Vol. 564: 77–86, 2017
doi: 10.3354/meps12007

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published February 3

# Occurrence of basking shark *Cetorhinus maximus* in southern Portuguese waters: a two-decade survey

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ABSTRACT: There is a general consensus that many shark species are declining in numbers. However, effective management measures often depend on knowing how trends in abundance and distribution are influenced by environmental conditions. Several efforts to describe the occurrence and distribution of basking sharks *Cetorhinus maximus* have been made in northern Europe, particularly around the UK, but nothing is known regarding their occurrence in southern areas, such as the south of Portugal. Using 2 decades of observational data collected in the south of Portugal, we show that the occurrence of basking sharks in the area was highly seasonal, with individuals being observed mainly during spring. Based on *in situ* and satellite-derived environmental variables and climate indices, we also demonstrate that temporal trends were associated with the beginning of the upwelling season and that the inter-annual changes were related to lower values of sea surface temperature, North Atlantic Oscillation index, upwelling index, 2-mo lagged chlorophyll *a* and 3-mo lagged Atlantic Multidecadal Oscillation index, and higher values of 2-mo lagged upwelling index. These findings suggest that basking sharks are associated with the expansion of cold waters following upwelling events in the region, probably due to the aggregation and increase of zooplankton. Although the temperature recorded during our study years ranged from 14 to 24°C, sharks were mainly observed when temperatures were lower than 20°C, corroborating their preference for colder water. This study provides the first knowledge on the habitat use of basking sharks in southern European Atlantic areas.

KEY WORDS: Upwelling · North Atlantic Oscillation · Atlantic Multidecadal Oscillation · Sea surface temperature · Zooplankton



## INTRODUCTION

Pelagic sharks and rays are regularly caught either as targets, for their meat and valuable fins, or as bycatch of fisheries targeting other species such as tuna, swordfish and other billfish (Dulvy et al. 2014). It is a general consensus in the scientific community that many shark species are declining in numbers and therefore appropriate management and conservation measures must be implemented (Musick et al. 2000, Baum et al. 2003, Dulvy et al. 2008, Worm & Branch 2012, Worm et al. 2013). There are several examples of shark stocks that experienced brief period of intense fisheries exploitation followed by a sudden collapse (Camhi 1998). For example, rapid declines in catches were reported over a period of less than 10 yr for the basking shark *Cetorhinus maximus*, Gunnerus 1765 in several locations, with reductions of 50 to 90% in their numbers (CITES 2002). These declines have resulted in long-term re-

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ductions in local populations. In some regions, for example the northeast Pacific Ocean, populations have apparently shown no signs of recovery, despite cessation of targeted exploitation (Sims 2008, Field et al. 2009). For mobulids, while global fisheries appear to be increasing due to a high demand for gill plates in several countries, catch rates in some regions are declining, indicating potential overexploitation (Croll et al. 2015). However, it is difficult to separate natural fluctuations from fishing effects (Maguire et al. 2006). Therefore, in order to devise effective management measures, it is first necessary to understand how trends in abundance and distribution are influenced by environmental conditions (Cotton et al. 2005).

Several studies have tried to understand the relation between shifts in the distribution of planktivorous elasmobranchs, such as basking sharks and whale sharks *Rhincodon typus*, Smith 1828, and environmental factors, including sea temperature and climate effects (e.g. Sims & Quayle 1998, Sims et al. 2000, 2006, Cotton et al. 2005, Sleeman et al. 2007, Rowat et al. 2009, Sequeira et al. 2012, Rohner et al. 2013, Miller et al. 2015). Sightings of basking sharks, as well as other filter-feeding elasmobranchs, are strongly linked to zooplankton abundance and distributions (Sims et al. 1997, 2003a, 2005, Cotton et al. 2005) that in turn are influenced by numerous environmental drivers (Fromentin & Planque 1996, Cotton et al. 2005). For instance, sea surface temperature (SST), occasionally combined with other variables such as wind speed (Rowat et al. 2009), chlorophyll *a* (chl *a*) and bathymetry (Sleeman et al. 2007), appears to influence whale sharks numbers in the western Indian Ocean (Sequeira et al. 2012), particularly in the Seychelles (Rowat et al. 2009), and on Ningaloo Reef, Australia (Sleeman et al. 2007). The occurrence of this species at Ningaloo Reef was also influenced by atmospheric and climatologic events such as El Niño Southern Oscillation (ENSO), described by the Southern Oscillation Index (SOI), mainly due to its direct influence on oceanographic processes such as current intensity (Wilson et al. 2001, Sleeman et al. 2010).

