scale migrations and hence atmospheric oscillations might have an effect in their biology. Along this line, Báez *et al.*, (2013a) reported a direct relationship between variations on the physical condition of the Bluefin tuna and the North Atlantic Oscillation; affecting tuna fisheries by triggering migrations, changing migratory routes or modifying the fitness condition of the individuals.

In case of small tunas species; they also migrate for spawning and wintering purposes (Garcia *et al.*, 2005; Sabatés & Recasens, 2008). Nonetheless their abundance is much higher than that of large tuna species and constitutes an important fraction of the whole tuna fisheries. The example of the skipjack tuna *Katsuwonus pelamis* (Linnaeus, 1758) reflects clearly this situation since it constitutes the largest tuna fisheries in the world as well as the fourth largest fishery globally. In case of *A. rochei*, this species constitute an important fishery resource worldwide, and its fisheries constitute 39% of the global tuna landings worldwide, (9829 tons in 2010, according to FAO, 2011). Within these species, abundance, recruitment and catchability are strongly controlled by the atmospheric oscillations that alter the surrounding environment. (Forchhammer *et al.*, 2002).

1.4. Bullet tuna (Auxis rochei) biology

Regarding the species considered in this study, *A. rochei* (taxonomical position shown in table 1.1) is one of the smallest members of the Scombridae family. It has been usually misidentified, being confused with *A. thazard* (Lacepède, 1800); however, *A. rochei* is the only *Auxis* species considered in the Northern Atlantic and Mediterranean Sea, a fact supported by genetic studies. (Yesaki & Arce, 1991; Orsi Relini *et al.*, 2008; Froese & Pauly, 2015; UICN, 2015).

The body size and weight of *A. rochei* varies depending on the region. Thus, its maximum length in the Eastern Atlantic Ocean is 51 cm (fork length, FL) (Neves dos Santos & García, 2006), while in the Strait of Gibraltar it is 47 cm (FL) and 1.9 kilograms (Rodriguez-Roda, 1983). Its common length is 35 cm (FL) (Collette & Nauen, 1983).

Table 1.1: Taxonomic position of bullet tuna Auxis rochei.

PHYLUM	***Chordata***
SUBPHYLUM	***Vertebrata***
SUPERCLASS	***Gnathostomata***
CLASS	***Osteichthyes***
SUBCLASS	***Actinopterygii***
ORDER	***Perciforms***
SUBORDER	***Scombroidei***
FAMILY	***Scombridae***

The external appearance (**Figure 1.1**) is characterized by (Valeiras & Abad, 2006):

- An iridescent bluish color of the dorsal region, turning into dark purple (almost black) on the head.
- At least 15 dark oblique to nearly vertical or undulated lines, in the scaleless zone above the lateral line.
- White belly; showing neither stripes nor spots.
- Purple pelvic and pectoral fins, with dark inner sides.
- Black spot on the ventral-posterior border of the eye.

Internally, the most characteristic features are:

- Lack of swim bladder.
- Right liver lobe very elongated, occupying a large portion of the gut cavity; on the contrary, the left lobe is reduced and almost absent.
- 39 vertebrae.
- Presence of cutaneous arteries, divided in dorsal and ventral branches. Ventral branch poorly developed.

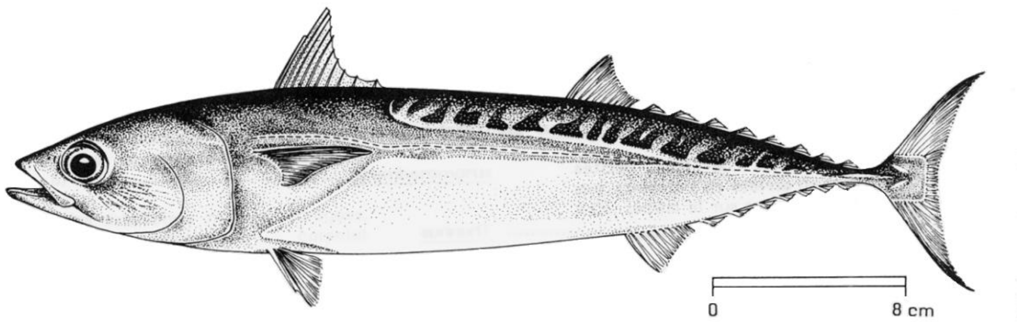


Figure 1.1: *External appearance of the bullet tuna,* Auxis rochei *(Risso, 1810). Source: FAO, 2010.*

Regarding its taxonomical features, *A. rochei* presents:

- Round, robust and fusiform body.
- No scales except on the corselet, which is well developed. Wide corselet in the posterior part.
- Strong median keel on each side of caudal peduncle, between two smaller keels.
- Two dorsal fins separated by a wide gap (as wide as the base of the first dorsal fin). The second dorsal fin is followed by 8 finlets.
- Anal fin followed by 7 finlets.
- Short pectoral fin, which does not reach the scaleless area above the corselet.
- Between 10 and 12 dorsal rays.
- Between 38 and 47 gillrakers in the first arc.
- Single and very large inter-pelvic process, as long as the pelvic fins.

This species is worldwide distributed in coastal areas of both tropical and subtropical waters, associated to the continental shelf of the continents (see **Figure 1.2**). It is present in the Atlantic Ocean, including the Mediterranean Sea. Its latitudinal distribution ranges between 45º N and 35ºS, but it is also found at latitudes beyond Norway and South Africa, or along the coast of Argentina.

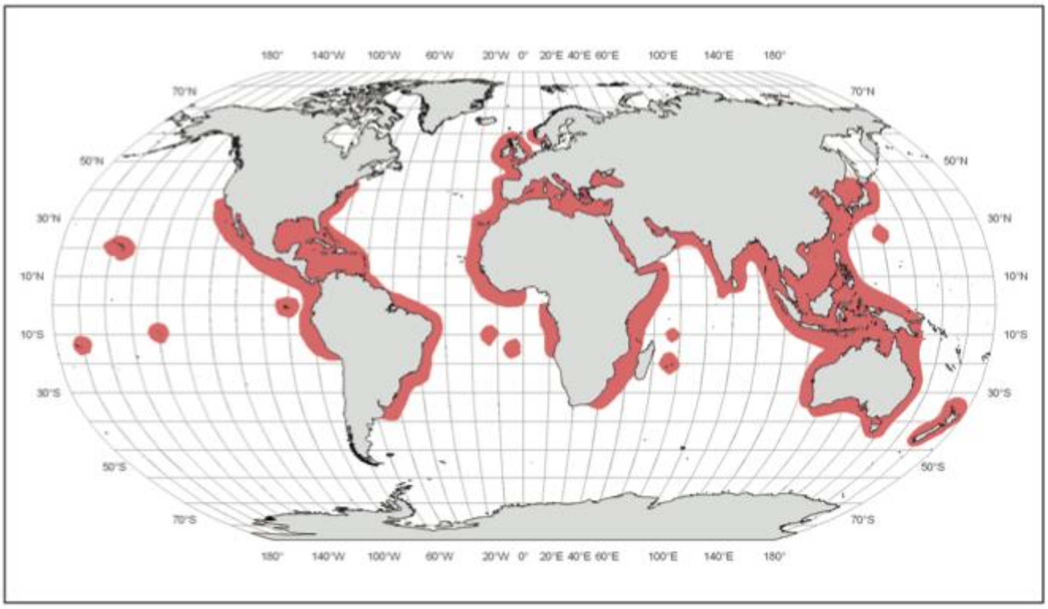


Figure 1.2*: Geographical distribution of* Auxis rochei. *Source: Valeiras & Abad (2006).*

Bullet tuna is a neritic pelagic species that inhabits warm waters ranging between 21.6 and 30.5 ºC (optimal temperature range between 27-27.9ºC), with schooling tendency, that makes them suitable to be exploited by fishing gears such as purse seines, traps or longlines, (landing trends shown in **figure 1.3**). However, information about recruitment is still scarce and information about early life stages is limited since juveniles are not present in fisheries. Immature individuals are caught at around 25 centimeters.

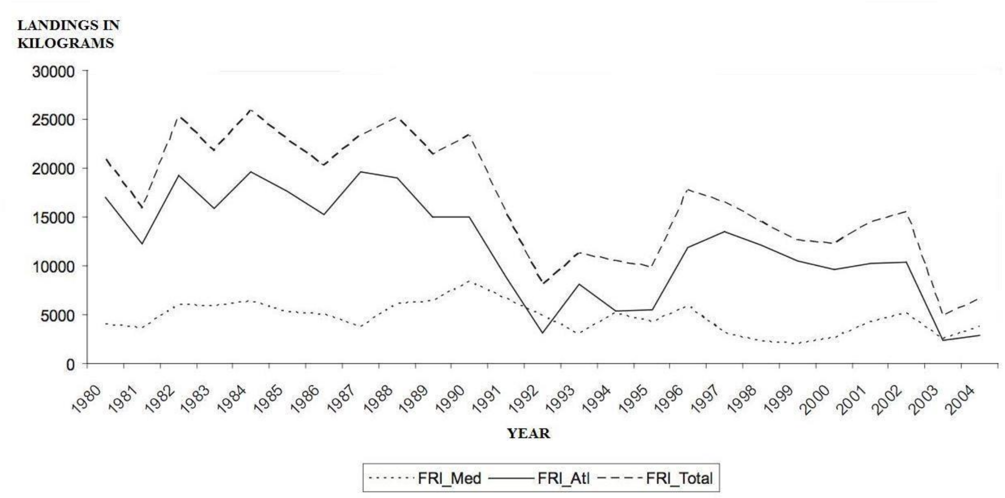


Figure 1.3*: Interannual distribution of captures in kilograms of* Auxis rochei *in the Atlantic Ocean and Mediterranean Sea. Source: www.fao.org.*

Bullet tuna is found in the Western Mediterranean Sea in a sex ratio of 1: 1.7 (Macias *et al.,* 2005) and its reproductive biology is characterized by asynchronous oocyte development. Its spawning period varies with location; however in the Mediterranean Sea mature individuals are found from May, and the spawning period is reported to be between June and September (Piccinetti *et al.,* 1996 ;Alemany, 1997; Macias *et al.,* 2005; Kahraman *et al.,* 2010). Bullet tuna attains sexual maturity at 34.4 cm (fork length) with no sex differentiation, with an average fecundity of 233.941 oocytes per multiple spawning episode. Temperature, as in other tuna species, has been reported to be one of the main drivers for the spawning success, since they migrate towards spawning grounds where sea temperature exceeds 24ºC (Schaefer, 2001).

Regarding diet, food is selected by the size of the gillrakers. Thus according to Mele *et al.* (2014) there is change on the diet of *A. rochei* with the size of the individual as the fish grows. This species feeds on small crustaceans, cephalopods, and small pelagic species like anchovies and clupeids (Etchevers, 1957; Mele *et al.,* 2014). Due to the high abundance, *A. rochei* is considered as an important element of the trophic chain and constitutes an important prey for other commercial species like many tuna species, pelagic sharks, billfish and large pelagic species. (Olson, 1982; Mostarda *et al.,* 2007)

This small tuna species performs annual migrations towards its spawning grounds close to the Balearic Islands (Garcia *et al.,* 2005; Sabatés & Recasens, 2008). Although the full migratory behavior is yet to be fully understood, it is suspected to be affected at some point by the atmospheric oscillations that modulate the environmental conditions. The migratory cycle is composed of a massive movement towards Mediterranean waters in the Balearic islands and surrounding waters, followed by an exit towards the Atlantic Ocean through the Strait of Gibraltar. Both migrations occur close to the shore, where they are fished massively in traps. Moreover, they perform local migrations at a smaller scale around the spawning grounds in neritic habitats, although little is known about this migratory behaviour (Reglero *et al.,* 2012). As aforementioned, since the full migratory behavior is not fully understood yet, the existence of other spawning grounds and wintering areas in the Mediterranean Sea cannot be rejected.

1.5.Atmospheric Oscillations.

It is widely accepted that the planet is experiencing several episodes of rapid Global Warming (Oreskes, 2004).This is considered a natural process, otherwise enhanced by anthropogenic activity (Keller, 2007) and yet to be fully understood in order to be modeled properly. Nonetheless, and despite the increasing concern over the impact of Global Warming on marine biodiversity and fisheries ecology (Yatsu *et al.*, 2005), it is difficult to predict how the atmospheric oscillations could alter marine biodiversity. Recent studies postulate that aquatic ecosystems may become less predictable and modify the timing of certain process, which would decouple with biological dynamics conducted by the migratory species (Robinson *et al.*, 2009). In this sense, different climate oscillation indexes have been proposed to describe punctual shifts in the atmospheric conditions depending on the region studied and the time scale approached. These indexes denote shifts in the atmospheric status that trigger a series of chain reactions in the temperature, salinity and nutrients availability.

For instance, it is a well-known fact the El Niño Southern Oscillation (ENSO hereafter) is a very important atmospheric interannual oscillation in terms of the impacts caused on the Southern Pacific region. This index is given by differences in the atmospheric pressures between the islands of Tahiti (Low Pressure Centre) and Darwin (High Pressure Centre). During its positive phase, warm water masses move towards the South American Pacific coast and the rainfall increase substantially. This situation causes increases on the abundance, recruitment and catchability of many valuable resources; specially pronounced in case of the skipjack tuna on the Southeastern Pacific Coast (Lehodey *et al.*, 1997; Ñiquen & Bouchon, 2004).

In the same sense, the North Atlantic Oscillation (NAO) and the Artic Oscillation (AO) (analyzed in this study) are the most used atmospheric oscillations indexes in the Northern Hemisphere and the Atlantic Ocean, and hence also applicable to the Mediterranean Sea. Both atmospheric oscillations indexes have been widely used to model climate oscillation effects and climate variability in the Atlantic Ocean.

The Mediterranean Basin has become one of the most important “hot-spots” of climate change in the world whose dynamics are yet to be fully understood. According to Robinson *et al.*, 2009, natural processes taking place in inner water bodies (like the Mediterranean Sea) might become less predictable and temporarily decoupled.

Nonetheless, the latest trends reveal a shift to drier and hotter climate; this will lead to changes in the circulation patterns affecting the natural environment and several socioeconomic activities.

The North Atlantic Oscillation is given by a difference between high pressures center, located over the Azores archipelago and the low atmospheric pressures center in the Atlantic Ocean near Iceland. This index represents the main source of climatic variability in the North Atlantic (Serrano & Trigo, 2011), by modifying the intensity and direction of the westerlies (Hurrell, 1995). The positive phase is governed by a reinforcement of the high pressures center; leading to sunny and dry environmental conditions, as well as a reinforcement of the westerlies. A movement of the cyclones southwards defines the negative phase, which increases the rainfall in the Western Mediterranean area, with a subsequent salinity drop. Moreover cloudiness and hence the radiation that reaches the surface gets altered, with the subsequent effect on temperatures (Trigo *et al.*, 2002). **Figure 1.4** represents graphically both phases of the NAO:

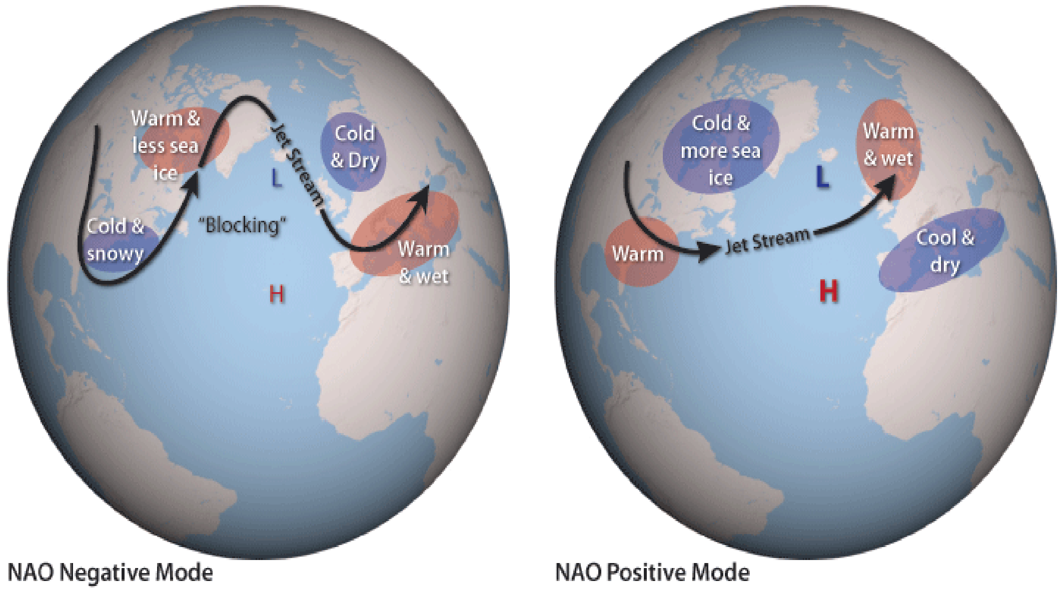


Figure 1.4: *Schematic representation of both phases of the North Atlantic Oscillation. Source: NOAA.*

Regarding the NAO, the winter season has been reported to be the period where the variability in this index has shown to be the greatest (Hurrell, 1995). According to this, most of the observed annual variability in the NAO index occurs during winters, which will condition the predominant climatology during the rest of the year. Moreover, a temporal lag has to be considered when studying the biological effects provoked by atmospheric oscillations shifts; since these oscillations and the biological impacts might be decoupled (Robinson *et al.,* 2009).

Within the Mediterranean region, several impacts are associated with NAO shifts. For instance, and focusing only on local fisheries; Baez *et al*., (2014) reported positive relationships between the annual landing of blackspot seabream, *Pagellus bogaraveo* (Brünnich, 1768) and a positive phase of NAO in the area of the Strait of Gibraltar. Furthermore, the condition factor of the Bluefin tuna, a very valuable resource was found to be enhanced by a positive phase of the NAO (Baez *et al.,* 2013a).

The Artic Oscillation determines the polar vortex intensity, given by a pressures gradient between the inner part of the polar vortex (negative pressures) and the outer part, where the high atmospheric pressures are found. During its positive phase; a reinforcement of the polar vortex occurs, leading to rainfall in the North Atlantic and droughts in the Mediterranean Sea; while the negative phase is characterized by a weakening of the polar vortex leading to intense rainfalls over the Mediterranean area (Baldwin & Dunkerton, 1999). Nonetheless, the Artic Oscillation has been reported to be one of the main sources of NAO shifts (Serrano & Trigo, 2011), exerting a direct influence over the NAO index. **Figure 1.5** represents both phases of the Arctic Oscillation.

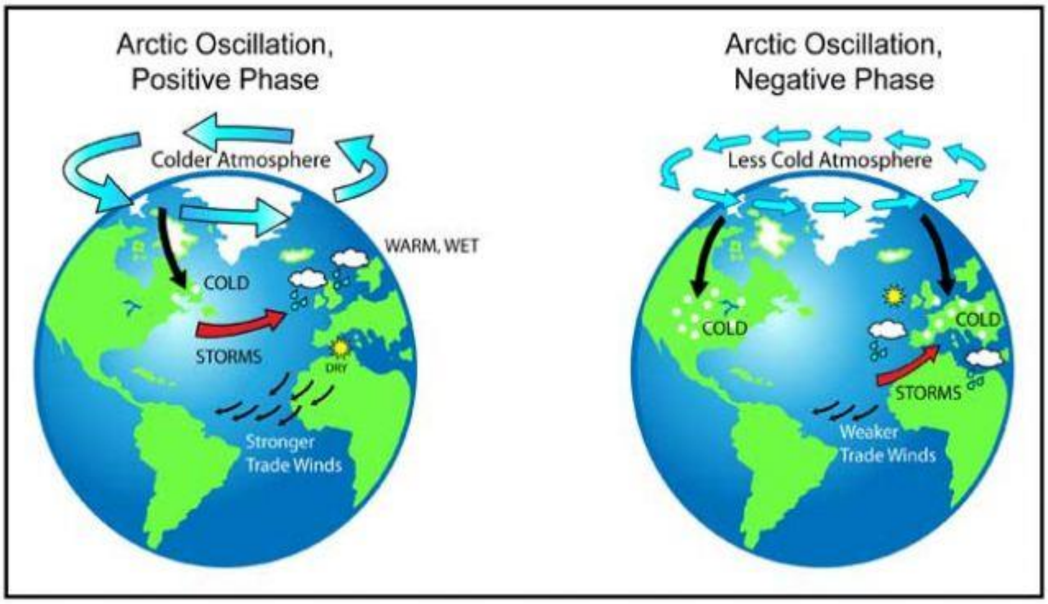


Figure 1.5: *Schematic representation of both phases of the Arctic Oscillation. Source: NOAA.*

Finally, an interconnection between both atmospheric indexes has been postulated (Baez *et al.,* 2013b), although the connectivity patterns remain unclear. According to the hypothesis postulated so far, the Arctic Oscillation seems to control the North Atlantic Oscillation index: a positive AO phase implies a colder atmosphere in the Polar Regions, which could enhance occasional cold waves over the Iberian Peninsula which, when coupled with precipitations favored by a negative NAO, may result in snow precipitation.