The basking shark is a planktivorous coastal-pelagic shark, with a global distribution covering boreal to warm-temperate waters of the continental and insular shelves. In the northeastern Atlantic, its habitat range covers as far north as the Russian White Sea (southern Barents Sea), extending south to the Mediterranean (Sims 2008). This species has been exploited commercially for centuries in several parts of the world, mainly for its liver oil, and population stocks are thought to have declined in several regions (Sims 2008). Concern regarding their population status led to the species being listed as Vulnerable on the IUCN Red List of Threatened Species (Fowler 2005). It is protected under Appendix II of the Convention on International Trade in Endangered Species (CITES) and Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS) (Sims 2008). Efforts to describe the occurrence and distribution of basking sharks have been made in northern Europe (e.g. Sims et al. 1997, 2003b, Sims & Reid 2002, Cotton et al. 2005), particularly in the UK, where studies on the relationship between their presence and changes in environmental variables revealed a close association with lagged effect of SST in the previous month (Cotton et al. 2005) and zooplankton abundance (Sims et al. 1997, Sims & Reid 2002). However, studies regarding the occurrence of this species in more southern areas, such as the south of Portugal, are still lacking.

In this study, we examined, for the first time, the long-term relationship between environmental variables, such as SST, chl *a*, upwelling and climate indices, and the number of basking shark sightings off southwest Portugal between 1995 and 2015. This provides the first long-term investigation into the presence and distribution of basking sharks in the south of Portugal.

## MATERIALS AND METHODS

### Data collection

Occurrences of basking sharks within a tuna pen (Tunipex) located at Olhão in the south of Portugal (37° 01′ N, 7° 71′ W; Fig. 1) were recorded by tuna pen operators between 1995 and 2015. A tuna pen is composed of several nets with diameters ranging between 90 and 900 mm and a depth of 20 to 60 m. The main target is the bluefin tuna *Thunnus thynnus*, that leaves and returns to the Mediterranean Sea before and after spawning, respectively. The tuna pen usually operates between April and November. During this period, trips to the tuna pen were made twice a day (early morning and afternoon). When possible, individual sizes (in m) of basking sharks sighted were estimated visually and recorded.

### Environmental variables

*In situ* SST was recorded daily starting in 1996. An upwelling index (UI) was calculated according to Krug et al. (2012), based on the difference in remotely

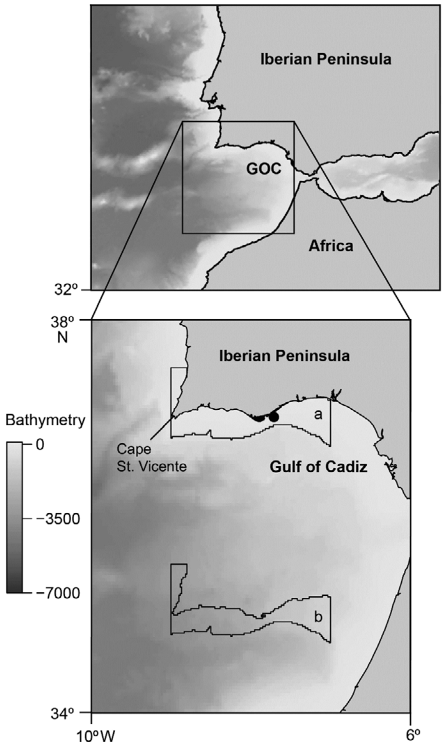


Fig. 1. Location of the tuna pen in the Gulf of Cádiz (GOC) in southern Portugal (black circle; 37° 01′ N, 7° 71′ W), where the occurrence of basking sharks was monitored from 1995 to 2015, and locations of (a) inshore and (b) offshore areas used to calculate the upwelling index

sensed SST between coastal waters, delimited by the coastline and the shelf break, and an offshore area (Fig. 1). Positive (negative) UI values are indicative of favourable (unfavourable) upwelling conditions (Krug et al. 2012). For these calculations, nighttime SST obtained from the Advanced Very High Resolution Radiometer (AVHRR, www.nodc.noaa.gov/), with a 4 km spatial resolution, was used until 2012, after which there is no data available. Therefore, after 2012, data was extracted from a moderate-resolution imaging spectroradiometer (Aqua-MODIS, http://oceancolor.gsfc.nasa.gov/), in operation from 2002 until present.

Satellite-derived monthly chl *a* data also came from 2 different sources. Between September 1997 and December 2002, chl *a* data was obtained from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, http://oceancolor.gsfc.nasa.gov/). For the subsequent period, when SeaWiFS data was unavailable, until 2015, chl *a* data was obtained from from Aqua-MODIS with a spatial resolution of approximate 4 km. Differences between these sensors were assessed by Zhang et al. (2006), who observed similar spatial and temporal patterns between the sensors and concluded that in the absence of SeaWiFS data it would be possible to use only MODIS.

### Climate indices

Due to their influence on North Atlantic climate and consequent alterations in marine environment (Nye et al. 2014), 3 climate indices were considered in the model: the North Atlantic Oscillation (NAO), the Artic Oscillation (AO), both obtained from the NOAA Climate Prediction Center (www.cpc.noaa.gov/), and the unsmoothed Atlantic Multidecadal Oscillation (AMO), which was obtained from the Physical Sciences Division (PSD) of NOAA Earth System Research Laboratory (www.esrl.noaa.gov/).

### Generalized linear model

A Poisson regression under a generalized linear model (GLM) was applied to the data using the Stats package implemented in the R software, http://CRAN.R-project.org. Regression models are commonly used to analyse the occurrence and distribution of planktivorous megafauna in relation to environmental variables (e.g. Gregr & Trites 2001, Cañadas et al. 2002, Redfern et al. 2006, Rowat et al. 2009). The Poisson regression, an extension of GLM, is generally used when the response variable is a count (Redfern et al. 2006, Friedlaender et al. 2008). *A priori*, chl *a* values were log transformed [$\log_{10}(x + 1)$] to more closely fit the model assumptions (e.g. normality). Initially, all environmental variables (SST, chl *a*, UI) and climate indices (NAO, AMO and AO) were considered in the model as explanatory variables and basking counts as the dependent variable. To incorporate the gradual effects of abiotic variables, the lagged values (1, 2 and 3 mo) were also incorporated in the model (Cotton et al. 2005). To ensure that there was no collinearity, variance inflation factors (VIF) were calculated for each predictor, using the 'car' package in R (Fox & Weisberg 2010). The variable with highest VIF was sequentially eliminated and the process repeated until all values were below the cutoff value of 2, as proposed by Zuur et al. (2010). The presence of correlated covariates can increase Type II errors, i.e. failure to reject the null hypothesis when it is untrue (Zuur et al. 2010).

A stepwise regression based on Akaike's information criterion (AIC) was then applied to the model to identify only the relevant variables (e.g. Koski et al.

Table 1. Summary of the generalized linear model (GLM) relating the probability of basking shark sightings in a tuna pen in southern Portugal between 1995 and 2015 to the independent variables kept in the final model: sea surface temperature (SST); chl *a* (2-mo lag); upwelling index (UI) (no lag and 2-mo lag); Atlantic Multidecadal Oscillation (AMO) (3-mo lag); and North Atlantic Oscillation (NAO). Model results are given in the following format: β ± SD, p-value, where β is the slope.

| | β | SD | p |
|---|---|---|---|
| SST | −0.444 | 0.091 | <0.001 |
| UI | −2.209 | 0.446 | <0.001 |
| UI (2-mo lag) | 0.938 | 0.356 | 0.008 |
| Chl *a* (2-mo lag) | −0.776 | 0.257 | 0.003 |
| NAO | −0.634 | 0.210 | 0.003 |
| AMO (3-mo lag) | −4.040 | 1.845 | 0.029 |