1.6. Objectives

The major aim of this study is to elucidate a possible connection between atmospheric oscillations, expressed by the means of the North Atlantic Oscillation and the Arctic Oscillation and the biology of *A. rochei*. In order to accomplish this statement, both physical condition indexes and fisheries landings were tested against the atmospheric oscillation indexes proposed. Moreover, since bullet tuna is considered as a highly migratory species (carries out annual migrations towards its spawning grounds in the Mediterranean Sea and the other way around towards the wintering areas outside the Mediterranean Sea) both migratory phases were considered differently and tested apart. Additionally, the ultimate goal of this study is to contextualize the biological and ecological dynamics of this species and its possible future perspective against Global Warming Forecasts.

Finally, the specific objectives within the context of this study are:

1. To provide interannual Length-weight relationships (LWR, hereafter) for both pre-reproductive and post-reproductive bullet tuna that will allow estimating the physical condition parameters individually (i.e. Kmean and LeCren condition index) to be tested against the atmospheric oscillation indexes. Additionally, LWR are an important tool used to infer certain biological dynamics such as lifespan, growth, or reproductive status.

2. To model the direct relationship between the physical condition of pre-reproductive bullet tuna and the atmospheric oscillations proposed. For that aim both sexes and age class will be considered.

3. To model the direct relationship between the physical condition of post-reproductive bullet tuna and the atmospheric oscillations proposed. For that aim both sexes and age class will be considered.

4. To explore a possible connection between bullet tuna landings in the Atlantic and Mediterranean regions (provided by ICCAT) as well as local landings (provided by IDAPES) and the atmospheric oscillation indexes.

2. MATERIAL AND METHODS

2.1 Study area

The study area covers the Spanish Mediterranean Coast (see **figure 2.1**); more specifically, the sub-basins of the Alboran Sea and Western Mediterranean sea, which present independent and interconnected oceanographic features. This fact makes these two smaller basins play different roles in the biology of the bullet tunas studied.

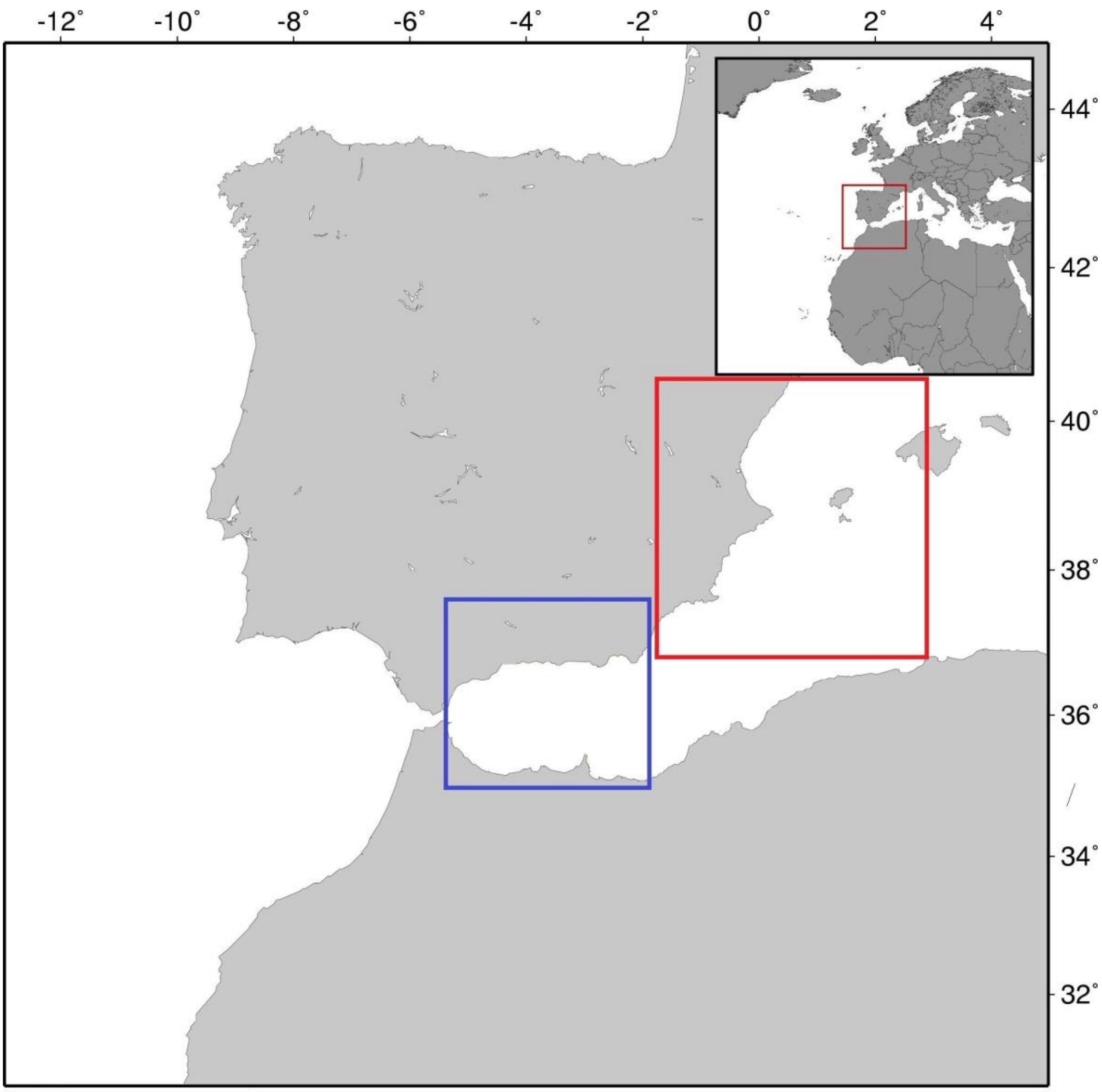


Figure 2.1: *Areas where bullet tunas were obtained Alborán Sea (blue square) and Western Mediterranean Sea (red square). Source: www.seaturtle.org*

Generally, the Mediterranean basin is considered as an inner basin within the Atlantic Ocean. It has a surface area of approximately 2.5 million km^2 with a volume of 3.7 million of km^3, where the Strait of Gibraltar is the only natural connection with the Atlantic Ocean. It has an average depth close to 1400 meters, while the maximum known depth is 5121 meters, reported in the Hellenic trench (Rodriguez, 1982)

The Mediterranean Sea presents a negative hydric balance; meaning that losses due to evaporation exceed the rainfall and run-off inputs. This situation origins the existence of an incoming shallow current from the Atlantic Ocean penetrating into the Mediterranean basin, whereas a denser and deeper Mediterranean water mass flows out towards the Atlantic Ocean (known as thermohalyne circulation). This currents system makes the area of the Strait of Gibraltar to become an especially productive area.

This situation makes primary production heterogeneously distributed; highly influenced by marine currents, freshwater incomes and vertical mixings, indirectly linked to local winds (Notarbartolo di Sciara *et al.,* 2008). According to this a nutrient gradient is created eastwards, leading the western Mediterranean part to become more productive than the Eastern part (Krom *et al.,* 1991), although the whole Mediterranean basin has been reported to be oligotrophic (Würtz, 2010).

The Mediterranean Sea presents warm temperatures during the whole year, no lower than 12.5-13ºC at any depth level, that make the Mediterranean Sea be considered as a warm sea. The average sea surface temperature ranges between 21ºC in the Eastern basin and 15.5ºC in the Western basin. On the other hand, surface salinity values range between 36 and 38 p.s.u. (practical salinity units) (Rodríguez, 1982), increasing eastwards.

Moreover, the present variety of climatic and hydrologic situations found within the Mediterranean pelagic ecosystem allows for the presence of both temperate and subtropical species. Regarding its biodiversity, the Mediterranean Sea is host to a substantial number of different species, despite accounting for only 0.82% of the area and 0.32% of the water volume of the total oceans (Defant, 1961). With regard species richness, the Mediterranean Sea hosts approximately 8500 macroscopic marine species, of which 30 % of them are pelagic (Ribera *et al.,* 1992), and a quarter are endemic (Fredj *et al.,* 1992).

Finally, the current scenarios are characterized by an increase of the anthropogenic activity that has caused impacts on physical, chemical and biological resources. This situation, combined with the numerous environmental values in the Mediterranean Sea have led to the establishment of Marine Protected Areas, where the human activity is restricted, aiming to protect and conserve those values.

2.1.1 Alboran Sea

The Alboran Sea comprises a small Mediterranean basin located between southern Europe and Northern Africa, and between the Strait of Gibraltar and the Almería-Orán front (**Figure 2.2**), which constitutes an important thermohalyne front (Parrilla & Kinder, 1987) usually considered as a reference to establish the eastern limit of this sub-basin

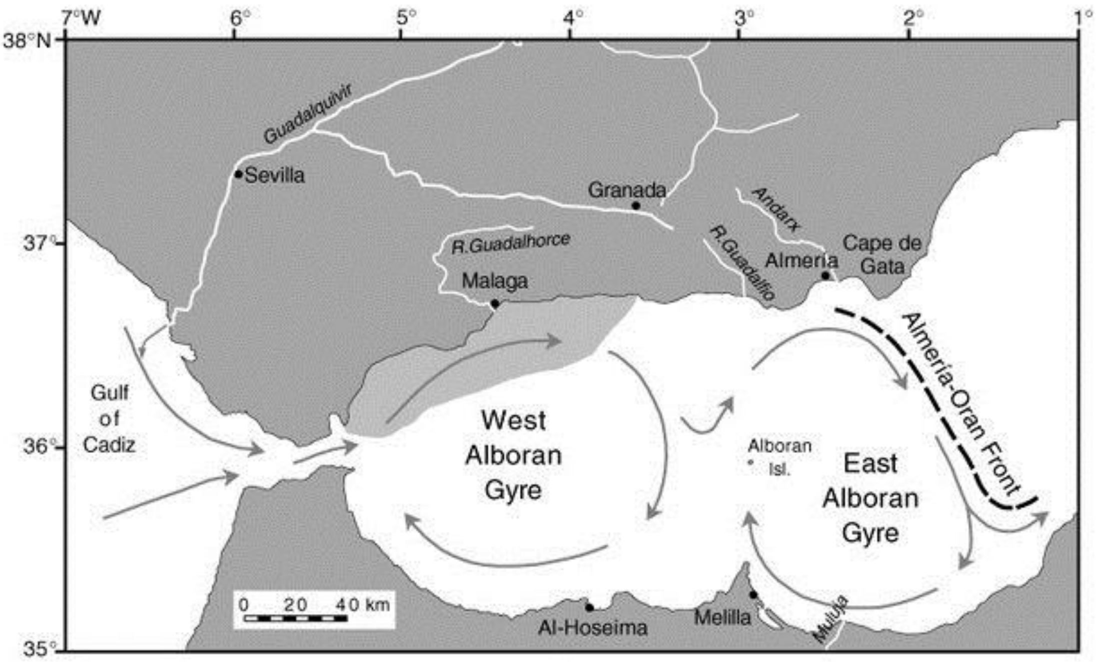


Figure 2.2: *Map of the Alboran Sea showing the gyres that originate the upwelling events .The grey area shows the major phytoplankton productivity area. Source: Hauschildt et al., (1999).*

The currents system originated by the thermohalyne circulation is the origin of the anticyclonic gyres that appear in the Spanish coast of the Alboran Sea, that trigger a series of up-welling events that enhance the distribution of Atlantic water eastwards. The high input of nutrients in the area makes the Alboran Sea a more productive area than the rest of the Mediterranean Sea. This is one of the reasons why the biodiversity in the Alboran Sea is greater than other Mediterranean sub-basins and why it also has been reported to be a feeding area for migratory species (Würtz, 2010).

Regarding the Oceanographic characteristics, the Alboran Sea presents surface temperatures ranging between 15ºC in winter and 21ºC in summer; and salinity values between 36.6 and 37.2 p.s.u. (practical salinity units) in autumn and spring, respectively. Moreover, due to the longitudinal gradient aforementioned, the Alboran Sea is slightly colder and saltier than the rest of the Mediterranean Sea. Finally, the Alboran basin average depth is set around 1000 meters with a narrow continental shelf that make the up-welling events to be especially intense. In terms of this study, the Alboran Sea plays an important since it constitutes a migratory pathway for the bullet tuna towards the spawning grounds (Valeiras & Abad, 2006).

2.1.2 North-Western Mediterranean Sea

The North-Western Mediterranean Sea extends beyond the north of Nao Cape and the Balearic Islands, including the Eastern Spanish coast and the Northern and Western part of Corsica.

It covers an area of 87.500 km^2, presenting a wide continental shelf, although it is quite reduced in some areas (Astraldi *et al.,* 1999). Oceanographically, this area is highly influenced by the intense supply of freshwater from river run-offs. This produces an increase of the suspended matter and hence an increase of the primary production and a partial reduction of the salinity. Moreover, seasonal upwelling events keep a high productivity and biological diversity.

Within the framework of this study, this area is important since it has been widely reported to be the spawning ground for many tuna species, that perform annual migrations to this sub-basin for reproductive purposes.(Garcia *et al.,* 2005; Sabatés & Recasens, 2008).

2.2. Biological data

A total of 2381 individuals of *A. rochei* were collected from different locations along the Spanish Mediterranean coast (**Figure 2.3**). These sampling locations are spatially divided between the Alboran Sea and Western Mediterranean Sea.

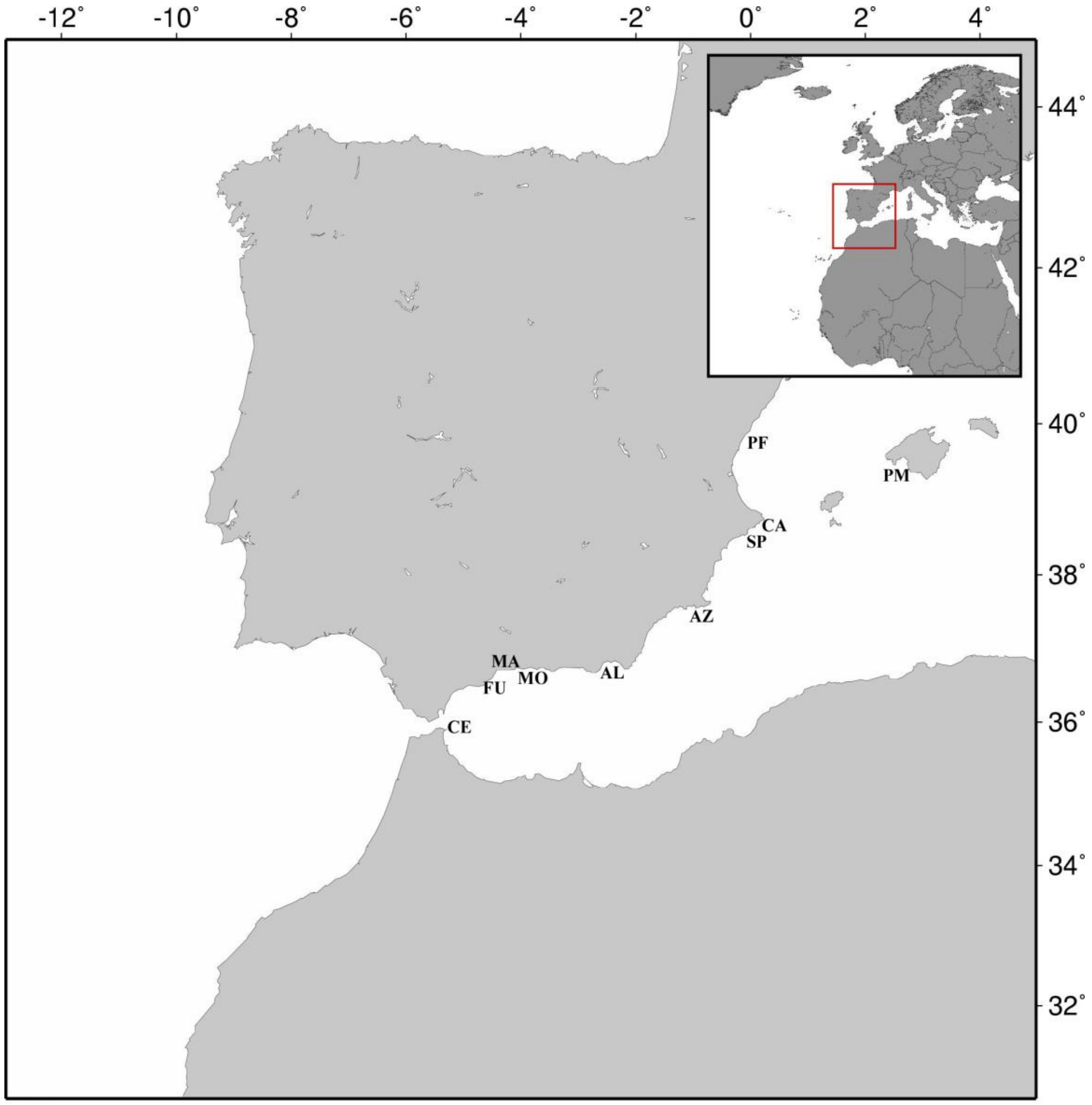


Figure 2.3: *Detail of the sampling locations along the Alboran Sea and Western Mediterranean Sea. Key: CE=Ceuta; FU=Fuengirola; MA=Málaga; MO=Motril; AL=Almería; AZ=La Azohía; SP=Santa Pola; CA=Calpe; PF=Pobla de Farnals; PM=Palma de Mallorca. Source: www.seaturtle.org.*

Bullet tunas considered in this study were collected from Spanish commercial fisheries in two different time periods. The first one is comprised between 1983 and 1984; while the other period surveyed occurs between 1993 and 2015.

These samplings were conducted according to a random stratified design covering the length range of this species in the studied area, within the framework of the National Monitoring Program (NMP) developed by the ICCAT. Fork length of each individual was measured to the nearest centimeter (cm), and weight recorded to the nearest gram (g) (**Figure 2.4**):

Figure 2.4*: Detail of the measurement of one individual.*

Posteriorly, the fish were eviscerated and sexed (nevertheless not all the records were sexed) by mean of visual examination of the gonad (detail of the external appearance of the gonad shown in **Figure 2.5**), preserving a piece of the gonad, fixed in Bouin`s fixative solution for a complementary histological analysis (disregarded in this study):

A

B

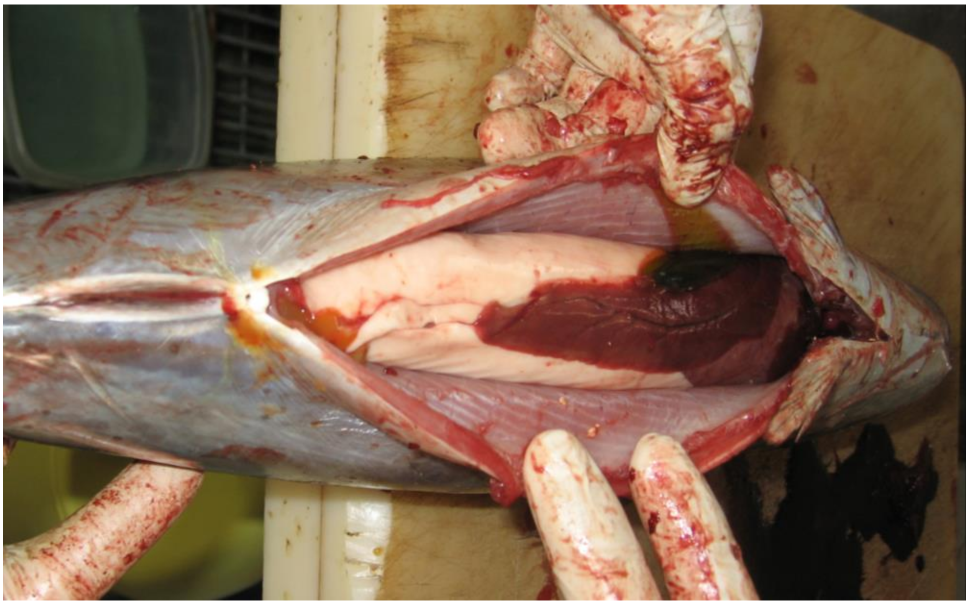


***Figure 2.5**: Detail of the external appearance of the gonads of A. rochei. A) Female gonads; B) Male gonads.*

In addition, an estimated age was assigned to each individual according to the age-length key provided by Valeiras *et al.* (2008). This key (given in table 2.1) is based on ageing of the individuals by otoliths reading and posteriorly reflecting the proportion of individuals found in each age class at each centimeter interval. Thus, an estimated age can be assigned to each individual based only on the fork length. Three different age classes were assigned: 1, 2 and 3+, with age class 3+ including the individuals belonging to age class 3 and older individuals. This consideration aims to minimize the associated error of ageing larger individuals that could be included in more than one age class:

Table 2.1: Age-length key representing the percentage of individuals per age class observed according to the furcal length of the specimen in centimeters.

Furcal Length (cm)	Age 1	Age 2	Age 3+
<34	100	0	0
35	96	4	0
36	93	7	0
37	80	20	0
38	69	31	0
39	7	61	32
40	0	57	43
41	0	29	71
42	0	25	75
43	0	17	83
>43	0	0	100

Posteriorly, a length-weight relationship per year was obtained and fitted to a non-linear power regression curve, as follows: $Weight = a * Length^b$ (Equation 1); where "a" and "b" are the power regression coefficients, and "Weight" and "Length" are the weight of the individual expressed in grams (g) and the length of the fish expressed in centimeters (cm), respectively.