2009). The independent variables kept in the final model are shown in Table 1. Model results are given in the following format: β ± SD, p-value, where β indicates the slope of the relation. Finally, to evaluate the model performance, the concordance index (C-index; Harrell et al. 1984) was calculated using the Hmisc package in R (Harrell 2006) which estimates the probability of concordance between predicted and observed responses (Swets 1988). A chi-square test of the goodness-of-fit between the actual and expected values was used to see if the distribution of counts was close to the Poisson distribution (Gardner et al. 1995).

Due to the inevitably high degree of correlation between abundance and temperature found in seasonal migrants such as basking sharks (Cotton et al. 2005), a linear model was performed to check for a correlation between shark numbers and annual mean SST.

## RESULTS

### Interannual and intra-annual variability

A total of 45 sightings of individual basking sharks were made in the tuna pen between 1995 and 2015. In general, basking shark sightings occurred during spring (March to May), particularly during April (Fig. 2). Exceptionally, one individual was found in the pen in August 2011. Nonetheless, a large interannual variation was observed throughout the study period, with several years where no occurrences were reported (1995, 1997, 1998, 2000, and 2007) and a maximum of 13 individuals observed in 1999 (11 of them in April) (Fig. 3).

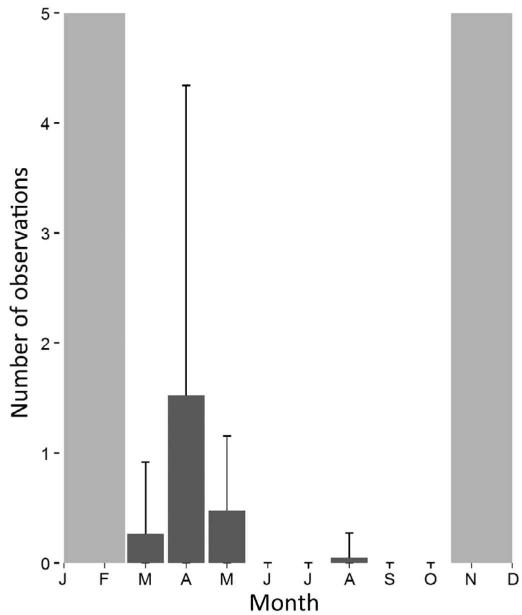


Fig. 2. Intra-annual variability of observations of basking sharks in a tuna pen in southern Portugal between 1995 and 2015 (dark grey bars). Values are monthly means ± SD. Grey shaded areas represent months with no data available, as the tuna pen was not in operation

During this study, SST ranged from 13.8 to 24.1°C. However, basking sharks were only observed when SST was between 13.8 and 20.3°C. The results of the linear model analysis showed a significant negative correlation between annual SST and number of observations (Fig. 4; β = −0.42 ± 0.19, p = 0.04)

For a total of 27 individuals, length was roughly estimated, with values ranging from 1 to 9 m. The analysis of the mode indicate that the most common length observed was 5 m, corresponding to putative sub-adults/adults (Sims 2008) (Fig. 5).

### Relationship with environmental variables and climate indices

The final and best GLM model, with a lower AIC value (134.73; compared with the initial value of 138.6 after the elimination of collinear predictors), and a C-index of 0.84 indicating a good performance of the model (Swets 1988), revealed a negative and significant relation between number of basking sharks and SST, UI, NAO, 2-mo lagged chl *a* and 3-mo lagged AMO. By contrast, there was a positive and significant relation between 2-mo lagged UI and number of sightings (Table 1).