Parameter "b" provides information about certain biological dynamics of the species. In this point, according to the cube law, reviewed by Froese (2006), that parameter "b" should have a value of 3 for species with isometric growth (i.e. the individuals grow in the same proportion in the three spatial dimensions), presenting the same condition status and form for both the small and the large specimens. If b≠3, allometric growth is assumed. According to this, b>3 is interpreted as positive allometric growth and large specimens have increased height or width more than length. This could be due to ontogenic changes (which are rare) or because large specimens analyzed were thicker than the smaller ones (quite common). Finally, a value of "b" lower than 3 (b<3) is interpreted as a negative allometric growth and then large specimens have changed their shape to become more elongated or they present a better nutritional status or fitness condition than the small ones.

Two different condition indexes were also calculated individually, using the annual regression coefficients obtained previously from the LWR. On the one hand, the modified Fulton´s condition index was calculated according to the following expression (in Froese, 2006) (Equation 2):

$$K_{mean} = 100 * (a * L^{(b-3)})$$

Equation 2: Mean condition index (K_{mean}) expression; where "a" and "b" are the regression coefficients, and L is the length of the individual introduced in centimeters (cm).

This index (K_{mean}) is equivalent to the Fulton condition index and provides important information about the nutritional and fitness status (Sutton *et al.,* 2000). In addition, it removes the effect of the change of weight of the individuals and allows estimating a condition index at a certain length (Froese, 2006).

The LeCren relative condition index was calculated individually according to equation 3 (see Froese, 2006). This expression represents a relationship between the empirical weight (measured *in-situ*) and the weight estimated by means of the LWR (LeCren, 1951; reviewed by Froese, 2006):

$$LC = W/((a * L\hat{}b\ )\ )$$

Equation 3: LeCren condition index (LC) expression; where "a" and "b" are the regression coefficients, L is the length of the individual introduced in centimeters (cm) and W is the weight expressed in grams.

This index expresses a relationship between the observed weight in grams (W) and that obtained by means of the LWR (a*(L^b)). This expression represents a relative condition factor that compensates for any change in form or condition with the increase in length. Thus, this index "measures the deviation of an individual from the average weight for length" (Froese, 2006).

A database containing the whole data set with 2381 records was created and archived in the Spanish Institute of Oceanography (I.E.O. according to the Spanish acronym). Table A.I. (See annex I for un-filtered data and results) gives the number of individuals of bullet tuna captured per location and also per fishing gear. However, prior to any analysis, the database was filtered aiming to detect and delete the presence of possible outliers.

Outliers' removal procedure***:*** The database was filtered taking into account the LeCren condition index obtained individually. This parameter provides information about the relationship between the observed weight and the weight that should be expected applying the mathematical fitting expression. In a first step, the 2381 records were ordered according to the individual LeCren condition factor. Secondly, 1 % of the largest and the smallest values were deleted. This operation aims to eliminate those values that might be outliers. In order to know the percentage of data that should be deleted (10%, 5%, 2% and 1%) the P-value for the chi-square distribution was obtained (α=0.05) until a non-significant difference between the observed and the expected value was obtained.

After the removal of the outliers, a total of 2357 individuals were finally obtained (24 records were deleted). Table 2.2 shows in detail the provenance of the individuals as well as the fishing gear used to collect them.

Table 2.2: Provenance of the 2357 individuals of bullet tuna post-filtered. Key: "Location" corresponds to the place where the individuals were landed; "Fishing gear" refers to the collecting method; and "Subtotal" and "Total" are the partial and total amount of A. rochei per fishing gear and location.

LOCATION	FISHING GEAR	SUBTOTAL	TOTAL SAMPLES
Almeria	Purse Seine	75	75
Calpe	Trolling	4	4
Ceuta*	Trap	151	151
Fuengirola	Purse Seine	99	99
La Azohía	Trap	1845	1918
	Trolling	19	
	Longline	2	
La Pobla de Farnals	Trolling	6	6
Málaga	Purse Seine	7	7
Motril	Purse Seine	24	24
Palma	Trolling	4	62
	Purse Seine	58	
Santa Pola	Trolling	2	2
"No location recorded"	Trolling	6	9
	Trap	3	

2.3. Atmospheric data

Atmospheric data were provided by the National Oceanic and Atmospheric Administration (NOAA), available in the website (see http://www.noaa.gov). Monthly values for both North Atlantic Oscillation and Arctic Oscillation were obtained from this website for the whole period studied and the annual average was obtained. Posteriorly, since the winter season has been reported to be the period of time when climatic variability is the greatest and there is probably a lag between the prevalence of the atmospheric conditions and the biological consequences, the following modified atmospheric oscillation indexes were proposed:

- NAO/AO: Corresponds to the value of the index calculated for the current year with no temporal alterations.
- NAO_{acum}/AO_{acum}: These indexes correspond to the individual mean value of the index according to the age of the specimen. It gives an approach about the atmospheric oscillations that each individual has experienced during its lifetime.
- NAO_{py}/AO_{py}: This modified index corresponds to the value of the index reported the year before. Taking into account this modification a one year-lag between the atmospheric status and the biological response triggered is assumed.
- $^{*}NAO_{pw}/AO_{pw}$: This modification is calculated as the mean value of the winter months for the cited index reported for the previous year. In this case, a six months-lag is assumed between the atmospheric oscillation and the biological response considering only the winter months when variability is the greatest.
- $^{*}NAO_{w}/AO_{w}$: Corresponds to the average value of the winter months considering the previous and the current year winter months.

* It is assumed that winter period covers the time-gap between October of the previous year and March of the current year. Thus, “previous winter” involves only the period between October and December, while “winter” comprises the whole period between October and March.

The atmospheric oscillation indexes, whose interannual trend is shown in **figure 2.6**, present temporal variations as well as a periodicity between positive and negative phases:

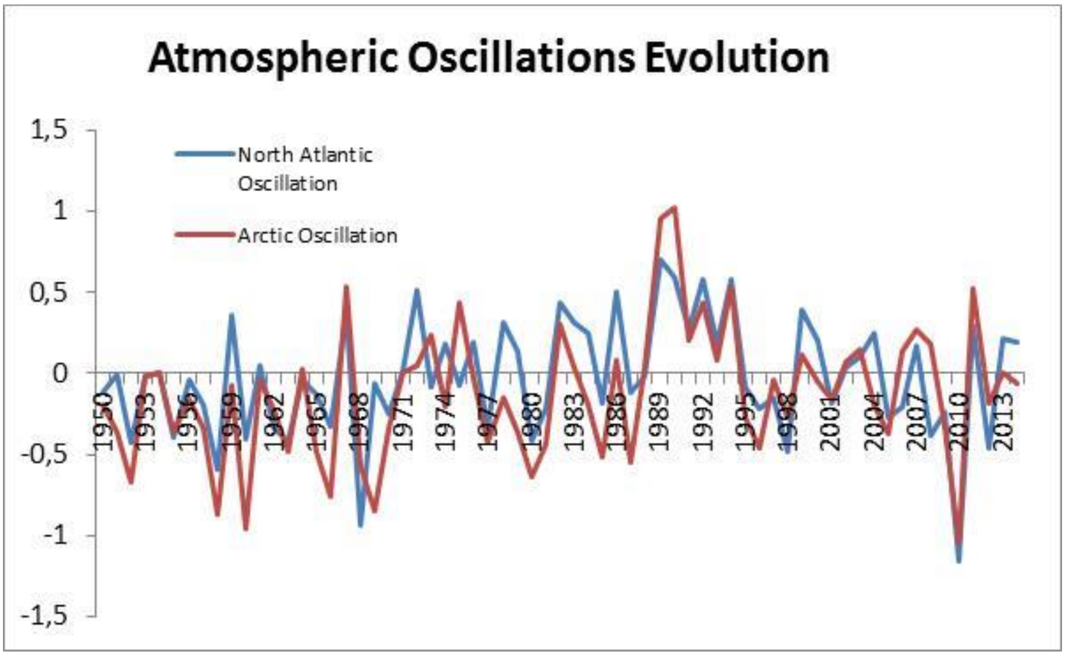


Figure 2.6: Interannual variations of the atmospheric oscillation indexes. Source: NOAA.

Finally, since winter is the period where climatic variability has been demonstrated to be the largest, **figure 2.7** reflects the evolution of the atmospheric oscillation during winter periods.

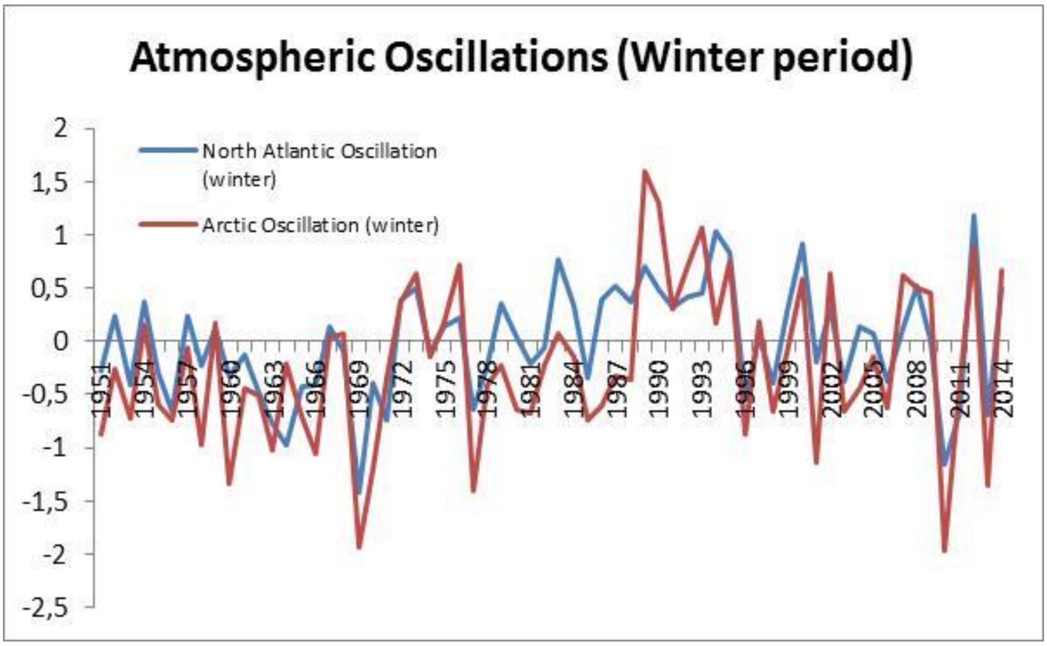


Figure 2.7: Interannual variations of the atmospheric oscillation indexes during winter phase. Source: NOAA.

Finally, a spectral analysis was performed by mean of the PAST software (Hammer *et al.*, 2001) over these data series. This step aimed to find possible temporal trends on the data series that could present a certain ciclycity.

2.4. <u>Fisheries data</u>

Fisheries data were obtained from the ICCAT website (see www.iccat.int), where fisheries data corresponding to the different species are published. These data contained information about nominal catches by species (sorting bullet tuna only), region where the individuals were collected, fishing gear and the flag of the cruise, as well as some other fishing statistics disregarded in this study.

These data were filtered obtaining annual fisheries data only from Spanish fleets in the Mediterranean and Atlantic region. Posteriorly, an annual catch in tonnes was obtained and subsequently separated by the different fishing gears used for the data collection.

Moreover, bullet tuna annual landings from the Andalusian region were obtained from the website: www.idapes.org for both the Atlantic and Mediterranean areas. Finally, a spectral analysis was conducted over these data in order to find any possible temporal trend.

2.5. <u>Data analysis</u>

Normality was tested by using the Kolmogorov-Smirnov test (Sokal & Rohlf, 1995) using the IBM SPSS Statistics software v.19. After that, dependency with time was tested aiming to obtain an interannual cyclic variability in relation with time by means of a spectral analysis (Hammer *et al.*, 2001) for both the atmospheric and fisheries data using PAST software version 2.17c.

A non-parametric Mann-Whitney test at 95% confidence interval (α=0.05) was performed in order to elucidate possible significant differences between the condition factors obtained for males and females. The same test was conducted aiming to test significant differences in K_{mean} and LeCren indexes between pre-spawners and post-spawners individuals.

Subsequently, a Spearman non-parametric test, 99% confidence intervals (α=0.01) was used aiming to correlate the variability observed in the atmospheric oscillation indexes previously proposed and the variability observed in the condition factors. This operation occurred for the individuals in a pre-spawning status and the individuals in a post-spawning status separately. The same test was conducted for the whole data set and, considering only the sex of the individuals and finally considering the three different age classes. Moreover, variability observed in annual landings of *A. rochei* was also tested against the variability of the atmospheric indexes by means of this non-parametric test.

A Spearman non-parametric test 99% confidence interval was chosen due to the large amount of records that constitute the data set, in order to minimize the type 1 error associated with this test.

3. RESULTS

As a general result, the assumption of normality was rejected for all the distributions examined by means of the Kolmogorov-Smirnov test (α=0.05). This fact conditioned the use of non-parametric statistics.

3.1. Atmospheric and landings data

No temporal trend was found for any of the indexes previously proposed, neither for the indexes itself nor for the winter components of these.

The annual trends of bullet tuna landings collected by Spanish commercial fisheries and landed in both Atlantic and Mediterranean ports are presented in **Figure 3.1**. The series shows interannual variability with the presence of peaks repeated after certain years, followed by a marked decrease in the tonnes landed.

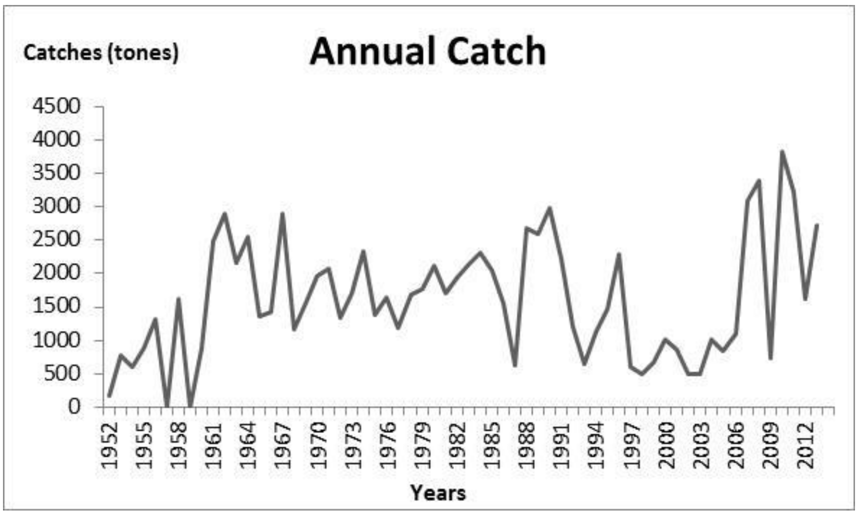


***Figure 3.1**: Evolution of the bullet tuna catches between 1952 and 2013. (Source: ICCAT).*

The figure reflects the evolution of this fishery for the period between 1952 and 2013(the maximum period of data availability provided by ICCAT), where an increasing tendency of total landings of *A. rochei* for the whole period is detected. The lowest catch rates are found between the decade of 1990`s and the first years of the 21st century.

In addition, the proportion of specimens caught by the different fishing gears, operating by Spanish fleet, is showed in the **Figure 3.2.**

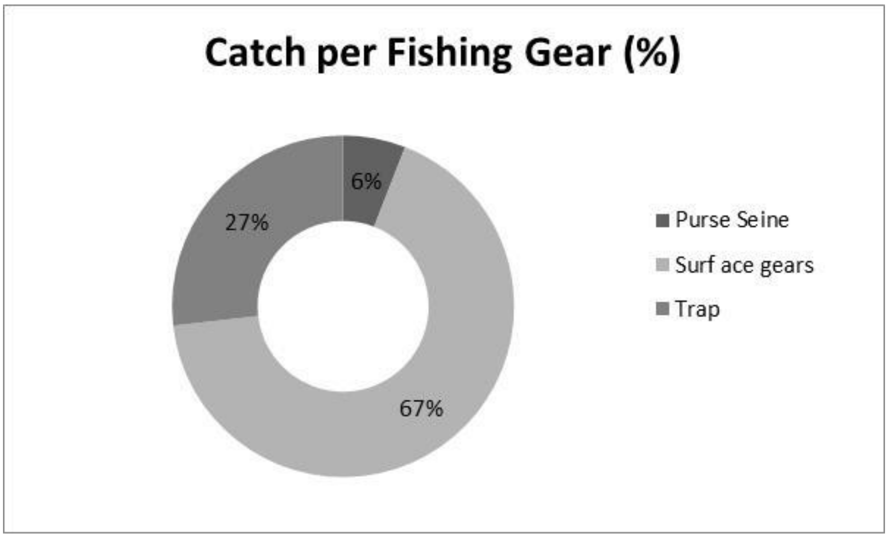


Figure 3.2*: Proportion of individuals caught by the different fishing gears.*

A major proportion of individuals were caught by mean of surface gears (67%), namely different types of longlines, trolling, gill nets, drift nets or caught by small trawlers) since *A. rochei* is usually caught as by-catch species in fisheries targeting other tuna species (Valeiras & Abad, 2006). In addition, a substantial proportion of the specimens were caught in traps (27%) and finally a minor percentage corresponds to bullet tunas caught in purse seines (6%). Other unclassified fishing gears were not considered due to small proportion that represent (<0.1%), and hence they were not taken into account.

Additionally, landings of bullet tuna reported from the Fisheries Statistics of the Spanish southern region (IDAPES) are shown in **Figure 3.3**:

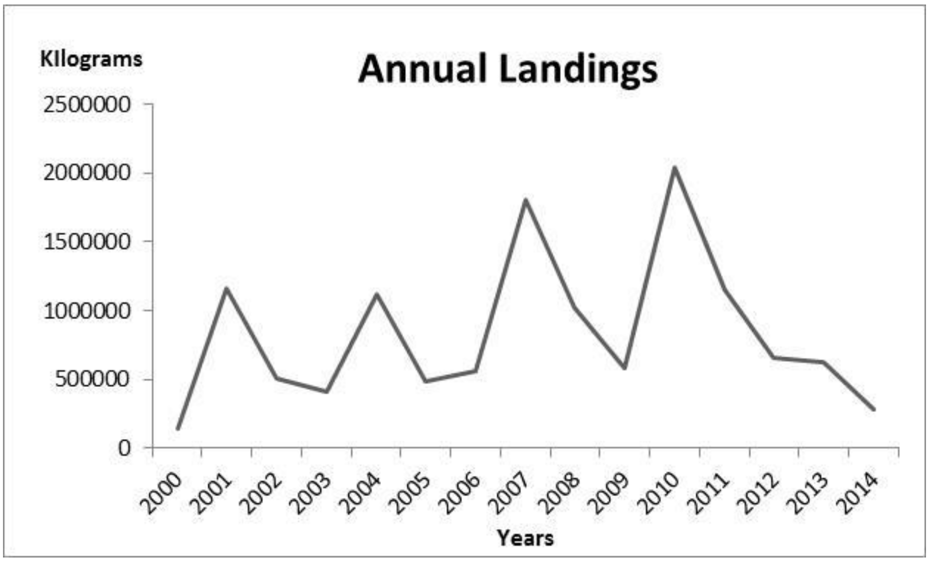


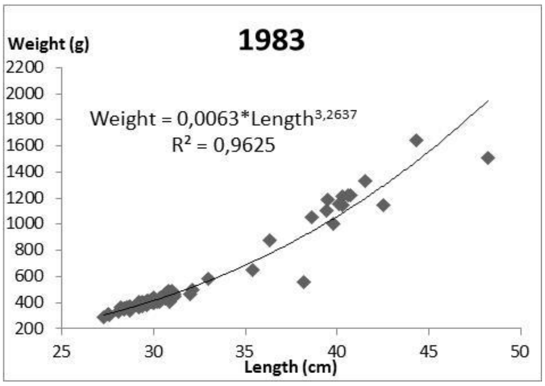
***Figure 3.3**: Evolution of the bullet tuna regional catches between 2000 and 2014. (Source: IDAPES).*

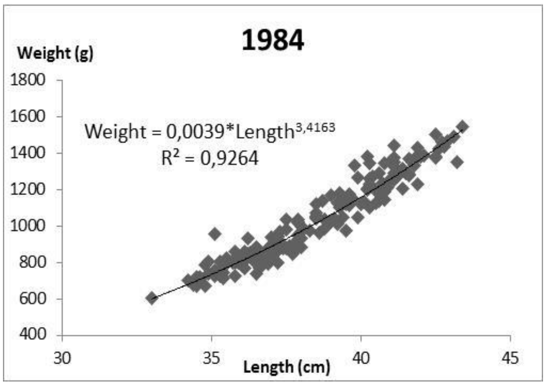
As obtained in case of the ICCAT fisheries data (**figure 3.1**), interannual variability was also found in local landings. During the last fifteen years, strong variations in the bullet tuna landings were found with marked peaks every few years followed by strong decreases in catches. The highest landing was reported in 2010 (close to 2000 tonnes); while the lowest record belongs to year 2000. However, the spectral analysis performed did not reveal any temporal tendency within this series.