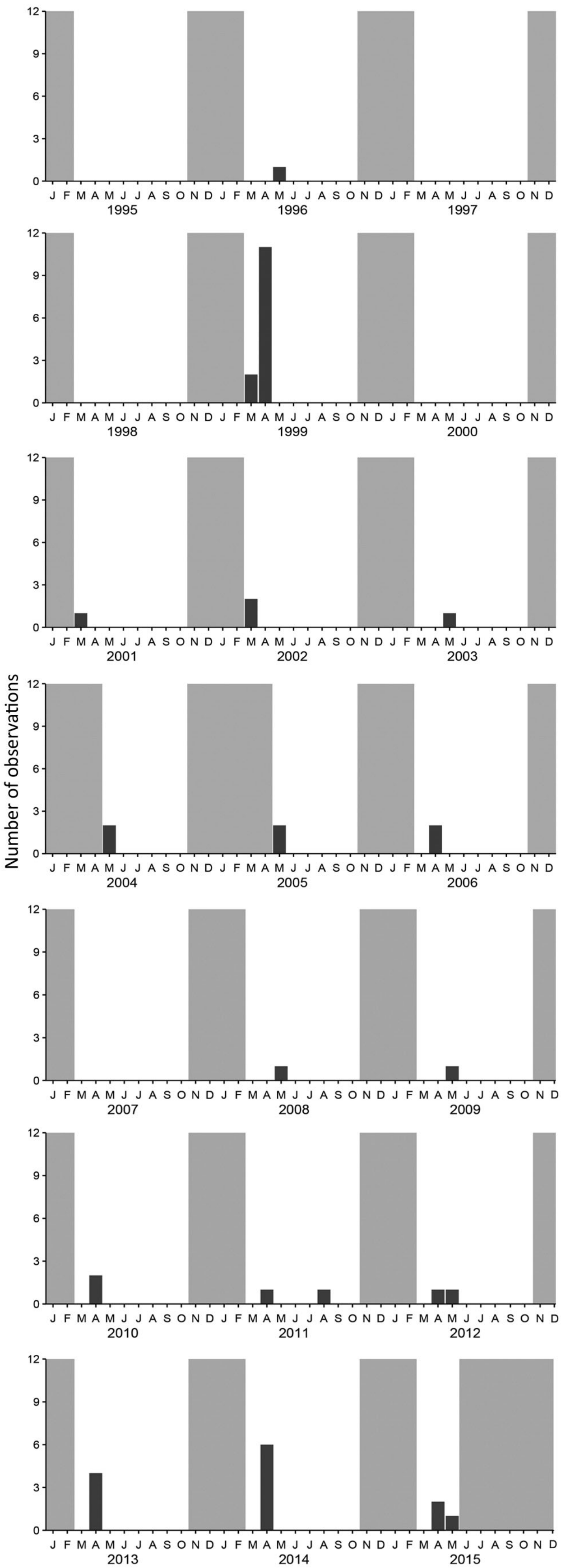


Fig. 3. Interannual variability of observations of basking sharks in a tuna pen in southern Portugal between 1995 and 2015 (dark grey bars). Grey shaded areas represent months with no data available, as the tuna pen was not in operation

## DISCUSSION

### Seasonality of basking shark occurrence in relation to environment

In spite of the dataset limitations (e.g. no data during winter periods, sightings restricted to a small area and surface data only) we showed, for the first time, that the occurrence of basking sharks in coastal southern Portugal appears highly seasonal, which confers with the patterns found in other study areas. For instance, in the UK, an increase in the surface sightings of basking sharks is generally observed in May and early June when zooplankton abundance is high (Sims et al. 1997, 2008, Sims & Quayle 1998). In the Mediterranean, this species is more frequently observed in late winter, particularly in March (Mancusi et al. 2005, de Sabata et al. 2013) and usually associated with areas of high productivity. In both cases, sightings are linked with increased zooplankton abundance and associated with productive areas and/or periods. In our study, basking shark sightings occurred almost exclusively between March and May (spring period).

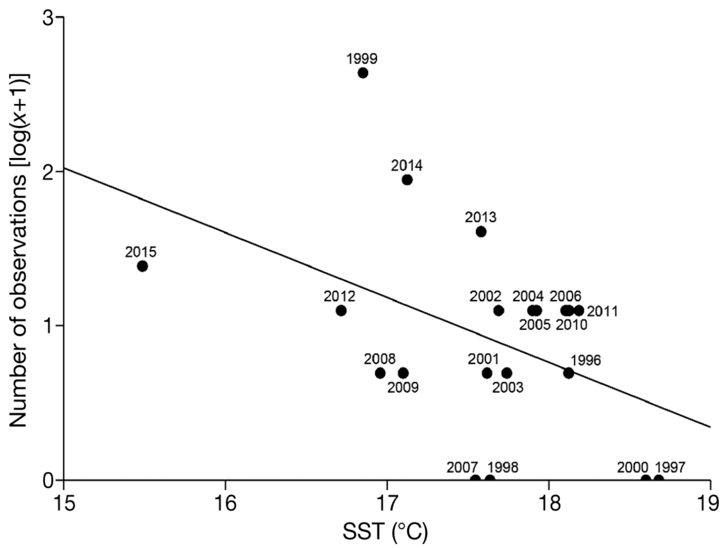


Fig. 4. Relationship between annual SST (°C) and annual numbers of basking sharks observed within a tuna pen in southern Portugal between 1995 and 2015. The line represents the linear regression

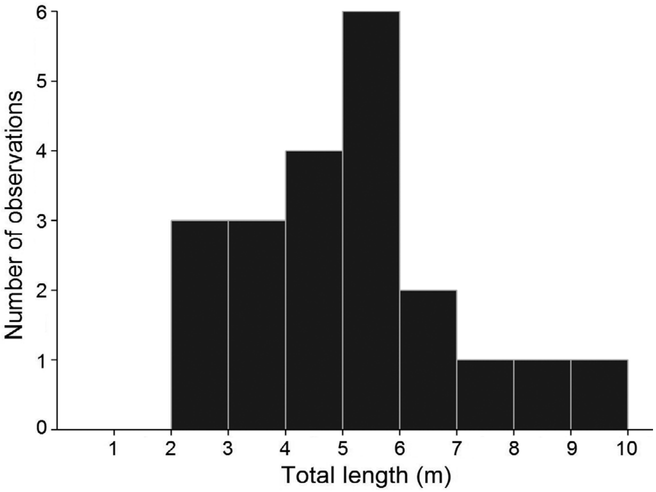


Fig. 5. Size distribution of basking sharks (n = 27) observed within a tuna pen in southern Portugal between 1995 and 2015

It appears that the times of year when most basking sharks are seen shifts progressively towards later in the year northwards to England and Scotland. However, it is possible that this observed pattern is only a reflection of the fact that sharks come to the surface to feed earlier in southern locations as the waters warm earlier. Another possible explanation is that animals migrate north when the conditions become favourable in one region, as has been previously observed (Sims et al. 2003b).

Nevertheless, surface sightings in our study appeared to be related to oceanographic processes affecting the coastal region of the SW Iberian Peninsula. On the southern coast of Portugal occasional upwelling occurs in association with favourable westerly winds (Relvas & Barton 2002, Cravo et al. 2013). After a prolonged period of strong northerly winds, upwelled water can circulate around Cape St. Vicente (located at the tip of the peninsula) and flow eastwards along the southern continental shelf (Fiúza 1983, Relvas & Barton 2002, Vargas et al. 2003), eventually merging with local upwelled water. This cold water tongue extends towards the southeast along the continental shelf break (slope of the eastern Gulf of Cádiz) known as the 'Huelva front' (Stevenson 1977), and has been observed on a number of occasions by several authors (e.g. Relvas & Barton 2002, García-Lafuente et al. 2006, Navarro & Ruiz 2006). Higher phytoplankton biomass values have been found in this cold water tongue than in recent upwelled water, probably due to the time lag of phytoplankton response (Reul et al. 2006). Cold water tongues have been linked with an increase in plankton biomass and production (Keister et al. 2009a, 2009b). This increase in plankton may consequently lead to the aggregation of upper trophic level planktivorous organisms such as whales and elasmobranchs (Sims et al. 1997, Sims & Quayle 1998, Rendell et al. 2004, Tynan et al. 2005, Etnoyer et al. 2006, Sims 2008, Cotté et al. 2011, Gill et al. 2011, Scales et al. 2014).