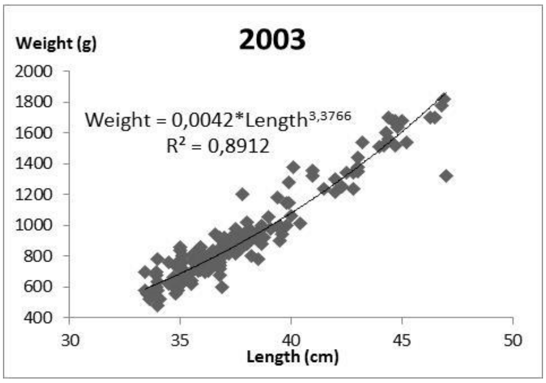
No statistically significant correlation was found between the annual landings and any of the atmospheric oscillation proposed (i.e. NAO, NAO_w, NAO_{py}, NAO_{pw} and AO, AO_w, AO_{py} and AO_{pw}).

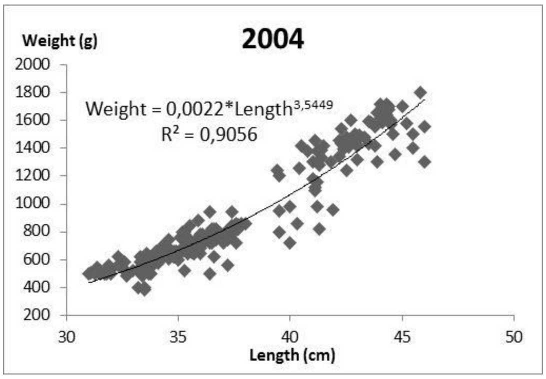
3.2. Length-weight relationship and condition indexes

3.2.1. Pre-Spawning Individuals: Length-weight relationships were obtained for those individuals caught in pre-spawning status (N_{total}=2206). These relationships are presented annually in the figures below (**Figure 3.4**).


1983
Weight (g)
Weight = 0,0063*Length^3,2637
R² = 0,9625
Length (cm)


1984
Weight (g)
Weight = 0,0039*Length^3,4163
R² = 0,9264
Length (cm)


2003
Weight (g)
Weight = 0,0042*Length^3,3766
R² = 0,8912
Length (cm)


2004
Weight (g)
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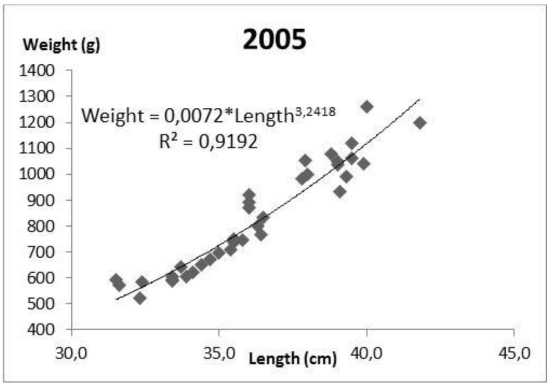
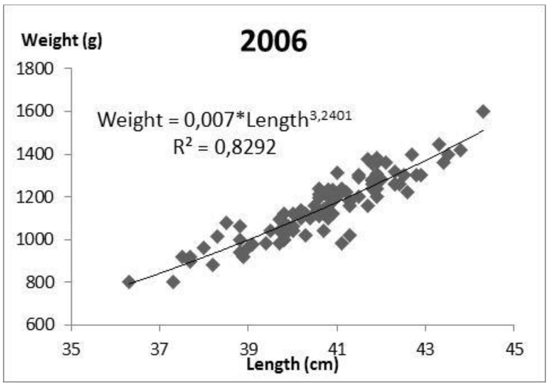
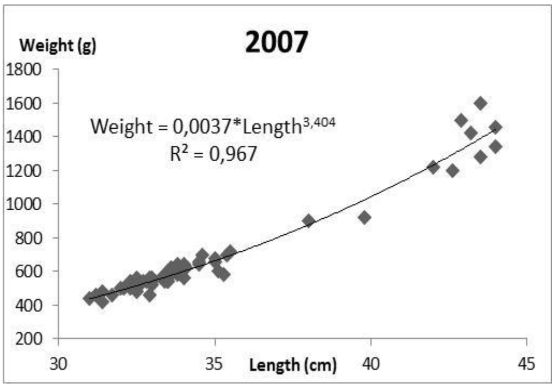
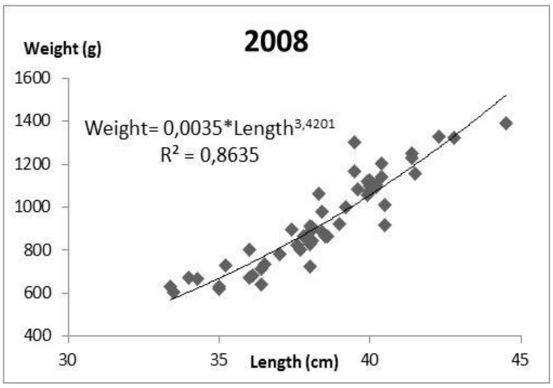
R² = 0,9056
Length (cm)


2005
Weight (g)
Weight = 0,0072*Length^3,2418
R² = 0,9192
Length (cm)


2006
Weight (g)
Weight = 0,007*Length^3,2401
R² = 0,8292
Length (cm)


2007
Weight (g)
Weight = 0,0037*Length^3,404
R² = 0,967
Length (cm)


2008
Weight (g)
Weight= 0,0035*Length^3,4201
R² = 0,8635
Length (cm)

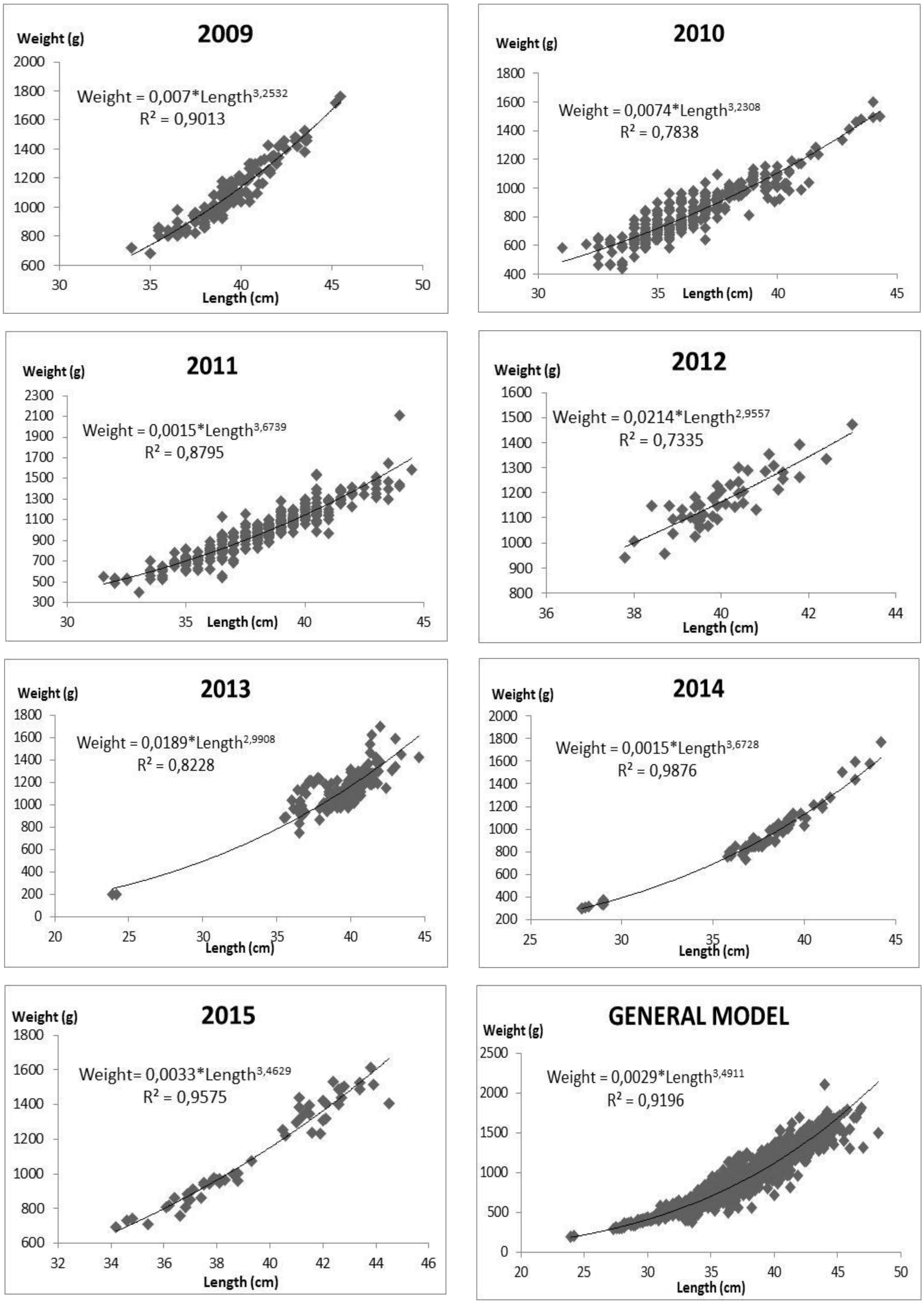


Figure 3.4: *Interannual and general length-weight relationships for pre-spawning A. rochei.*

Table 3.1 summarizes the regression coefficients obtained per each LWR. Additionally, table IV also shows both the average condition index (K_{mean}) and LeCren condition index (LC) per year, calculated by means of equations 2.1 and 2.2. The mean b value (3.343) reflects a positive allometric growth for pre-spawning *A. rochei*. Moreover, regarding both condition indexes mean values, in case of K_{mean}, the result obtained was 1.697; while in case of LeCren index the value obtained was 1.004.

Table 3.1: Regression coefficients obtained for pre-spawning bullet tunas, as well as the condition indexes obtained per year, showing the number of individuals analyzed annually. Key: "a" and "b" are the regression parameter, R^2 is the coefficient of determination and K-mean and LeCren represent the mean condition factors per year.

YEAR	a	b	R^2	K-Mean	LeCren
1983 (N=77)	0.0063	3.26	0.9625	1.485	1.054
1984 (N=180)	0.0039	3.41	0.9264	1.779	1.0008
2003 (N=173)	0.0042	3.37	0.8912	1.649	1.006
2004 (N=226)	0.0022	3.54	0.9056	1.579	1.023
2005 (N=37)	0.0072	3.24	0.9192	1.713	0.997
2006 (N=94)	0.007	3.24	0.8292	1.704	0.999
2007 (N=124)	0.0037	3.4	0.967	1.549	0.996
2008 (N=51)	0.0035	3.42	0.8635	1.619	1.005
2009 (N=115)	0.007	3.25	0.9013	1.775	0.999
2010 (N=445)	0.0074	3.23	0.7838	1.694	1.0001
2011 (N=359)	0.0015	3.67	0.8795	1.746	0.997
2012 (N=50)	0.0214	2.95	0.7335	1.817	1.001
2013 (N=152)	0.0189	2.99	0.8228	1.827	1.0024
2014 (N=71)	0.0015	3.67	0.9876	1.704	0.988
2015 (N=52)	0.0033	3.46	0.9575	1.792	1.0007

Further, regarding a possible correlation between both condition indexes and the atmospheric oscillations indexes proposed, table 3.2 details the correlation found for a 99% confidence interval Spearman test (α=0.01):

Table 3.2: Statistical correlations found between the condition and the atmospheric indexes. Only results with a p-value 0.01 are presented.

Condition Index	Atmospheric Oscillation Index	Rho Spearman
LeCren	AO_{py}	0.265
$\mathbf{K_{mean}}$	NAO_{py}	0.318
$\mathbf{K_{mean}}$	AO_{acum}	- 0.300

Additionally, after sorting by sex LWR for both males and females were obtained (**Figure 3.5**):

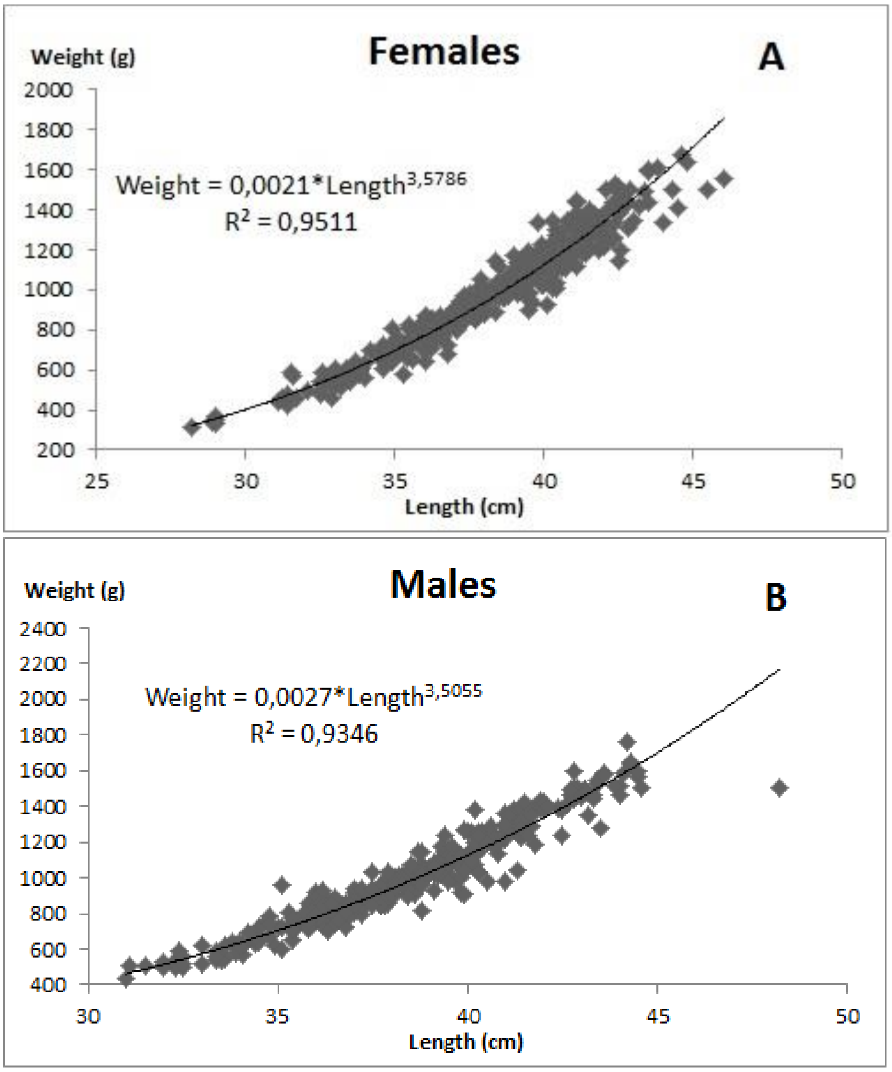


***Figure 3.5**: LWR obtained for both pre-spawning females (A) and males (B).*

Both males and females have positive allometric growth (3.505 and 3.578, respectively). Furthermore, an average K_{mean} value for males of 1.733 and 1. 713 were obtained for females. Regarding the LeCren results, the male average index was found to be 1.006; while for females it was 1.002. A total of 376 females and 307 males were analyzed (the remaining records were not sexed), resulting in a sex ratio of 1:1.224. Finally, significant differences were found between K mean distributions for both sexes (α= 0.035, U=5.217E^4), meaning that physical condition in pre-spawning *A. rochei* does depend on the sex of the individual. In contrast, no significant differences were found between LeCren index for males and females (α= 0.390, U= 5.563E^4). All these results are given in table 3.2.

Table 3.3: Regression parameters and mean condition indexes obtained for both pre-spawning males and females.

Sex	B	R^2	K-mean	LeCren
Males (N=307)	3.505	0.934	1.733	1.006
Females (N=376)	3.578	0.951	1.713	1.002

No significant correlations were found between any atmospheric oscillation index for either of the sexes and the LeCren condition index. Nonetheless, statistically significant results were found in case of K_{mean} (see table 3.4):

Table 3.4: Statistical correlations found between the physical condition and the atmospheric indexes for males and females. Only results with a p-value lower than 0.01 are presented.

Atmospheric Oscillation Index	Rho Spearman
FEMALES	
NAO_{py}	0.268
NAO	0.139
AO	0.157
MALES	
NAO_{py}	0.287
NAO	0.247
NAO_{pw}	0.289

These results confirm a direct relationship between atmospheric oscillations and the fitness condition of both males and females. NAO is the index that explains the greater part of the variability in K_{mean} (26.8% in case of females and 28.7% in case of females, considering the previous year NAO). Furthermore, these results confirm the existence of one-year lag between the environmental shift and the biological response. In the case of males, the previous winter component is also correlated with K_{mean} variability; a period when atmospheric variability has been reported to be the highest. In the case of females, the Arctic Oscillation is also positively correlated with fitness condition, since the Arctic Oscillation acts directly on the North Atlantic Oscillation. A positive correlation was found in all cases.

The LWR obtained for the three different age classes are presented in the figure shown below (**Figure 3.6**):

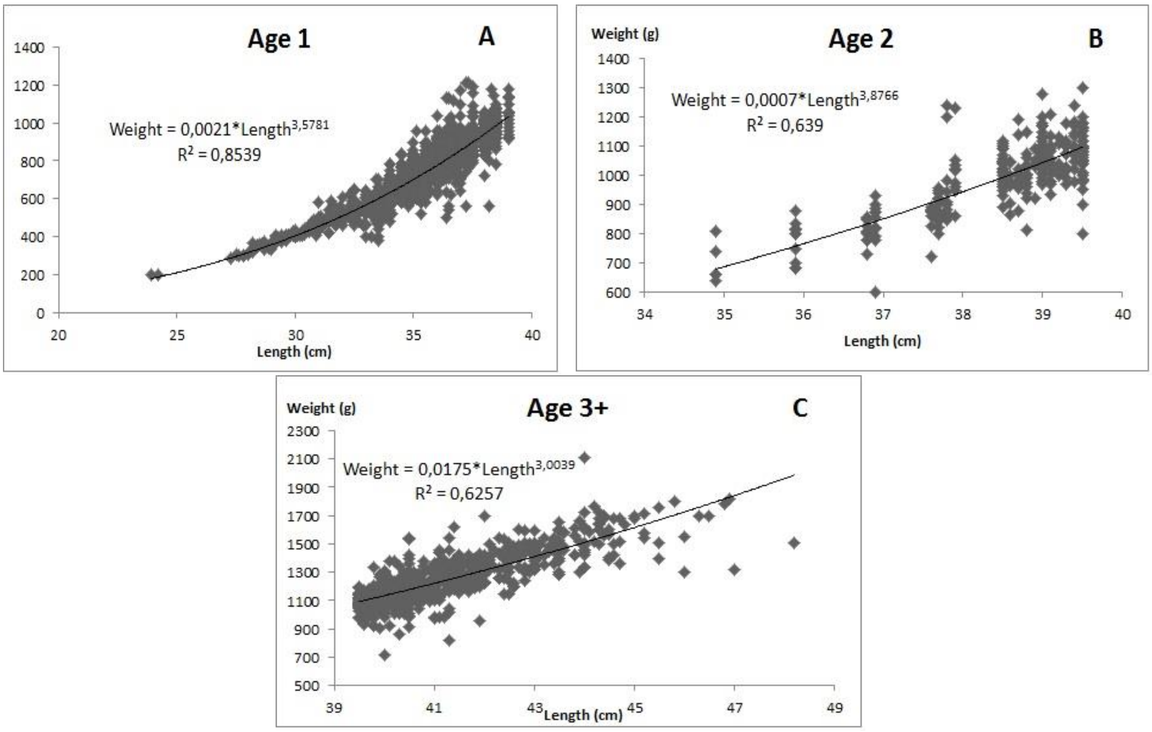


Figure 3.6*: LWR obtained for the different age classes. A: Age 1; B: Age 2 and C: Age 3+.*

Table 3.5 shows in detail growth parameters and mean condition indexes obtained for each age class:

Table 3.5: Regression parameters and mean condition indexes obtained for the different age classes. Key: % represents the percentage of bullet tunas distributed among the different age classes, "b" and "R^2" are the regression coefficients and Kmean and LeCren represent the mean condition factor per year.

Age Class	%	b	R^2	K-mean	LeCren
1 (N=1272)	57.66	3.578	0.852	1.664	1.006
2 (N=274)	12.44	3.876	0.639	1.742	1.001
3+(N=660)	29.9	3.004	0.625	1.781	0.999

The pre-spawning *A. rochei* population is dominated by age 1 class, since it is the most abundant age class (57.66%). All groups presented positive alometric growth despite a change in growth can be inferred for age class 3+; this group represents a 29.9% of the population; this fact suggests a shift on the type of growth as the specimens grows, becoming thicker rather than more elongated. Regarding condition indexes, similar results were obtained for the mean LeCren index for all age classes (1.0066, 1.0013 and 0.999 were obtained for age classes 1, 2 and 3+). However, a slight increment in the K_{mean} index can be seen with age (see Table 3.2). Finally, table 3.6 shows the results obtained for the correlation between the North Atlantic Oscillation and Artic Oscillation shifts and both condition indexes:

Table 3.6: Correlations found between the physical condition and the atmospheric indexes for males and females. Only results with a p-value lower than 0.01 are presented.

Atmospheric Oscillation Index	Condition Index	Rho Spearman
Age 1		
NAO_{py}	LeCren	0.257
NAO_{acum}	LeCren	0.256
NAO_{py}	Kmean	0.312
NAO	Kmean	0.316
AO_{py}	Kmean	-0.347
AO	Kmean	0.243
AO_{pw}	Kmean	-0.330
NAO_{acum}	Kmean	0.281
Age 2		
NAO_{py}	LeCren	0.333
NAO_{w}	LeCren	0.336
NAO_{pw}	LeCren	0.302
AO_{py}	LeCren	0.336
AO_{pw}	LeCren	0.319
NAO_{acum}	LeCren	0.295
NAO	Kmean	0.413
NAO_{w}	Kmean	0.268
AO	Kmean	0.468
Age 3+		
NAO	Kmean	0.673
NAO_{w}	Kmean	0.302
AO	Kmean	0.726

A direct correlation was obtained for the three age classes with the different atmospheric oscillation indexes proposed. In the case of age class 1, K_{mean} was found to be the most correlated index with atmospheric indexes, while in the case of age class 2 the LeCren index was more correlated with atmospheric shifts. Finally, considering age class 3+, only the LeCren index was found to be significantly correlated with atmospheric variability. A lag was also obtained between the environmental situation and the biological response.

3.2.2 Post-Spawning Individuals: A total of 151 individuals were analyzed after the spawning period. All of these individuals were collected in the tuna trap set in Ceuta, Northern Africa (see **Figure 2.3**). The length-weight relationship obtained for the whole set of individuals is shown in **figure 3.7**:

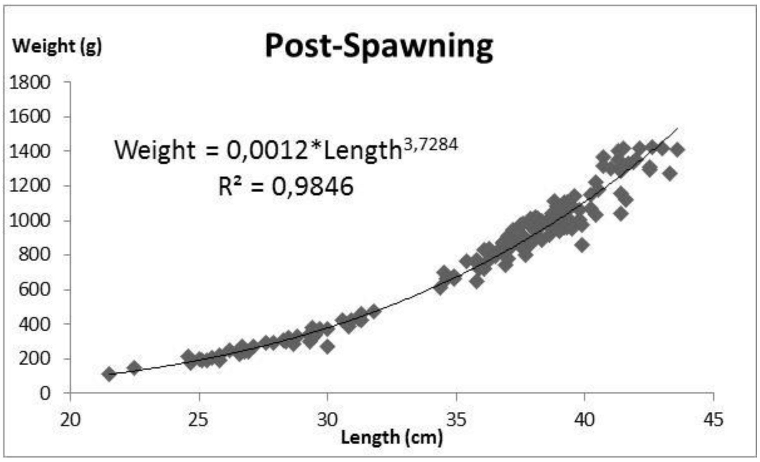


***Figure 3.7**: Length-weight relationship obtained for the post-spawning bullet tunas in the Mediterranean Sea.*

The largest growth parameter for post-spawning *A. rochei* was obtained, and thus the highest positive allometric growth. On the other hand, mean condition indexes values were 1.6559 in the case of K_{mean} and 0.9645 for LeCren. A statistically, significant correlation between the negative phases of NAO_{acum} and K_{mean} was obtained (α= 0.05) (Rho Spearman= -0.185; P= 0.023) for the whole data set.

In addition, length-weight relationships for males and females after the spawning period were obtained and shown in **Figure 3.8**:

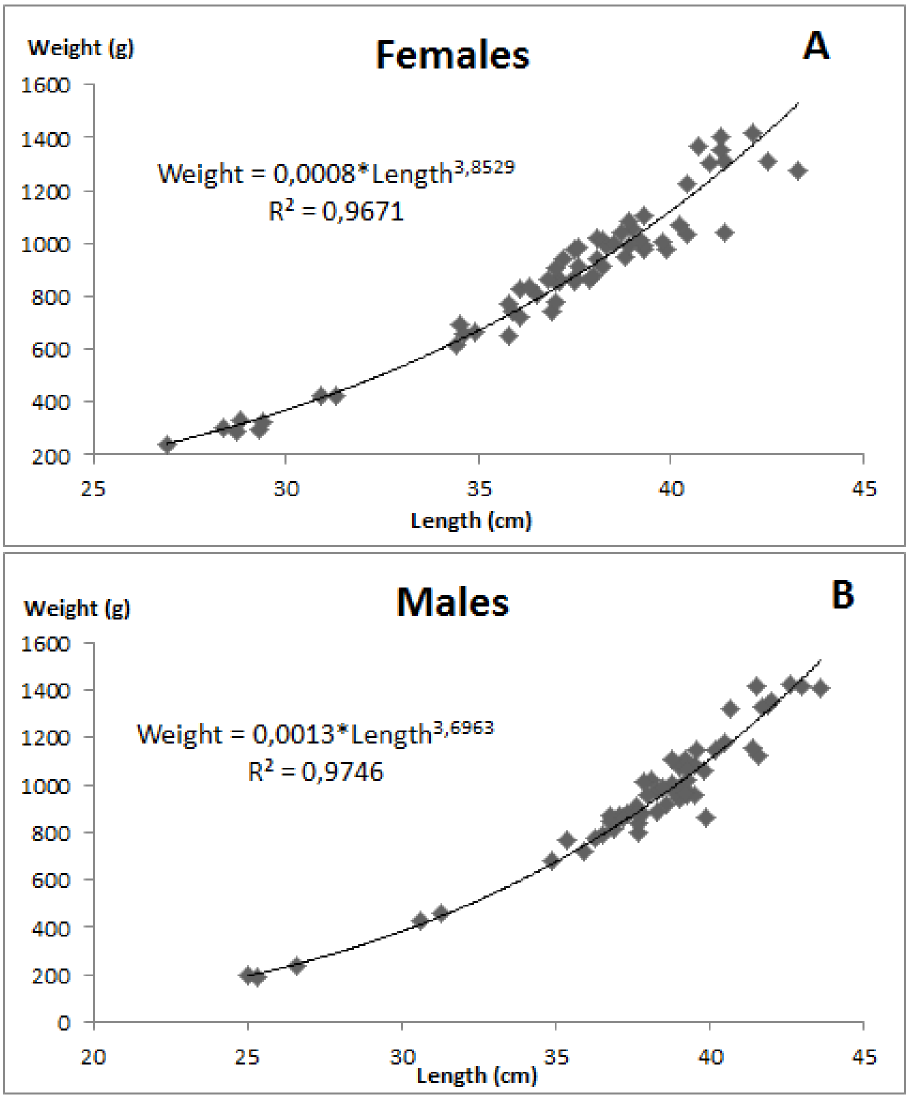


Figure 3.8*: LWR obtained for both post-spawning females (A) and males (B).*

A total of 64females and 58 males were examined (29 records were not sexed). The sex-ratio obtained was 1:1.1. An average K_{mean} value of 1.708 was obtained for females and 1.722 in case of males. Regarding the LeCren condition index, 0.9846 and 0.9854 were obtained both males and females respectively. No significant differences were found between both distributions either for the condition factor, K_{mean} (U= 0.202, P= 1610); or for the LeCren index (U= 0.628, P= 1761) for the two sexes. However, no significant correlations between any of the atmospheric oscillation indexes proposed and the condition indexes for any of the sexes were found. Table 3.7 reflects graphically these findings.

Table 3.7: Regression parameters and mean condition indexes obtained for both post-spawning males and females.

Sex	b	R^2	K_{mean}	LeCren
Males (N=58)	3.696	0.974	1.722	0.984
Females (N=64)	3.852	0.967	1.708	0.985

Furthermore, length –weight relationships were also obtained for each age class (**Figure 3.9**).

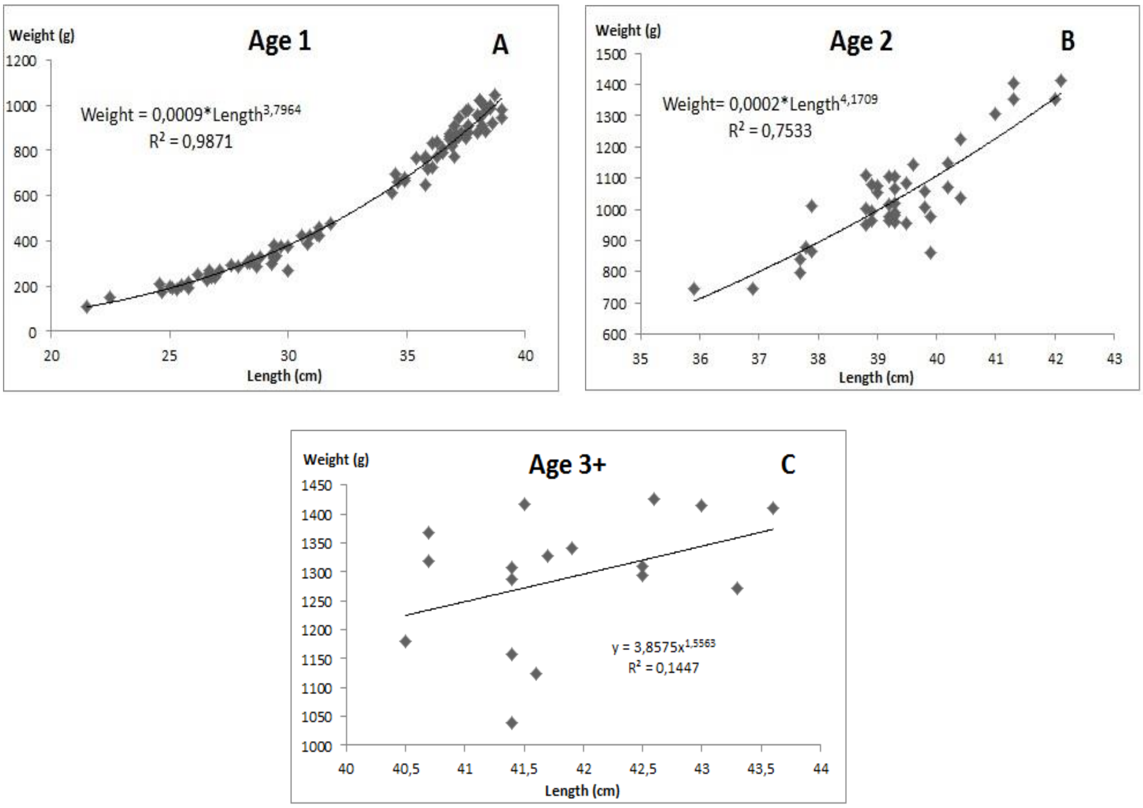


Figure 3.9: LWR obtained for the different age classes. A: Age 1; B: Age 2 and C: Age 3+.

Age 1 was also found to be the most abundant age class (N= 93), representing a 61.58% of the population. Positive allometric growth was found for age classes 1 and 2. In contrast, as found in the case of pre-spawning individuals, a shift in the type of growth is detected in case of age class 3+. Moreover, increasing values were obtained for LeCren condition indexes (0.959, 0.9703 and 0.9804 for ages 1, 2 and 3+). K_{mean} average values also present a slight increasing tendency with age, resulting in 1.587 for age 1, 1.752 for age 2 and 1.801 in case of age class 3+. The following table (Table 3.8) details the information regarding these results:

Table 3.8: Regression parameters and mean condition indexes obtained for the different age classes. Key: % represents the percentage of bullet tunas distributed among the different age classes, "b" and "R^2" are the regression coefficients and Kmean and LeCren represent the mean condition factor per year.

Age Class	%	b	R^2	K_{mean}	LeCren
1 (N=93)	61.58	3.769	0.987	1.587	0.959
2 (N=41)	27.15	4.171	0.753	1.751	0.970
3+(N=17)	11.27	1.556	0.145	1.801	0.980

No statistically significant correlations were found for any of the age classes except for age 3+. Additionally, K_{mean} was the only index that was significantly correlated with atmospheric oscillation indexes (95% confidence intervals). Results are shown in Table XII:

Table 3.9: Significant results obtained by mean of the Spearman non-parametric test for the analyzed records of age 3 and Kmean index. P< 0.05.

Atmospheric Oscillation Index	Rho Spearman
AGE 3+	
NAO_{py}	0.502
AO_w	0.502
AO_{acum}	-0.502
AO_{pw}	0.531

Only age class 3+ was found to be influenced by atmospheric oscillations. No significant results were obtained when considering the LeCren index. The Arctic Oscillation was found to be the most influential oscillation. In all cases a time lag with the biological response was obtained.

Finally, no significant differences were found for the K_{mean} condition index between pre-spawners and post-spawners bullet tunas (P= 0.477; U= 1.608E^5). On the contrary, significant differences were found between both reproductive stages while considering the LeCren condition index (P= 6.016E-9; U= 1.195E^5).

4. DISCUSSION

4.1 Atmospheric Oscillations

The results obtained from this study reveal no clear temporal periodicity for any of the biological indexes previously proposed. However a direct relationship with atmospheric oscillations was obtained. This fact suggests randomness in the interannual variability of the atmospheric oscillations trends with continuous shifts between negative and positive phases along the year, resulting in a difficult prediction of the atmospheric conditions among year *ergo* its effect on biological parameters. However many authors have concluded that average NAO and AO trends can be predicted at short and long term (for example Vicente-Serrano *et al.*, 2011 and references therein)

Apparently, both NAO and AO winter trends, as well as the annual indexes, appear to be slightly coupled (see figures 2.7 and 2.8). This fact suggests a possible interconnection between both indexes, since it has been proposed that the AO exerts a control over the NAO (Ambaum *et al.*, 2001; Douville *et al.*, 2009). However, both atmospheric indexes could have a differential and combined effect over local weather conditions (Baldwin *et al.*, 2007; Christiansen *et al.*, 2007; Baez *et al.*, 2013b). Thus, the AO would act as one of the main sources of variability over the NAO. This means that the intensity of the polar vortex has a direct effect in the Atlantic Ocean; exerting a control over the climatology of this area.

4.2. Fisheries Results

High interannual variability was found within the landings data (see figures 3.1 and 3.2), where periodic peaks are observed although no temporal trend was found within these data series. During the last decade, the highest catches rates were reported. This could be explained by the establishment of protection measurements, improvements in the fishing methods, or unknown changes of the migratory behavior.

Moreover, the absence of temporal trends in these data series as well as the absence of statistically significant relationships between the amount of *A. rochei* landed and any of the atmospheric indexes proposed, could be explained by numerous factors that influence annual landings of a certain species (i.e fleet dynamics, such as technical and commercial factors among others) besides environmental conditions (for example Gaertner & Dreyfus-Leon, 2004). The most plausible explanation for this result is that no fishing effort data were available from the ICCAT website. This means that annual landings analyzed were not related to any unit of effort. Nonetheless, previous studies in this field such as Baez *et al.* (2011b) and Baez *et al.* (2014) revealed a strong relationship between atmospheric indexes and annual landings of European anchovy (*Engraulis encrasicolus*) and Blackspot Seabream (*Pagellus bogaraveo*) respectively without taking into account any fishing effort. In this context, it is essential to study whether fishing effort is a major driver of the interannual variability of bullet tuna landings, rather than environmental factors. Thus, further research and monitoring are needed in order to obtain longer data series of both fishing effort and landings data, that could be used to elucidate a possible effect of the atmospheric oscillations in the bullet tuna landings in the region that would enhance the knowledge of this species and hence management and fisheries yield measurements more accurately.

4.3. Biological Results

With regard the different phases of the reproductive cycle, bullet tunas caught before the spawning period were found to be in a better fitness condition, according to their LeCren index (mean LeCren index: 1.004 ± 0.085) when compared with post-spawners (mean LeCren index: 0.964 ± 0.064) This could correspond to the increment of growth due to gonad development before the spawning process and the great increase of body size because of this reason, since gonadosomatic index of *A. rochei* in the Mediterranean Sea was found to range between 2.2% and 16.1% (Macias *et al.*, 2005). On the contrary, regarding individuals caught during the post-spawning migration, *A. rochei* presented significantly lower mean LeCren index. This fact, added to the largest growth rate found in post-spawners, could be explained by the weight loss that occurs during the reproductive period and the subsequent feeding migration, as found for other tuna species (Schaefer, 2001).

Regarding the age of the individuals; age 1 pre spawning bullet tunas were found to be influenced by previous climatic conditions, meaning that the atmospheric conditions and hence the surrounding environment prevalent during larvae and juvenile stages affect the fitness condition of posterior stages. In this sense, positive phases of the North Atlantic Oscillation were found to enhance the fitness condition of the individuals. The NAO explained an important percentage of the variability found in K_{mean} (between 28% and 34%). In the case of the Arctic Oscillation, a negative correlation with fitness condition was obtained. This result, which explains between 33 and 34% of the variability of K_{mean}, proves that physical condition of *A. rochei* in the early life stages gets enhanced by negative phases of the Arctic Oscillation. Nonetheless, a one-year lag was obtained for both atmospheric oscillation indexes and the biological responses triggered in the individuals.

This fact reinforces the previous statement that environmental conditions prevalent during the early life stages affect the fitness condition of *A. rochei* at age 1, since all these conditions like survival or nutrients availability determine the success of the recruitment process. According to this, the NAO positive phases, characterized by a reinforcement of the westerlies, originating currents that would help bullet tunas to migrate through the Strait of Gibraltar towards the spawning grounds and hence the energetic investment in the trip is reduced, with the subsequent enhancement of the fitness condition (Baez *et al.,* 2013a). On the contrary, negative phases of the AO, defined by a weakening of the trade winds would also facilitate the entrance in the Mediterranean Sea. This fact explains the correlation of the arctic oscillation in a negative phase with a better fitness condition of *A. rochei* entering the Mediterranean Sea before the spawning period.

Furthermore, for individuals belonging to age class 2 in a pre-spawning phase, strong correlations were found between K_{mean} and NAO_w (26.8%) and NAO and AO indexes (which were found to explain 41.3% and 46.8% of the variability of K_{mean}, respectively). Moreover, the LeCren condition index was also found to be highly correlated with the atmospheric oscillation indexes whose explanatory capacity of the variability of LeCren ranged between 29.5% in case of NAO_{acum} and 33.6% in case of NAO_w and AO_{py}. These positive correlations with the NAO could also be explained by the reinforcement of the westerlies that would enhance a better fitness condition. Nevertheless, the strong positive correlations obtained between the AO and the LeCren index for individuals belonging to age class 2 could be explained by an increment of the nutrients supply in the Alboran Sea as a result of the combination between trade winds and a decrease of the water temperature (Mercado *et al.*, 2005; Baez *et al.,* 2013b), which is a typical scenario of the positive phases of the Arctic Oscillation. Compared with age 1, nutrients availability could be a more important driver determining the fitness condition of older bullet tunas (age class 2). On the contrary, the physical condition of younger individuals could be more influenced by the energetic investment of the migration. A better physical condition (K_{mean}), associated with a higher amount of fats (Sutton *et al.*, 2000) during the reproductive migration could be related with a better reproductive status and a higher success of the spawning period.

Finally, the LeCren condition index for individuals of age class 3+ in a post-spawning phase was the only age class found to be significantly correlated with the atmospheric oscillation indexes during this reproductive phase. Thus, the correlation between LeCren and NAO_{py} and AO_{w} explained 50.2% of the variability; while the correlation with AO_{pw} explained 53.2% of the variability. Finally, a negative correlation with AO_{acum} explained 50.2 % of the variability observed for LeCren index. On the contrary, K_{mean} of pre-spawners was found to be strongly correlated with NAO (67.3%), NAO_{w} (30.2%) and AO (72.6%). These differences between the two reproductive phases reveal: firstly, that the amount of fats (K_{mean}) is a key driver for the success of the pre-spawners migration and spawning process, while LeCren index is the most influential index for the individuals in a post-spawning phase due to the loss in weight after the reproduction period. Secondly, the NAO is the most influential atmospheric index since positive phases enhance physical condition, while AO in a positive phase favors the exit from the Mediterranean towards the Atlantic Ocean. Furthermore, age 3+ was the age class which atmospheric indexes explained the highest variability in all cases. This statement could be related to a higher reproductive investment carried out by individuals belonging to older age classes (3+). Thus, they would be more sensitive to changes in the surrounding environment than younger specimens and hence changes in the atmospheric conditions produce a higher variability in their fitness condition indexes. Along this line, several authors highlight the fact that the older the individual is, the higher effort undergoes for reproductive purposes, resulting in an enhancement of the amount and the quality of the larvae produced (Berkeley *et al.*, 2004a; Berkeley *et al.*, 2004b).

With regard the sex of the individuals, during the pre-spawning status both sexes were found to be highly influenced by the effect of the atmospheric oscillations. Along this line, NAO_{py} explained 26.8% and 28.7% of the variability found in K_{mean} for both females and males, respectively. Moreover, the NAO index explained 13.9% and 24.7% of the variability of Kmean of females and males. This positive correlation with NAO and NAO_{py} shows, on the one hand the presence of a time lag between the prevalence of the environmental conditions and the biological consequences and, on the other hand, confirms that positive phases of the NAO favor the biological migration towards the spawning grounds due to intensification of the westerlies that could reduce the energetic investment of the trip. Additionally, the fitness condition factor (K_{mean}) of the females was found to be slightly higher than the males. This fact could represent that the reproductive investment carried out by the females is higher than of the males (Adams & Huntingford, 1997).