Our results further support these observations. It appears that SST and upwelling conditions influenced the number of basking sharks sighted within the tuna pen. Higher numbers of basking sharks were observed during low temperatures and following periods of strong upwelling events. This sequence of events is consistent with the formation and expansion of a cold front post-upwelling described in the previous paragraph, indicating that the presence of basking sharks near the surface was related to these features.

Additionally, a negative correlation between basking shark sightings and NAO and 3-mo lagged AMO was observed. Due to their influence on SST and winds, NAO and AMO have been linked to variations in the plankton abundance (Fromentin & Planque 1996, Drinkwater et al. 2003, Piontkovski et al. 2006), which can consequently modify the whole community structure through bottom-up processes (Hátún et al. 2009). Shifts in zooplankton communities related with changes in NAO phases were reported by several authors for the northeast Atlantic (e.g. Fromentin & Planque 1996, Drinkwater et al. 2003). In some locations, lower abundances of zooplankton were observed under a high NAO index (Drinkwater et al. 2003), most likely due to a reduction in stratification caused by higher wind stresses, low phytoplankton abundance, and consequently a reduction in food available for zooplankton (Drinkwater et al. 2003). On the Iberian coast, low NAO values have been related with high recruitment of sardine *Sardina pilchardus* (Guisande et al. 2001, Borges et al. 2003) and hake *Merluccius merluccius* (Mendes et al. 2008), 2 species that spawn in this area in winter and spring (Guisande et al. 2001, Mendes et al. 2008). When NAO is negative, oceanographic conditions are moderate, favouring recruitment under the optimal environmental window theory (Guisande et al. 2001), which states that moderate upwelling conditions have a positive effect on recruitment since an increase in primary production boosts food availability, while wind mixing remains low (Cury & Roy 1989). As the annual production of larvae matches the production of their food (Cushing 1990), larval abundance is likely to increase under these optimal conditions, thereby increasing the amount of food available for basking sharks.

Moreover, south or southwest equatorial trade winds blow along the coast, retaining eggs and larvae in coastal waters (Guisande et al. 2001). Therefore, a higher abundance of small fish and eggs near the coast when NAO values are lower may attract more basking sharks, which may explain the negative correlation observed between NAO and basking shark abundance. The presence of basking sharks in areas with high abundance of fish eggs was observed in other studies (e.g. Francis & Duffy 2002), possibly corroborating our hypothesis.

Another possible explanation is that these indices influence basking shark distribution directly due to their influence on SST. In particular, AMO has been linked with the cooling of the entire North Atlantic in its negative phase (Enfield et al. 2001, Bakun et al. 2015), particularly in Europe (Wang & Zhang 2013). More specifically, a study revealed that AMO regulates changes in temperature in our study area (Pardo et al. 2011). This cooling of SST may influence the movement of basking sharks due to the expansion of areas within their preferred temperature range (8 to 16 °C; Sims et al. 2003a). While the temperature recorded during our study years ranged from 14 to 24°C, sharks were mainly observed when temperatures were lower than 20°C. In a previous study (Cotton et al. 2005) the presence of basking sharks around the UK, where SST typically varies between 6 and 20°C, was related to higher SST values and positive NAO index values, supporting the hypothesis that basking shark distribution and movements are influenced by variations in SST and NAO. Changing movement patterns associated with climate indices have been observed for other species. Studies have found a relationship between abundance and migrations of fish populations (e.g. *Engraulis encrasicolus*, *S. pilchardus*, *Sprattus sprattus*, *Clupea harengus, Salmo salar*) in the eastern North and Central Atlantic and the different phases of the AMO and NAO. These changes have been linked to variations in either SST or plankton abundance (Condron et al. 2005, Alheit et al. 2014, Nye et al. 2014). Therefore, a higher number of basking sharks in a lower latitude region such as southern Portugal can be expected when both these indices are negative because this can lead to water temperatures more closely within preferred ranges of *C. maximus* and, concomitantly, more prey-abundant conditions. Our modelling results support this scenario for basking sharks in southern Portugal.