Nevertheless, regarding post-spawners, no significant differences were found between males and females for any of both condition indexes (K_{mean} and LeCren). Furthermore, no significant correlation was obtained between both condition indexes and the atmospheric oscillation indexes. These results confirm that sex is not an influential factor on different physical condition of post-spawning *A. rochei* and both sexes are equally influenced by the environmental variables and follow the same biological dynamics without distinctions.

By analyzing the growth dynamics of *A. rochei*, it becomes clear that this species present a positive allometric growth in all cases with no differentiation between pre-spawners and post-spawners and no significant differences between males and females and the three age classes examined. This fact confirms that the type of growth does depend neither on the reproductive phase nor on sex or the age of the individual. Nevertheless, a larger growth parameter value was always obtained in the case of post-spawning individuals. This could also be related to the weight loss that occurs during the spawning period. Moreover, significant changes in the type of growth were detected among age classes in a post-spawning status turning into a negative allometric growth in case of age class 3+, which suggests that a bigger investment in reproductive purposes is performed by older individuals or to changes in feeding needs as the specimens grow. This, as aforementioned, leads to a higher number and a better quality of the larvae produced. Finally, changes in the interannual nutrients availability would cause an effect on the weight of the individual and hence the LeCren index (which by definition is a quotient between the theoretical and empirical weights) is affected.

Nonetheless, in all cases the age structure of *A. rochei* was found to be dominated by the specimens of age class 1. Nevertheless, despite age classes 1 and 2 presented allometric growth, age class 3+ showed a reduction in the growth rate. This change in the growth rate is explained by the own dynamics of the individuals since once they attain the maximum length they do not grow neither in weight nor in length with age. Thus, from age class 3+ and ahead, individuals of *A. rochei* tend to become more elongated than thick. This structure seems obvious due to the high recruitment levels that this species present (Valeiras & Abad, 2006) and is in agreement with the theory of von Bertalanffy (1938) and the biological dynamics followed by many fish species (Pauly, 1980).

In a general way, the fitness condition of pre-spawners was also found to be highly correlated with atmospheric conditions. A negative correlation between K_{mean} and AO_{acum} (30% of the variability) and a positive correlation with NAO_{py} (31.8% of the variability) were obtained. These results confirm on the one hand the existence of a time lag between the environmental conditions and the appearance of the biological responses. On the other hand, it clarifies the fact that positive phases of NAO indexes enhance the physical condition of *A. rochei* since the reinforcement of the westerlies reduce the migratory effort; while negative phases of the AO also favor the migration due to the weakening of the trade winds.

On the contrary, a negative correlation between post-spawners bullet tunas with the atmospheric conditions was found between the Fulton condition index (K_{mean}) and the NAO_{acum} index. This correlation explained the 18.5% of the variability found in K_{mean}. According to this, positive phases of the NAO, which produce a reinforcement of the trade winds, would interfere negatively with the migration towards the Atlantic Ocean through the Strait of Gibraltar. Thus, spawning individuals whose corresponding accumulated NAO resulted in a positive value are likely to present lower condition indexes. These results are in agreement with those presented by Baez *et al.* (2013a) where the fitness condition of the pre-spawning bluefin tuna was found to be enhanced by positive phases of the NAO index.

The AO was found to be the atmospheric oscillation index that most affects *A. rochei* individuals after the spawning period. These strong results suggest that the physical condition of the bullet tuna is more dependent on the Arctic Oscillation phases, where positive phases of this index are found to enhance the LeCren condition index of *A. rochei* (despite the negative correlation with AO_{acum}). Since positive phases of the AO are characterized by stronger trade winds as well as warmer temperatures, the combination of these two factors enhances the migratory trip towards the Atlantic Ocean and hence the physical condition will also be higher. Finally, in the light of these results, it becomes difficult to predict the lag period, since strong results are obtained for both previous year and previous winter components of the indexes. Nevertheless the existence of this lag between the prevalence of the atmospheric conditions and the biological responses is confirmed.

In the light of these findings, it is clear that the fitness condition of *A. rochei* is influenced by variations on the surrounding environment; indexed by the North Atlantic Oscillation and the Arctic Oscillation. In a general way, the reproductive migration towards the spawning grounds close to the Balearic Islands was found to be enhanced by positive phases of the NAO and negative phases of the AO. On the contrary, the post-spawning migration returning into the Atlantic Ocean was found to be strongly influenced by positive phases of the AO. Additionally, K_{mean} was found to be the most affected condition index during the pre-spawning migration since the amount of fats contained in the living tissues is a key factor in the success of the reproductive migration, while the LeCren index was mainly affected during the post-spawning period due to the weight loss produced by the wear of the spawning.

Moreover, these results are mostly associated to a certain lag between the prevalence of the environmental condition and the biological response triggered. These facts could otherwise be used as a plausible explanation for the shifts on interannual landings, since this could affect the availability and catchability of the individuals that indeed did not respond directly to changes in the environmental conditions.

All these results also coincide with those obtained by Baez *et al.* (2013a) in the case of blue-fin tuna, whose fitness condition indexes were found to be strongly correlated with the atmospheric conditions, where AO explain 75% of the variability in K_{mean} and NAO and explained 73% and 70% of the variability found within the LeCren index, with the existence of a six-months lag between the prevalence of the environmental status and the biological consequences triggered in the individuals. In addition, spawning albacore were also found to be strongly influenced by the effect of changes in the surrounding environment depending directly on the NAO (Baez *et al.*, 2011a), whose age-class abundance responding directly to cumulative effects of shifts in the NAO index.

4.4. <u>Future Research</u>

Finally, although *A. rochei* does not attain neither the commercial values nor the socioeconomic importance of other tuna species, it is a widely studied species and much is known about its biology (diet, reproduction, or growth). Nevertheless, several aspects of the biology of this species remain unclear. In this sense, the full migratory behavior is yet to be fully understood; since although it is known that it performs reproductive migrations towards the spawning grounds in the surrounding waters of the Balearic Islands and posteriorly they penetrate again into Atlantic waters, the rest of the movements remain unclear. No tag-release studies have been conducted so far. Under this framework, future researches on this species should be focused on understanding the unclear aspects of the biology of *A. rochei,* like the migratory behavior that would help to achieve management and conservation policies more effectively, since these studies could provide evidences of the migratory of this species more accurately, and its connection with climatic oscillations.

4.5. Effects of Global Warming perspectives over *Auxis rochei*

As aforementioned in the introductory section, the earth is experiencing continuous episodes of Global Warming (Oreskes, 2004) with a high anthropogenic component. It is also a well-known fact that global warming will produce a dramatic shift of the NAO and AO trends towards more negative extreme values of these indexes (Vicente-Serrano *et al.*, 2011). In this context, the predominant climatology in the studied area will turn into a drier and cooler environment with decreases in the sea surface temperature. The presence of storms in Southern Europe is expected to increase, as well as the intensity of the westerlies and trade winds.

Within this context, according to these Global Warming predictions, as well as the results obtained in this study, a more negative phase of the North Atlantic Oscillation is expected to affect the physical condition of *A. rochei* during the reproductive migration towards the Mediterranean Sea. In this sense mature bullet tunas will present worse conditions to face the spawning process, which could interfere in the success of the reproduction as well as the production of greater numbers of larvae that are also more likely to survive and be recruited to the exploitable stocks. Nonetheless, this situation of negative NAO, that leads to an increase in the sea water temperature, could also provoke changes in the reproductive behavior of this species like alterations of the spawning period and changes in the spawning grounds since tuna species have been reported to be highly influenced by the water temperature for the success of the spawning process (Schaefer, 2001). Moreover, in light of these results, the nutrients availability after the spawning process is expected to be reduced due to changes in the predominant winds as well as changes of the oceanographic features of the Alboran Sea.

Thus, post-spawners bullet tunas in the Mediterranean will present lower physical condition, and consequently they could change their migratory patterns towards different feeding areas.

5. CONCLUSIONS

The main conclusions extracted from this study are:

i. There is no relationship between landings of bullet tuna in the Mediterranean Sea and any of the atmospheric indexes proposed in this study. Thus, further research is needed in order to provide plausible explanations for the interannual variability in the landings of *A. rochei*.

ii. The physical condition, indexed by K_{mean} and LeCren, of *A. rochei* was found to be strongly influenced by the atmospheric oscillations, indexed by the NAO and AO. Moreover a time lag between the prevalence of the atmospheric conditions and the biological consequences was obtained in most of the analysis. This time lag period ranges between six months and one year.

iii. The K_{mean} index was found to be the most appropriate index to investigate the physical condition of the bullet tuna during the pre-spawning migration. On the contrary, the LeCren index was found to be more suitable to analyze the physical condition of post-spawning individuals.

iv. Generally, positive phases of the NAO index were found to enhance physical condition of the bullet tuna during the pre-spawning migration for all the three age classes explored. On the contrary, the physical condition was also found to be enhanced by negative phases of the AO.

v. Generally, positive phases of the AO index were found to enhance physical condition of the bullet tuna during the pre-spawning migration for all the three age classes explored. On the contrary, the physical condition was also found to be enhanced by negative phases of the NAO.

vi. Females during the pre-spawning migration were found to be in a better physical status than pre-spawning males due to the differential investment on the gonads development. On the contrary, no differences were found between both sexes during the post-spawning migration.

vii. Bullet tuna from the Mediterranean Sea presents positive allometric growth in all cases, independently of the reproductive status. Nevertheless, growth was found to be slightly higher in the case of post-spawning individuals. Moreover, a descended growth rate with age was observed in post-spawners due to the higher reproductive effort carried out by older individuals.

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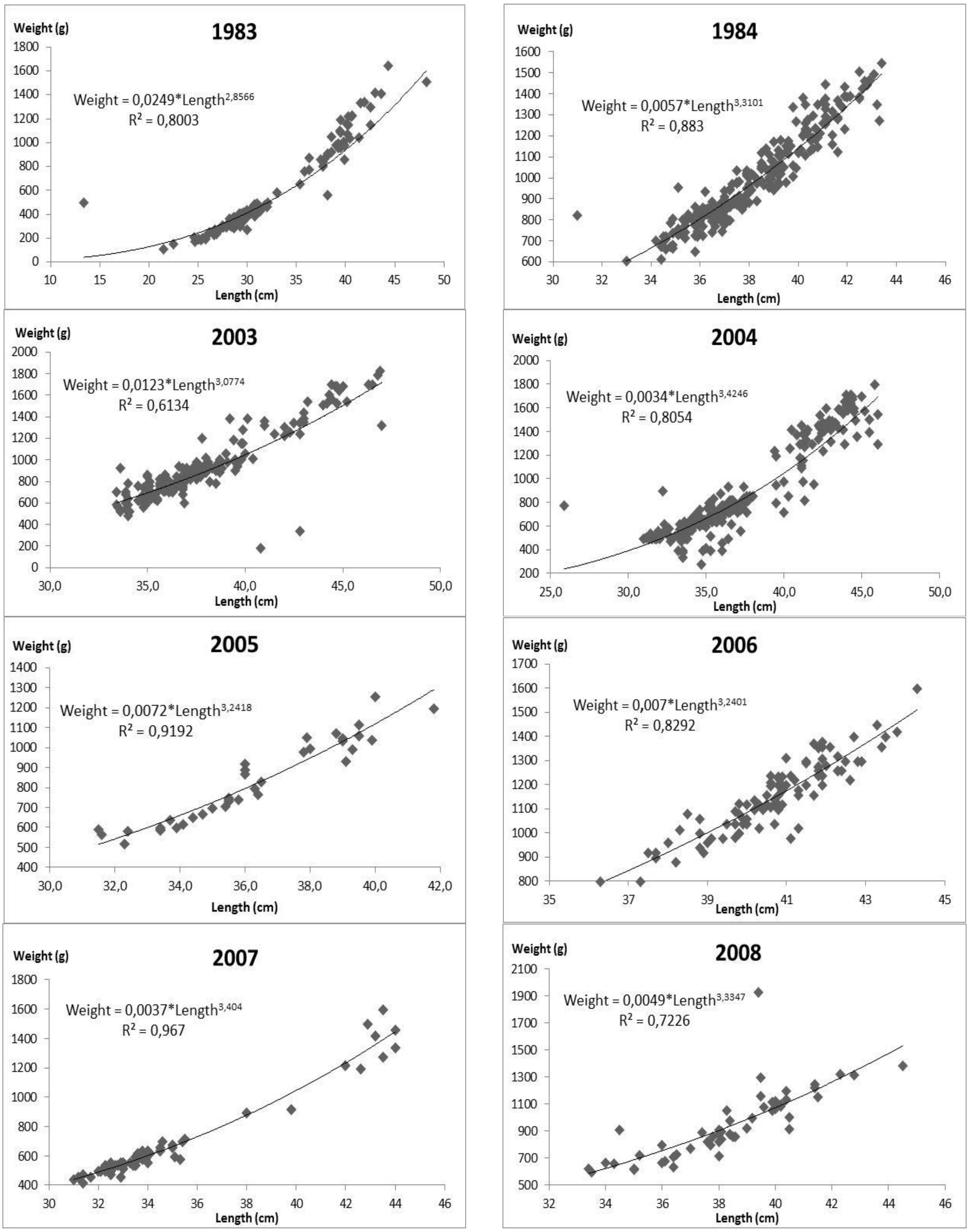
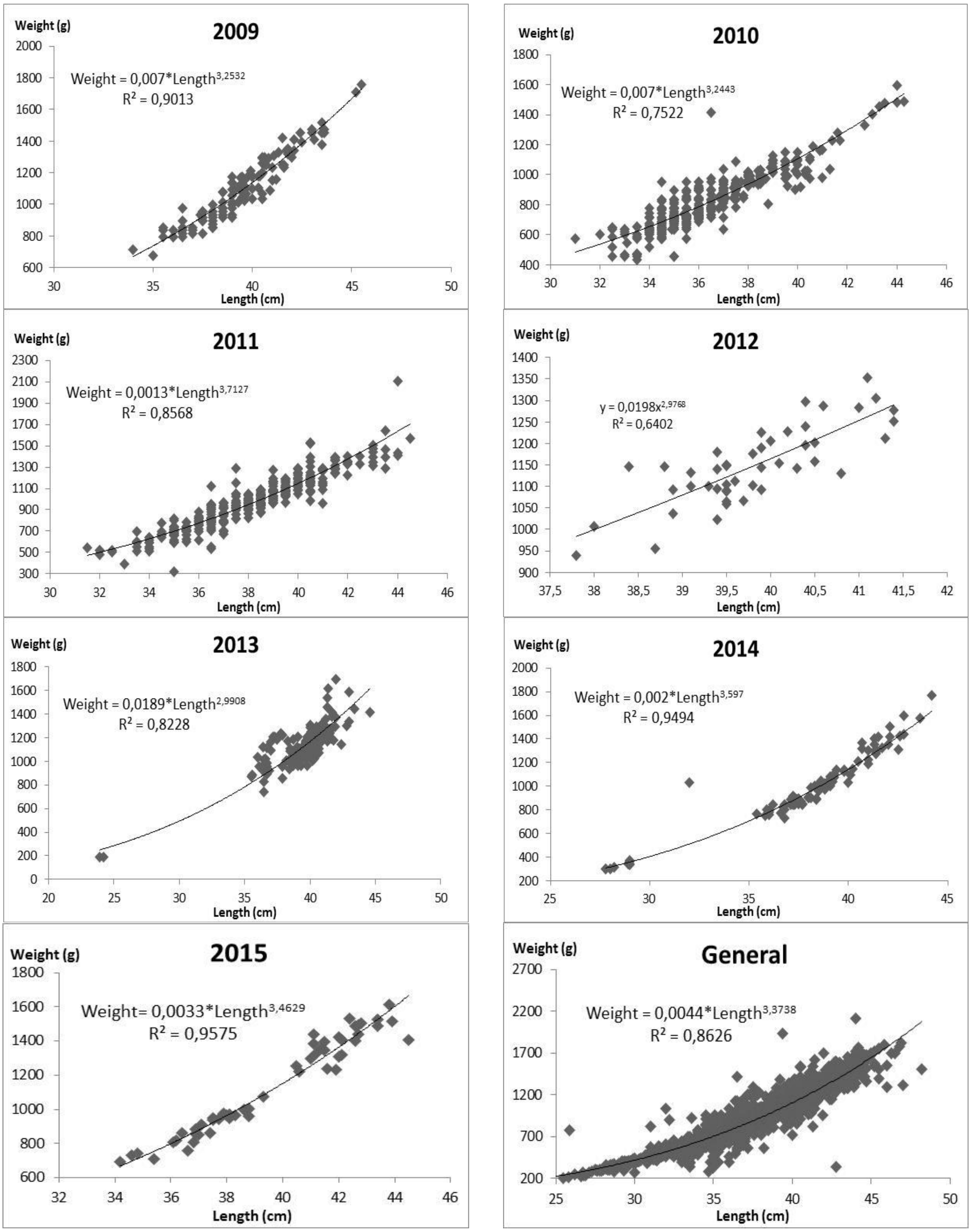
ANNEXES

<u>Annex 1</u>: Length-weight relationships obtained before the analysis of the data (N=2381) before the outliers' removal.





2009
Weight (g)
Weight = 0,007*Length^3,2532
R² = 0,9013
Length (cm)
2010
Weight (g)
Weight = 0,007*Length^3,2443
R² = 0,7522
Length (cm)
2011
Weight (g)
Weight = 0,0013*Length^3,7127
R² = 0,8568
Length (cm)
2012
Weight (g)
y = 0,0198x^2,9768
R² = 0,6402
Length (cm)
2013
Weight (g)
Weight = 0,0189*Length^2,9908
R² = 0,8228
Length (cm)
2014
Weight (g)
Weight = 0,002*Length^3,597
R² = 0,9494
Length (cm)
2015
Weight (g)
Weight= 0,0033*Length^3,4629
R² = 0,9575
Length (cm)
General
Weight (g)
Weight = 0,0044*Length^3,3738
R² = 0,8626
Length (cm)

<u>Annex 2</u>: Interannual mean condition factors and regression parameters prior the filtration of the database.

Years/Parameters	a	b	R2	K-mean	LeCren
General (N=2381)	0.0044	3.37	0.8626	1.682	1.013
1983 (N=142)	0.0249	2.85	0.8003	1.554	1.069
1984 (N=252)	0.0057	3.31	0.883	1.732	1.007
2003 (N=177)	0.0123	3.07	0.6134	1.629	1.014
2004 (N=235)	0.0034	3.42	0.8054	1.574	1.022
2005 (N=37)	0.0072	3.24	0.9192	1.713	0.997
2006 (N=94)	0.007	3.24	0.8292	1.704	1.000
2007 (N=124)	0.0037	3.4	0.967	1.547	0.996
2008 (N=53)	0.0049	3.33	0.7226	1.659	1.005
2009 (N=115)	0.007	3.23	0.9013	1.775	1.080
2010 (N=449)	0.007	3.24	0.7522	1.681	1.008
2011 (N=361)	0.0013	3.71	0.8568	1,739	0.999
2012 (N=50)	0.0214	2.95	0.7335	1.817	1.002
2013 (N=152)	0.0189	2.99	0.8228	1.827	1.0025
2014 (N=88)	0.002	3.6	0.9464	1.735	0.991
2015 (N=52)	0.0033	3.46	0.9575	1.792	1.0007

Annex 3: Interannual values obtained for the North Atlantic Oscillation (NAO) index and the modifications of the index.

Years	NAO	NAOw	NAOpy	NAOpw
1950	-0.1208	0.32	---	---
1951	-0.0083	-0.2783	-0.1208	0.32
1952	-0.425	0.235	-0.0083	-0.2783
1953	-0.0175	-0.415	-0.425	0.235
1954	0.0025	0.3617	-0.0175	-0.415
1955	-0.3992	-0.3	0.0025	0.3617
1956	-0.0442	-0.6633	-0.3992	-0.3
1957	-0.1958	0.2317	-0.0442	-0.6633
1958	-0.5892	-0.2317	-0.1958	0.2317
1959	0.3525	0.1267	-0.5892	-0.2317
1960	-0.41	-0.3233	0.3525	0.1267
1961	0.0433	-0.1283	-0.41	-0.3233
1962	-0.3417	-0.4833	0.0433	-0.1283
1963	-0.4167	-0.775	-0.3417	-0.4833
1964	-0.0417	-0.9717	-0.4167	-0.775
1965	-0.13	-0.4333	-0.0417	-0.9717
1966	-0.3283	-0.4133	-0.13	-0.4333
1967	0.3667	0.135	-0.3283	-0.4133
1968	-0.94	-0.09	0.3667	0.135
1969	-0.0583	-1.4283	-0.94	-0.09
1970	-0.2533	-0.4	-0.0583	-1.4283
1971	0.01	-0.7417	-0.2533	-0.4
1972	0.51	0.3817	0.01	-0.7417
1973	-0.0867	0.5017	0.51	0.3817
1974	0.1808	-0.1133	-0.0867	0.5017
1975	-0.0742	0.1333	0.1808	-0.1133
1976	0.1875	0.2167	-0.0742	0.1333
1977	-0.3358	-0.6417	0.1875	0.2167
1978	0.3175	-0.2317	-0.3358	-0.6417
1979	0.135	0.355	0.3175	-0.2317
1980	-0.4125	0.0367	0.135	0,355
1981	-0.2125	-0.21	-0.4125	0.0367
1982	0.43	-0.0567	-0.2125	-0.21
1983	0.31	0.775	0.43	-0.0567

Years	NAO	NAOw	NAOpy	NAOpw
1984	0.2475	0.3283	0.31	0.775
1985	-0.1833	-0.3383	0.2475	0.3283
1986	0.5033	0.3783	-0.1833	-0.3383
1987	-0.1225	0.515	0.5033	0.3783
1988	-0.0133	0.375	-0.1225	0.515
1989	0.7017	0.7017	-0.0133	0.375
1990	0.5942	0.4817	0.7017	0.7017
1991	0.2683	0.3183	0.5942	0.4817
1992	0.5808	0.4267	0.2683	0.3183
1993	0.1792	0.445	0.5808	0.4267
1994	0.5758	1.0283	0.1792	0.445
1995	-0.0808	0.835	0.5758	1.0283
1996	-0.2142	-0.5483	-0.0808	0.835
1997	-0.1567	0.0617	-0.2142	-0.5483
1998	-0.4808	-0.4017	-0.1567	0.0617
1999	0.3908	0.265	-0.4808	-0.4017
2000	0.2067	0.9217	0.3908	0.265
2001	-0.1825	-0.19	0.2067	0.9217
2002	0.0392	0.2983	-0.1825	-0.19
2003	0.0975	-0.3833	0.0392	0.2983
2004	0.2425	0.1383	0.0975	-0.3833
2005	-0.2675	0.0783	0.2425	0.1383
2006	-0.2075	-0.375	-0.2675	0.0783
2007	0.1733	0.1217	-0.2075	-0.375
2008	-0.3783	0.5117	0.1733	0.1217
2009	-0.2433	-0.0033	-0.3783	0.5117
2010	-1.1525	-1.1583	-0.2433	-0.0033
2011	0.2933	-0.6617	-1.1525	-1.1583
2012	-0.4558	1.1883	0.2933	-0.6617
2013	0.21	-0.6967	-0.4558	1.1883
2014	0.1867	0.5	0.21	-0.6967

Annex 4: Interannual values obtained for the Arctic Oscillation (AO) index and the modifications of the index.

Years	AO	AOw	AOpy	AOpw
1950	-0.1993	0.1863	---	---
1951	-0.3647	-0.8735	-0.1993	0.1863
1952	-0.6749	-0.2555	-0.3647	-0.8735
1953	-0.0164	-0.7287	-0.6749	-0.2555
1954	-0.0006	0.147	-0.0164	-0.7287
1955	-0.3618	-0.5892	-0.0006	0.147
1956	-0.1629	-0.7417	-0.3618	-0.5892
1957	-0.3422	-0.065	-0.1629	-0.7417
1958	-0.8677	-0.9728	-0.3422	-0.065
1959	-0.0763	0.1725	-0.8677	-0.9728
1960	-0.9593	-1.3372	-0.0763	0.1725
1961	-0.0452	-0.4378	-0.9593	-1.3372
1962	-0.2256	-0.506	-0.0452	-0.4378
1963	-0.4869	-1.0245	-0.2256	-0.506
1964	0.0236	-0.2127	-0.4869	-1.0245
1965	-0.4858	-0.7138	0.0236	-0.2127
1966	-0.7647	-1.0608	-0.4858	-0.7138
1967	0.5358	0.034	-0.7647	-1.0608
1968	-0.5675	0.0773	0.5358	0.034
1969	-0.8483	-1.9403	-0.5675	0.0773
1970	-0.3442	-1.2088	-0.8483	-1.9403
1971	0.0061	-0.3498	-0.3442	-1.2088
1972	0.05192	0.3763	0.0061	-0.3498
1973	0.24067	0.6342	0.05192	0.3763
1974	-0.2026	-0.1408	0.24067	0.6342
1975	0.4343	0.1728	-0.2026	-0.1408
1976	-0.0308	0.7207	0.4343	0.1728
1977	-0.4323	-1.3997	-0.0308	0.7207
1978	-0.1503	-0.4172	-0.4323	-1.3997
1979	-0.3652	-0.2265	-0.1503	-0.4172
1980	-0.6433	-0.651	-0.3652	-0.2265
1981	-0.4346	-0.672	-0.6433	-0.651
1982	0.2977	-0.2343	-0.4346	-0.672
1983	0.0319	0.0672	0.2977	-0.2343

Years	AO	AOw	AOpy	AOpw
1984	-0.1917	-0.1528	0.0319	0.0672
1985	-0.5192	-0.7475	-0.1917	-0.1528
1986	0.0848	-0.612	-0.5192	-0.7475
1987	-0.5442	-0.326	0.0848	-0.612
1988	0.0403	-0.358	-0.5442	-0.326
1989	0.95	1.5985	0.0403	-0.358
1990	1.0243	1.2957	0.95	1.5985
1991	0.197	0.2963	1.0243	1.2957
1992	0.4365	0.717	0.197	0.2963
1993	0.0791	1.0702	0.4365	0.717
1994	0.5324	0.1773	0.0791	1.0702
1995	-0.2746	0.7525	0.5324	0.1773
1996	-0.4563	-0.8825	-0.2746	0.7525
1997	-0.0397	0.1868	-0.4563	-0.8825
1998	-0.271	-0.6583	-0.0397	0.1868
1999	0.1125	-0.117	-0.271	-0.6583
2000	-0.0464	0.5905	0.1125	-0.117
2001	-0.1615	-1.1477	-0.0464	0.5905
2002	0.0716	0.6318	-0.1615	-1.1477
2003	0.1521	-0.6528	0.0716	0.6318
2004	-0.1923	-0.4432	0.1521	-0.6528
2005	-0.3753	-0.145	-0.1923	-0.4432
2006	0.1378	-0.6293	-0.3753	-0.145
2007	0.2688	0.6138	0.1378	-0.6293
2008	0.1768	0.5047	0.2688	0.6138
2009	-0.3303	0.4442	0.1768	0.5047
2010	-1.0428	-1.9632	-0.3303	0.4442
2011	0.5257	-0.3597	-1.0428	-1.9632
2012	-0.1815	0.8768	0.5257	-0.3597
2013	0.001	-1.3627	-0.1815	0.8768
2014	-0.0667	0.6747	0.001	-1.3627

Annex 5: Values of the bullet tuna landings (in tons) considered for the analysis performed obtained from ICCAT.

Year	Weight (tonnes
1952	176
1953	772
1954	612
1955	877
1956	1324
1957	---
1958	1614
1959	---
1960	880
1961	2481
1962	2888
1963	2154
1964	2550
1965	1371
1966	1422
1967	2893
1968	1177
1969	1550
1970	1972
1971	2074
1972	1344
1973	1706
1974	2335
1975	1389
1976	1635
1977	1184
1978	1676
1979	1771
1980	2120
1981	1700
1982	1935

Year	Weight (tonnes)
1983	2135
1984	2301
1985	2047
1986	1555
1987	631
1988	2669
1989	2581
1990	2985
1991	2226
1992	1210
1993	648
1994	1124
1995	1472
1996	2296
1997	604
1998	487
1999	669
2000	1023
2001	861
2002	493
2003	495
2004	1009
2005	845
2006	1101
2007	3082
2008	3388
2009	726
2010	3812
2011	3227
2012	1620
2013	2718
2014	---

<u>Annex 6</u>: Regional data landings provided by IDAPES considered in the analysis of this study (in kilograms).

Years	Total Weight (kg)	Total Price (€)
2000	142869	148705.23
2001	1159106	931245.39
2002	508447	434399.64
2003	407201	398376.89
2004	1119985	1103789.18
2005	481755	415104.04
2006	563093	655643.9
2007	1800703	1466043.04
2008	1019446	1015187.07
2009	587201	503946.87
2010	2042304	1579687.92
2011	1154263	1043879.8
2012	653154	642217.09
2013	630325	566662.34
2014	278541	347722.43
2015	25694	39398.2
Average	785880	705750.56

Annex 7: List of the works originated from this study.

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Análisis preliminar del efecto de las oscilaciones climáticas sobre la condición física de la melva (*Auxis rochei*) post-reproductora en el Mar de Alborán

Preliminary analysis of the effect of climate oscillations on the physical condition of the post-spawning bullet tuna (Auxis rochei) in the Alboran Sea

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Abstract: The Mediterranean Sea is considered by several authors as a hot-spot of Climate Oscillation, such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). However, information about the effect of the climate oscillations on the fitness of the species is still scarce. In this context, bullet tuna is an important migratory species with a substantial socio-economical value, whose fisheries might be affected by the effect of certain climatological conditions. In fact, these atmospheric oscillations trigger a chain of hydrodynamic events, leading a change on the timing, destinations, and success of the migratory species in their search for spawning grounds. This study relies on the hypothesis of a correlation between the physical condition of the post-spawning bullet tuna and climate oscillation indexes. For that purpose, 151 individuals of bullet tuna, Auxis rochei, were collected in the traps of Ceuta (Alboran Sea) during three different years, (1983, 1984 and 2014). The physical condition index was calculated, and later statistically correlated with the climate oscillation indexes proposed. Significant differences were found between the physical condition of A. rochei and the average accumulated NAO index. Moreover, for age class 3+ we obtained a significant correlation with atmospheric oscillations.

Key words: Climate Oscillation, Migratory species, Bullet tuna, Condition factor, Alboran Sea.

1. INTRODUCCIÓN

El Mar de Alborán es considerado una importante zona de paso para gran número de especies en su migración hacia sus áreas de puesta en el Mediterráneo. Muchas de estas especies tienen importancia pesquera por su valor socioeconómico. Algunos ejemplos de este hecho son especies como el atún rojo, *Thunnus thynnus* (Linnaeus, 1758) (Báez *et al*. 2014), la bacoreta, *Euthynnus alletteratus* (Rafinesque, 1810) (Hajjej *et al*. 2010), el bonito, *Sarda sarda* (Bloch, 1793) (Sabatés & Recasens, 2001), o la melva, *Auxis rochei* (Risso, 1810; Sabatés & Recasens, 2001). Diversos autores coinciden en el hecho de que estas especies migradoras pueden alterar su fenología en respuesta a las oscilaciones climáticas (Báez *et al.* 2014).

La melva (*A. rochei*) es una de las especies de menor tamaño dentro de la familia Scombridae, con una longitud máxima en torno a 40 centímetros y con hábitos de vida gregarios. La formación de cardúmenes hace a la especie altamente susceptible a determinados artes de pesca como el cerco o las almadrabas (Valeiras & Abad, 2006). Presenta un ciclo de vida que comprende fases en el Mediterráneo y en el Atlántico. Durante la primavera y verano se adentra en el Mediterráneo para la puesta, para en otoño volver a cruzar el estrecho hacia sus zonas de invernada. Durante su migración de retorno post-reproductor hacia el Océano Atlántico son capturados en la almadraba de Ceuta (Sabatés & Recasens, 2001).

La oscilación del Atlántico Norte NAO (de sus siglas en inglés, *North Atlantic Oscillation*) y la oscilación ártica AO (de sus siglas en inglés, *Artic Oscillation*), son conocidas por ser tener una gran influencia sobre las condiciones climáticas en el Mediterráneo y el Margen Ibérico Atlántico. La NAO resume los cambios en la diferencia de presiones atmosféricas entre las bajas presiones de Islandia y las altas presiones de las Azores, mientras que la AO hace referencia a la intensidad del vórtice polar. Desde que la AO fue definida, ha existido un fuerte debate sobre su identidad física. Así, en la actualidad se discute si es un reflejo de la NAO, o si la AO y la NAO son dos efectos de una misma causa común en la troposfera (revisado en Báez *et al.* 2013b).

Teniendo en cuenta las anteriores premisas, el presente estudio tiene como objetivo la evaluación de la condición física de *la* melva durante su migración post-reproductora y la influencia que los índices climáticos NAO y AO podrían tener sobre la misma.

2. MATERIAL Y MÉTODOS

2.1 Área de estudio

El presente estudio se localiza en el mar de Alborán, la cuenca más occidental del Mar Mediterráneo. El mar de Alborán, debido a sus especiales características oceanográficas y topográficas ha sido catalogado por diversos autores como una de las zonas calientes en relación al cambio climático del planeta, y donde las oscilaciones climáticas tienen mayor influencia (Vicente-Serrano & Trigo, 2011). En esta zona un complejo sistema de corrientes da lugar a afloramientos de aguas profundas ricas en nutrientes lo que origina una elevada productividad primaria (Parrilla & Kinder, 1987). La alta productividad de la zona implica una alta disponibilidad de peces aprovechada como fuente de alimentación por muchas especies migratorias y como recurso pesquero.

2.2 Muestreo

Durante los años 1983, 1984 y 2014, un total de 152 individuos de *A. rochei* fueron analizados des entre los ejemplares capturados en la almadrabas situadas en la bahía sur de Ceuta durante el movimiento que anualmente lleva a cabo esta especie en su ciclo migratorio.

Los 152 individuos fueron medidos a la furca hasta el centímetro más cercano (FL), y pesados hasta el gramo más próximo. A continuación, por medio de la relación talla-peso, se obtuvo el índice de condición promedio (K_{mean}) para cada individuo por medio de la siguiente ecuación (Ec 1) (Froese, 2006):

$$K_{mean} = \left(a * LF^{(b-3)}\right) * 100$$

Ec. 1: Expresión utilizada para el cálculo del índice de condición donde "a" y "b" son los coeficientes de regresión y "LF" es la longitud a la furca.

Adicionalmente, se determinó el sexo mediante la visualización directa de la gónada, y se le asignó una edad aproximada a cada individuo de acuerdo con la clave talla-edad propuesta por Valeiras *et al.* (2008). Por otra parte, se obtuvieron los datos correspondientes a la NAO y AO correspondientes a los años de captura de los individuos y anteriores. Los datos fueron obtenidos en el sitio web de la Agencia NOAA (National Oceanic and Atmospheric Administration): http://www.cpc.noaa.gov/

Las oscilaciones atmosféricas presentan una fuerte variabilidad intra en interanual (Hurrell, 1995), y dichas oscilaciones pueden estar desacopladas en relación con la respuesta biológica que desencadenan.

Por esto, se decidió considerar las siguientes variables en relación a dichas oscilaciones; NAO_{ac}/AO_{ac}: Comprende el promedio de los valores obtenidos para el índice en cuestión acumulados por cada ejemplar considerando su edad. NAO_w/AO_w: Basado en el promedio del índice atmosférico durante los meses del último invierno. NAO_{wac}/AO_{wac}: Implica el valor promedio de los inviernos acumulados por cada individuo.

2.3 Análisis estadístico

Debido a la existencia de valores atípicos, se eliminó un registro del conjunto total de datos, quedando un total de 151 registros disponibles para ser analizados estadísticamente.

En primer lugar se comprobó la normalidad de las distribuciones y, debido a la escasez de años en el conjunto de datos se realizó una correlación no paramétrica de Spearman entre los índices de oscilaciones atmosféricas propuestos anteriormente, y la condición física de los ejemplares en conjunto, y por sexo.

3. RESULTADOS

Se obtuvo un valor de sex-ratio para la población en estudio de 1:1,1 (58 machos y 64 hembras). Los valores obtenidos para el índice de condición, así como los intervalos de talla-peso obtenidos aparecen reflejados en la tabla I.

Tabla I: Resumen de los intervalos de talla y peso, así como los índices de condición obtenidos por categoría.

	L_{min}-L_{max}	P_{min}-P_{max}	K_{min}-K_{max}(Promedio)
General (N=151)	*21.5-43.6*	*111-1425*	*1.244-1.878 (1.715)*
Machos (N=58)	*25-43.6*	*189-1425*	*1.332-1.877 (1.722)*
Hembras (N=64)	*26.9-43.3*	*239-1415*	*1.377-1.878 (1.708)*

En lo que respecta a las clases de edad, la tabla que se muestra a continuación (Tabla II) refleja el porcentaje de individuos capturados por clase de edad para los años de estudio.

Tabla II: Distribución de los individuos analizados por clases de edad.

Edad	Nº de Individuos	Porcentaje (%)
1	93	61.58
2	41	27.15
3+	17	11.26

Se obtuvo una correlación significativa entre el aumento de la condición física y la NAOacu en fase negativa (Rho Spearman= -0.185; P= 0.023) para el conjunto de los datos analizados; en el caso de la clase de edad 3+ además de dicha correlación se obtuvo una correlación positiva significativa con las oscilaciones climáticas testadas (ver tabla III). En lo relativo al índice AOacu, solo se obtuvieron diferencias significativas con la condición física en general, sin distinción de sexo o edad.

*Tabla III: Resultados significativos de los parámetros estadísticos obtenidos mediante la correlación no paramétrica de Spearman para los registros analizados de clase de edad 3+. Clave:*P= <0.05.*

Variables correlacionadas	Rho Spearman
K_{3+} - AO_{acu}	-0.502*
K_{3+} - NAO_{want}	0.502*
K_{3+}- AO_{w}	0.502*
K_{3+} - AO_{ant}	0.502*
K_{3+} - AO_{want}	0.531*

4. DISCUSIÓN

Los resultados obtenidos indican que el índice de condición física de la melva post-reproductora está influenciado por las condiciones climatológicas predominantes en el medio, fundamentalmente por la media de la NAO/AO que experimenta a lo largo de su vida. Estos resultados son consistentes con los obtenidos por Báez *et al.* (2011) para el caso del atún blanco, *Thunnus alalunga*.

Tanto la NAO como la AO en fase negativa favorecen la predominancia de las tormentas sobre el Mediterráneo occidental. Esta circunstancia aumenta el aporte de nutrientes desde la costa al mar por escorrentía, lo que determina un incremento de la productividad de la zona.

El hecho de que las mayores diferencias significativas se obtengan en relación al índice AO_{acu} puede implicar un desfase temporal entre la oscilación atmosférica y la respuesta biológica que desencadena en los individuos. Esta afirmación coincide con lo propuesto por Báez *et al.* (2013a), ya que las oscilaciones atmosféricas originan cambios en la disponibilidad de nutrientes en la cadena trófica lo que finalmente se traduciría en un aumento de la condición física de los individuos. De este modo, el hecho de conocer la evolución y modelado de la climatología podría permitir realizar estimaciones sobre el rendimiento pesquero de *A. rochei*.

En lo relativo a los valores obtenidos por sexo, no se encontraron diferencias significativas entre el índice de condición de machos y hembras. Este hecho refleja la respuesta independiente del sexo del individuo tanto a los cambios en las condiciones ambientales como al balance energético durante el periodo reproductivo. Según Palandri *et al.* (2008) la talla de maduración para *A. rochei* en el Mediterráneo se estima en torno a 32 cm (FL), por lo que, de acuerdo con nuestros datos los individuos capturados por la almadraba de Ceuta son sexualmente maduros y en periodo de reposo tras la época reproductora.

Este estudio supone la primera evaluación de la condición física de *A. rochei* en periodo post-reproductor. Nuestros resultados señalan la importancia de introducir el efecto de las oscilaciones climáticas en los procesos de evaluación de las especies sometidas a explotación.

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VARIACIÓN INTERANUAL DE LA CONDICIÓN FÍSICA DE LA MELVA (*Auxis rochei*) EN MIGRACIÓN PRE-REPRODUCTORA Y SU RELACIÓN CON LA OSCILACIÓN DEL ATLÁNTICO NORTE

P. Muñoz[1], D. Macias[1] & J.C. Báez[1]

SUMMARY

Several authors highlight the fact that atmospheric oscillations might have an effect on the migratory species abundance, recruitment and physical condition. The major aim of this study was to elucidate a possible relationship between the physical condition of the bullet tuna (*Auxis rochei*) and the atmospheric oscillation based on 2154 specimens collected by commercial fisheries along the Spanish Mediterranean coast in two different periods (1983-1984 and 2003-2014). The species conducts pre-reproductive migratory movements annually towards the spawning area along the Mediterranean coast. Both variations on sex-ratios and age were tested against the North Atlantic Oscillation (NAO). Significant differences between the LeCrem condition index for the individuals of the age class 3+ and NAO_w and NAO_{ant} were found. A better condition during years with positive NAO phase was found. These results could be explained by the environmental conditions during positive NAO phase that would enhance the migration process. Nonetheless, populations monitoring is recommended in order to elucidate the effect of climate on fitness of this migratory species.

RESUMEN

Las oscilaciones atmosféricas afectan directamente a muchas especies migradoras, reflejado en un cambio directo en su abundancia, reclutamiento o condición física. Este estudio tiene como principal objetivo elucidar posibles efectos de las oscilaciones climáticas (estandarizada por el índice NAO) sobre la condición física de la melva (*Auxis rochei*). Para ello se analizó el índice de condición de 2154 ejemplares capturados mediante diferentes artes de pesca por pesquerías comerciales a lo largo de la costa Mediterránea española durante los periodos comprendidos entre 1983-1984 y 2003-2014. Las capturas tuvieron lugar durante el movimiento migratorio que esta especie realiza hacia las áreas de puesta situadas en el Mediterráneo occidental. La condición física se testó en relación con las oscilaciones atmosféricas teniendo en cuenta la edad y sexo-ratio. Se obtuvieron diferencias significativas entre el índice de condición para los individuos de clase de edad 3+ y los índices NAO_w y NAO_{ant}. Los años con un índice NAO positivo se encontró una mejor condición física en los ejemplares estudiados. Esto podría deberse a que las condiciones ambientales durante los años de NAO en fase positiva facilitarían la migración. No obstante, se recomienda continuar con el seguimiento de las poblaciones para poder elucidar los efectos climáticos sobre la condición física de esta especie migratoria.