**Interannual variation of basking shark sightings**

Besides a highly seasonal presence of basking sharks in the south of Portugal, a high interannual variation was also observed. Our results indicated that, in general, there was an inverse relation between annual SST and annual observations. Although basking sharks have a wide range of tolerance to thermal variation, they seem to avoid warmer waters (Sims 2008). Previous studies have shown that basking sharks usually prefer a particular range of water temperatures. For example, in the western Atlantic, while recorded temperatures ranged between 5.8 and 21.0°C, 72% of the recordings were between 15 and 17.5°C (Skomal et al. 2004). Similarly, in the UK, temperatures ranged between 8 and 16°C (Sims 2008). It has been shown that, although basking sharks perform trans-equatorial migrations, moving from temperate feeding areas to tropical waters, they mostly travel at mesopelagic depths with cooler waters (Skomal et al. 2009).

Therefore, the absence of sharks near the surface in several years may be due to the fact that some annual SSTs were outside the preferred thermal range of basking sharks in this location. However, there were several years with similar SSTs and different numbers of observations. For example, in 2007 and 2013 the number of observations was different (no individuals observed in 2007 and 4 in 2013) yet the temperature was around 17.5°C in both years. Thus, other factors seemed to have also played a role on the inter-annual changes on shark occurrence. Sims & Quayle (1998) show that local wind conditions between years induced changes in the geographical position of a tidal front, extending the mixed zone further either further inshore or offshore, which consequently influenced basking shark foraging locations. Therefore, similar local effects could influence whether basking sharks in southern Portugal were further inshore, near the set net, or not.

Interestingly, in 2007, when no sharks where observed in south Portugal, basking sharks were also absent from the Mediterranean (de Sabata et al. 2013). This absence may indicate a possible connection between the European and Mediterranean populations, with the occurrence of sharks in one area influencing their presence in the other. It is possible that basking sharks move between the 2 areas, driven by wide-scale foraging opportunities. These movements have been observed in other marine planktivorous predators. For example, sunfish tagged in south Portugal entered the Mediterranean and spent large periods of time around the Alboran gyre, one of the most productive areas in the Mediterranean Sea (Sousa et al. 2016). Therefore, it is possible that basking sharks in the region exhibit similar behaviour, moving between the 2 regions in response to changing zooplankton abundances.

Long-distance foraging movements of sharks have been observed in other studies. One basking shark moved from eastern to western Atlantic at a time when upwelling and high abundance of phytoplankton was observed in the western Atlantic (Gore et al. 2008). There are also reports of trans-equatorial migrations (Skomal et al. 2009). However, further studies using other techniques such as satellite telemetry to investigate movement patterns and more extensive studies of the occurrence of this species in the Mediterranean should be conducted in order to confirm this hypothesis.

## CONCLUSIONS

In the period 1995 to 2015, the occurrence of basking sharks off the south coast of Portugal was highly seasonal, with individuals entering the set net mainly in spring, associated with the beginning of the upwelling season and expansion of cold waters. Additionally, climate-driven changes in SST and zooplankton abundance appeared to influence the presence of basking sharks in our study area. The seasonality of basking sharks observed in our study showed similarity with the results of other studies in different locations and may indicate connectivity between the European and Mediterranean populations. However, further studies should be conducted in order to confirm this hypothesis. By increasing the knowledge regarding basking shark distribution and habitat use in relation with environmental variables in SW Iberia, this study will contribute to improved management and conservation strategies for this vulnerable shark species.

*Acknowledgements*. We thank all the crew at Tunipex for allowing access to the data without which the current study would not have been possible. The 'Programa Operacional Pesca 2007-2013' supported this study through the PROMAR Project 31-03-05-FEP-0037 and the Portuguese Foundation for Science and Technology (FCT) through Investigator Fellowship FCT 2013 to R.R. and to N.Q.

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*Editorial responsibility: Myron Peck, Hamburg, Germany*

*Submitted: March 30, 2016; Accepted: December 7, 2016*
*Proofs received from author(s): January 26, 2017*