Keywords: A. rochei, Atmospheric Oscillations, Climate Change, Mediterranean Sea, Condition Index

1. Introducción

Las especies migradoras pueden ver alterada su abundancia (Gancedo et al., 2005; Báez et al., 2011), condición física (Báez et al., 2013) o reclutamiento (Borja & Santiago, 2002; Mejuto, 2003; Kell et al., 2004; Goñi & Arrizabalaga, 2005; Gancedo et al., 2009) en respuesta a cambios en las condiciones climáticas predominantes. No obstante, aún se desconocen los efectos que las oscilaciones climáticas pueden desencadenar en pequeños túnidos.

La melva, *Auxis rochei* (Risso, 1810) es un pequeño túnido del grupo de los escombriformes, con una talla y peso medios para el Mediterráneo en torno a 40 cm y 1.9 kg respectivamente (Valeiras & Abad, 2008) y con hábitos de vida gregarios, lo que les hace susceptibles de ser capturados por diferentes artes de pesca.

El índice NAO (por sus siglas en inglés *North Atlantic Oscillation*) es el más usado para abordar las oscilaciones atmosféricas en la zona del Mediterráneo (Vicente-Serrano & Trigo, 2011) el cual es considerado por la comunidad científica, como un punto caliente para los efectos del calentamiento global, pues sus consecuencias podrían ser aún más pronunciadas debido a su condición de mar interior. La NAO hace referencia a una diferencia de presiones atmosférica entre la zona de las bajas presiones situadas en torno a Islandia y la zona de altas presiones localizada próxima al archipiélago de las Azores.

El principal objetivo de este artículo es dilucidar los posibles efectos que las oscilaciones atmosféricas puedan ocasionar en la condición física de *A. rochei* capturados a lo largo de la costa Mediterránea española, durante el movimiento migratorio que anualmente realiza esta especie hacia sus épocas de puesta en torno a la zona de Baleares (Sabatés & Recasens, 2001).

2. Material y Métodos

2.1 Área de estudio y Datos pesqueros

El Mediterráneo occidental es una importante área de puesta para muchas especies de túnidos, ya que las temperaturas registradas durante la primavera y verano en la zona garantizan el reclutamiento y supervivencia de las larvas (García et al., 2005). Por ello, se ha convertido en el destino de numerosas rutas migratorias con el Estrecho de Gibraltar y el Mar de Alborán como única vía de entrada desde el Océano Atlántico (García et al., 2005)

Un total de 2154 ejemplares de *A. rochei* fueron analizados a partir de las capturas comerciales en distintas localizaciones a lo largo de la costa Mediterránea española por medio de diversos artes de pesca principalmente almadraba; durante los periodos de tiempo comprendidos entre los años 1983 a 1984, y 2003 a 2014.

Cada individuo fue medido a la horquilla hasta el centímetro más próximo, y pesados hasta el gramo más cercano. A continuación, cada individuo fue eviscerado, lo que permitió la identificación del sexo mediante examen visual de la gónada. Adicionalmente por medio de la clave talla-edad propuesta por Valeiras y Abad (2008), a cada individuo se le asignó una edad aproximada (2+ 3+ ó 4+).

A continuación, por medio de la relación talla-peso, se obtuvo el índice de condición de LeCren (LC) para cada individuo mediante la expresión propuesta por Froese (2006):

$$LC = \frac{P}{(a * LF^b)}$$

donde “a” y “b” son los coeficientes de regresión y “LF” es la longitud a la furca en centímetros y P es el peso en gramos.

2.2 Datos atmosféricos

Los datos correspondientes a los valores de las oscilaciones climáticas durante el periodo de estudio se obtuvieron en el sitio web de la Agencia NOAA (National Oceanic and Atmospheric Administration): http://www.cpc.noaa.gov/. No obstante, ya que se sabe que las oscilaciones atmosféricas presentan una fuerte variabilidad interanual y que además es lógico pensar que llevan asociado un cierto desfase temporal con respecto a la respuesta biológica, se consideró la utilización de las siguientes variables asociadas a dichas oscilaciones; NAO_w: comprende el valor promedio del índice en cuestión correspondiente a los meses de invierno (de Octubre del año anterior a Marzo del año de captura); NAO_{ant}: basado en el valor del índice en cuestión el año anterior a la captura del individuo; NAO_{want}: implica el valor promedio de cada índice relativo a los meses de invierno (Octubre, Noviembre y

Diciembre) del año previo a la captura de cada ejemplar. Finalmente, también se consideró el índice NAO.

2.3 Análisis de los datos

En primer lugar, se comprobó la normalidad de las distribuciones. Posteriormente se testaron las diferencias interanuales entre los valores de LeCren y el índice NAO mediante un test ANOVA, una vez confirmada la normalidad de las distribuciones, considerando intervalos de confianza del 95% (α=0.05); por medio del software estadístico SPSS. Este procedimiento se realizó tanto para testar el conjunto de los datos de manera general así como para testar ambos sexos y las diferentes clases de edad.

La tabla 1 muestra un resumen de la procedencia de los individuos estudiados, así como el arte de pesca empleado para su captura.

3. Resultados y discusión

En lo relativo a la estructura por sexos, se obtuvo un valor de sex ratio de 1:1.22. No se observaron diferencias significativas entre el índice de condición por sexo. Los valores obtenidos para el índice de condición por sexo, así como los intervalos de talla y peso obtenidos, son expuestos en la tabla 2. De manera similar no se observaron diferencias significativas por clase de edad (tabla 3).

Por otro lado, en lo relativo a los índices climáticos, se obtuvieron diferencias significativas entre el índice de condición de LeCren frente a NAO_{ant} y NAO_w para los individuos de la clase de edad 3+. La tabla 4 muestra los resultados estadísticos obtenidos.

Los resultados obtenidos reflejan la existencia de diferencias significativas entre el índice de condición de LeCren y el NAO_w y NAO_{ant}; ambos casos para la clase de edad 3+. En ambos casos, el índice de condición medio es superior en el caso de los años con NAO en fase positiva. En este contexto, de acuerdo con Báez et al., (2013) la fase de NAO positiva se caracteriza por vientos predominantes de componentes oeste que podrían facilitar la migración (Forchhammer et al., 2002), disminuyendo el esfuerzo ejercido por los individuos que migran al Mediterráneo. En contraposición, durante los años con NAO en fase negativa, los individuos en migración tendrían que aumentar el gasto de energía durante la misma. Del mismo modo esto podría explicar los desfases encontrados.
El hecho de que no se hayan observado diferencias significativas para las clases 2 y 4, puede ser debido a un efecto matemático ya que la mayor parte de los individuos analizados de estas clases de edad se concentran en años con poca variabilidad del índice NAO (Tabla 5). Por ejemplo, la clase de edad 4 presenta sus mayores efectivos en 5 años de fase positiva y un solo año de fase negativa. En este sentido las deficiencias de la serie de datos condiciona los resultados obtenidos en nuestro estudio

En lo que respecta al sexo, no se han encontrado diferencias significativas frente a las oscilaciones climáticas esto podría deberse a que las oscilaciones climáticas afectan por igual a ambos sexos.

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Tabla 1: Resumen de la procedencia de los ejemplares de A. rochei analizados así como el arte de pesca empleado en su captura.

LOCALIZACIÓN	Arte de Pesca	Subtotal (N)	Total (N)
Almeria	Cerco	75	75
Calpe	Curricán	4	4
Fuengirola	Cerco	99	99
La Azohía	Almadraba	1845	1866
	Curricán	19	
	Palangre	2	
La Pobla de Farnals	Curricán	6	6
Málaga	Cerco	7	7
Motril	Cerco	24	24
Palma	Curricán	4	62
	Cerco	58	
Santa Pola	Curricán	2	2

Tabla 2: Resumen de los valores intervalos de talla, peso y condición física para ambos sexos.

Sexo	L_{min}-L_{max}	P_{min}-P_{max}	LC_{min}-LC_{max}(Promedio)
Machos (N=307)	31-48.2	440-1766	0.767-1.287 (0.999)
Hembras (N=375)	28.2-46	318-1678	0.826-1.172 (0.993)

Tabla 3: Resumen de los valores intervalos de talla, peso y condición física para cada clase de edad.

Clase de Edad	L_{min}-L_{max}	P_{min}-P_{max}	LC_{min}-LC_{max}(Promedio)
2+(177)	31-39	440-1070	0.861-1.287 (0.999)
3+(N=131)	35.9-43	790-1474	0.807-1.247 (0.994)
4+(N=26)	40.4-48.2	982-1766	0.767-1.184 (1.004)

Tabla 4: Valores estadísticos obtenidos para el test ANOVA entre LC y los índices atmosféricos.

Variables correlacionadas	p- value	F
$LC_{Edad\ 3+}$ - NAO_{w}	0.026	8.612
$LC_{Edad\ 3+}$ - NAO_{ant}	0.026	8.612

Tabla 5. Frecuencia de años observados por clases de edad observados en años de NAO en fase negativa, y años de NAO en fase positiva.

Clase de edad	NAO_{ant} +	NAO_{ant} -
2+	6	2
3+	5	3
4+	5	1

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LENGTH-WEIGHT RELATIONSHIP OF BULLET TUNA FROM WESTERN MEDITERRANEAN SEA

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Summary

Length-weight relationships are used as an important tool in terms of biological assessing and management policies; since supply important information about biological dynamics, as well as the status of the stock, spawning periods or growth, among others. The major aim of this article is to provide length weight relationships of the bullet tuna *Auxis rochei* (Risso, 1810), based on 2329 specimens collected along the Spanish Mediterranean Coast in four different locations and caught by different fishing gears in both recreational and commercial fisheries. The results obtained are presented for the whole data set and also sorted out by sex.

Resumen

Las relaciones talla-peso son usadas como una herramienta importante en términos de evaluación biológica y el establecimiento de medidas de gestión pesquera; ya que proporcionan importante información sobre las dinámicas biológicas de las especies estudiadas, así como el estado del stock en cuestión o los periodos de desove o crecimiento, entre otros. Por ello, el principal objetivo de este articulo consiste en presentar las relaciones talla-peso de la melva *Auxis rochei* (Risso, 1810), basadas en los datos de 2329 especímenes capturados a lo largo de la costa mediterránea española en cuatro estaciones diferentes por medio de diferentes artes de pesca tanto de pesquerías comerciales como pesca recreativa. Las ecuaciones obtenidas se presentan para el conjunto de datos y dividido por sexos.

Resumeé

Key words: Length- weight relationship, bullet tuna, NW Mediterranean, small tunas, fisheries assessment.

1. Introduction

Bullet tuna *Auxis rochei* (Risso, 1810) is a small species belonging to the Scombridae family, with a high commercial value, whose exploitation needs to be managed (Valeiras and Abad, 2006) and cannot be disregarded. As well as other members of this family, bullet tuna is widely distributed all over the largest Oceans in the world, including the Mediterranean Sea, where they find their spawning area (García et al., 2005). The Strait of Gibraltar represents an important area within the Mediterranean Sea, since determines a geographical connection between the Atlantic Ocean and the Mediterranean Sea and represents a connective channel that numerous migratory species cross towards the Mediterranean basin.

Due to their migratory behavior, as well as other small tuna species, they cross the Strait of Gibraltar and penetrate into the Mediterranean Sea where they find their spawning area usually coinciding with warmer sea temperature that enhances the availability of resources (Teo et al., 2007; Báez et al.,

2014) during the spawning period. This migration is reflected on a peak on the fisheries yield (Uchida, 1981) during the months when this massive movement is more intense i.e. between May and September (Palandri et al., 2008).

Previous studies of the Length-weight relationships (LWR hereafter) for bullet tuna are scarce;Palandri et al., (2008), highlight the possibility of this species to form stable populations in the western Mediterranean Sea ; however many of the biological aspects of the bullet tune are yet to be understood, and the migratory behavior represents an impediment when analyzing the biological parameters of the species and interferes on the establishment of management policies, since the exploitation affects differentially to the different cohorts of the population.

LWR constitute a powerful tool to establish biological assessment and management policies. It basically consists on fitting the length against the weight observed for a certain individual, obtaining a statistical fitting expression for the whole set of individuals. This relationship provides information about the status of the stocks, lifespan, mortality, or growth rates, and permits asses about the temporal trend of the stock. From the equation obtained for a set of specimens, several biological implications can be deduced; one of the most relevant is growth. According to Froese (2006) LWR parameter b represents the type of growth followed by a determinate species. In concordance with this, b=3 represents an isometric growth (meaning that the animal growths equally in the three spatial dimensions) while a value for parameter “b” different than 3 represents an alometric growth. This kind of growth can be either positive alometric growth for those values of “b” larger than 3 (the specimens increases its thickness rather than the length), or negative alometric growth for “b” smaller than 3 (individuals growth elongated). According to this, presenting the LWR for this species will constitute an important improvement for the assessment and management of their stocks, since parameters obtained from these relationships provide useful information about biological dynamics. Moreover, the LWR in fish from a specific geographic region during a specific season could be useful to estimate their physical condition. The main aim of present paper is to provide the LWR for the bullet tuna collected along the Spanish Mediterranean Sea.

2. Materials and Methods

The samples were caught by Spanish fleets from the Western Mediterranean with different fishing systems (**Figure 1**). Detailed information about the number of individuals collected per sampling station is shown in **Table 1**.

A total of 2329 individuals of bullet tuna were collected during the whole year along the Spanish Mediterranean coast between 2003 and 2014. The individuals sampled came from different fishing gears: trap, purse seine and different types of longlines. Every specimen was measured to the nearest cm fork length (FL) and posteriorly weighed to the nearest gram. A database with the length-weight pairs of data belonging to the specimens of bullet tuna collected was created. However, the whole data set was filtered in order to remove the outliers. After elimination of outliers a total of 2305 samples were finally analyzed.

The outliers were eliminated following a two step procedure. First of all, the LeCren condition index was calculated individually by mean of the ratio between the observed and the expected weight (Froese, 2006) (given by the LWR equation). Secondly, those individuals with both the upper and lower 1% of the LeCren condition index were considered as outliers: and hence removed. We tested the randomness of the length-weight pairs deleted by mean of a chi-square test. The aim of this procedure was to ensure the randomness of samples per year.

The length-weight relationships were fitted to a power curve regression according to the equation:

$$W = a * FL^{\wedge}b$$

where W is the weight in grams, and FL is the furcal length in centimeters. This operation was performed considering both the whole data set and sorting the data by sex.

3. Results and Discussion

The LWR equation for both male and female, and with all data pooled together are shown in the figures Figures 2, 3 and 4 respectively.

Additionally, the LWR parameters (a and b), as well as the regression coefficient (R^2), the number of individuals per analysed group and the range of the lengths and weights that have been used to model the LWR is presented in the **Table 2**.

Finally, regression parameter "b" was found to be greater than 3 in all cases, reflecting positive allometric growth of the species, and also obtained for both males and females. These results reflect a slightly alometrically positive (b>3) growth for bullet tuna in all cases. Sorted out by sex, both males and females present alometric growth. In case of females, parameter b (as a growth parameter) is higher than in case of males **(Table 3)**. Nonetheless, no significant differences were found between both sexes for parameter b (greater than 3 in both cases) and hence a positive alometric growth for bullet tuna in the Western Mediterranean Sea (i.e. individual tend to grow more elongated than thick), with no effect of sex on growth could be concluded.

Uchida (1981) found similar parameters for individuals of *A. rochei* collected in the coast of Japan. Additionally, the results obtained by Ramos et al., 1985 correspondent to individuals collected by Spanish artisanal fisheries in the Mediterranean Sea, reflect a similar growth parameter (b=3.64). Palandri et al., (2008) also shows a similar growth parameter for both males and females in the Ligurian Sea (Palandri et al., 2008).

This study enhances the contribution to the length-weight relationship of the bullet tuna in the western Mediterranean Sea where in fact the find their spawning area.

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Table 1: Distribution of the individuals collected per sampling station.

LOCATION	N
Ceuta (CE)	176
La Azohía (LA)	1888
Málaga (MA)	7
Palma de Mallorca (PM)	62

Table 2: Parameters of the LWRs in a general context and sorted out by sex for A. rochei in the Eastern Mediterranean basin.

	N	L_{min}-L_{max}	W_{min}-W_{max}	A	b	R^2
General	455	23.9-47.0	197.28-2110	0.0027	3.5064	0.9039
Males	195	31-44.6	440-1766	0.002	3.5864	0.9501
Females	254	28.2-46	318-1678	0.0019	3.6011	0.9594

Table 3: Statistical parameters obtained from the LWR for both males and females.

Sex	b-min	b-max	b-mean	T-student	P
Males	3.470	3.703	3.586	60.599	0.975
Females	3.509	3.693	3.601	77.141	0.979

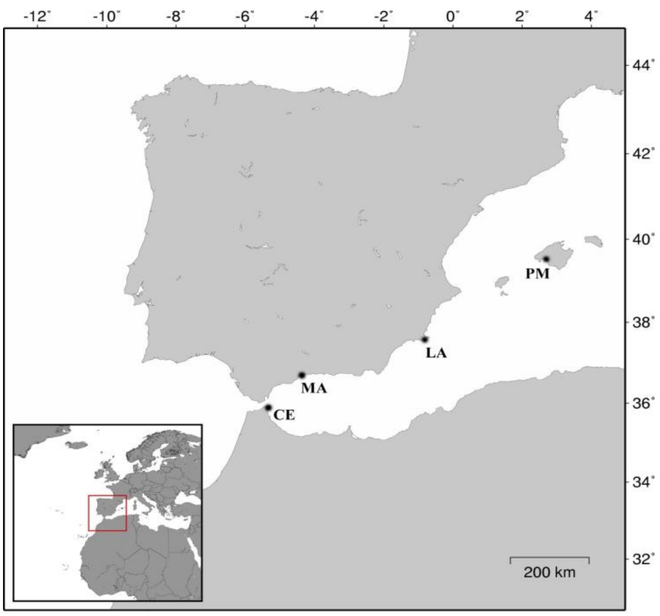

Figure 1: Map of the Mediterranean Sea, showing the sampling sites. Key: CE, Ceuta; LA, La Azohía; MA, Málaga; PM, Palma de Mallorca.

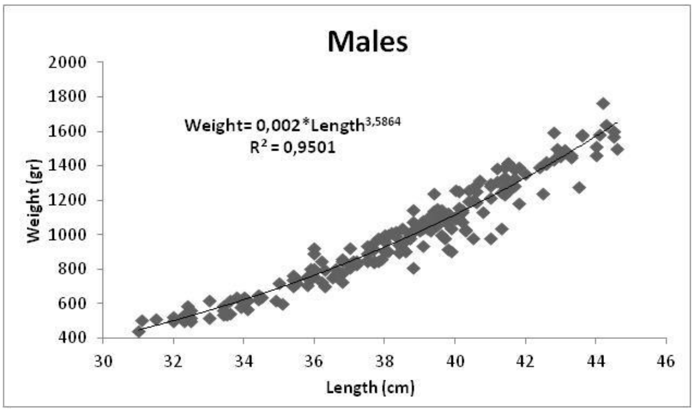

Figure 2: Length-weight relationship model obtained for males of bullet tuna in the Western Mediterranean Sea.

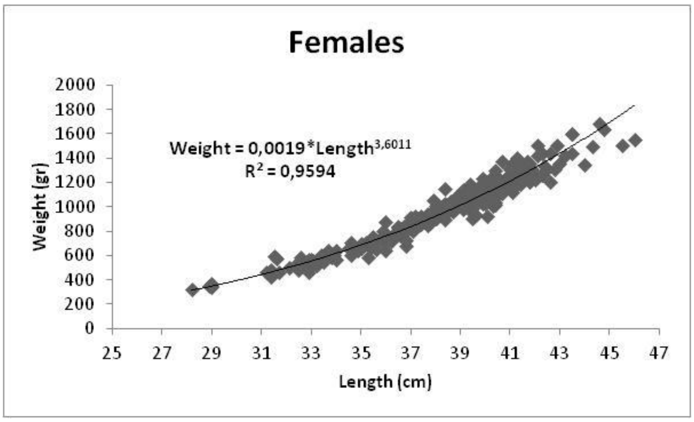

Figure 3: Length-weight relationship model obtained for females of bullet tuna in the Western Mediterranean Sea.

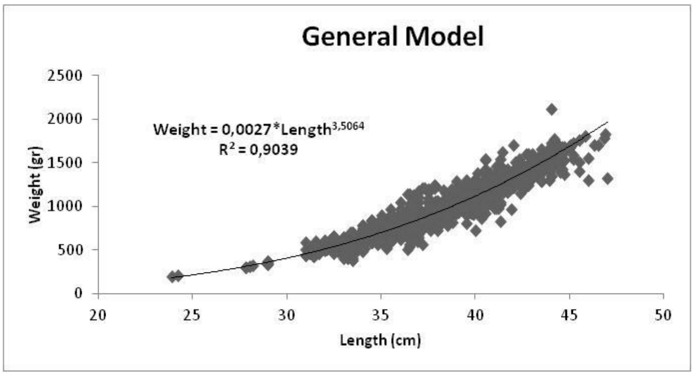

Figure 4: General length-weight relationship model for bullet tuna in the Western Mediterranean Sea.