



The NAO affects the reproductive potential of small tuna migrating from the Mediterranean Sea



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ABSTRACT

Several studies have confirmed that the North Atlantic Oscillation (NAO) has a direct effect on tuna across a range of biological aspects, such as abundance, catchability, recruitment, and physical condition (LC), especially during winter season (NAOw). However, its effect on reproductive biology has been barely investigated. Thus, the main aim of this study was to investigate the effect of the NAO on the physical condition index and gonadosomatic index (GSI) of the three most commercially exploited small species of migrating tuna (i.e. little tunny, bullet tuna, and Atlantic bonito) in the Mediterranean Sea. A positive direct correlation was found between little tunny and Atlantic bonito and the gonadosomatic and the physical condition indexes. In addition, a strong correlation was found between the NAOw and the gonadosomatic and LC indexes, which could lead to higher reproductive investment in gonad growth before the spawning season. In contrast, bullet tuna had a low LC index during peak gonad growth and were less affected by NAOw oscillations. In the case of bullet tuna, these results could be explained by a longer reproductive period that would lead to faster fat consumption before the reproductive period than in the other species considered and greater dependence on the surrounding environmental conditions for reproductive success.

1. Introduction

It is widely accepted that the North Atlantic Oscillation (NAO) is the main source of both seasonal and interannual climatic variability, especially during winter months (Hurrell, 1995), within the North Atlantic area, including the Mediterranean basin (Hurrell, 1995; Hurrell and Deser, 2009). This atmospheric phenomenon is characterised by fluctuations in atmospheric pressure at sea-level between the Icelandic Low Pressure Centre and the Azores High Pressure Centre. It is associated with many meteorological variations in the region that not only influence wind speed and direction but also changes in temperature and rainfall regimes (Hurrell, 1995).

Several studies have found that the NAO has a direct effect on fisheries in general (e.g., see Graham and Harrod, 2009; Brander and Mohn, 2011); however, the NAO has a stronger effect on migratory species (Forchhammer et al., 2002) such as tuna. In this sense, several authors have reported a relationship between the NAO and different tuna species in relation to fish abundance (Báez et al., 2011), catchability (Rubio et al., 2016), recruitment (Borja and Santiago, 2002;

Mejuto, 2003), and physical condition (Báez et al., 2013a, 2013b; Muñoz-Expósito et al., 2017). Moreover, Muñoz-Expósito et al. (2017) hypothesized that the NAO could determine the reproductive potential of migrating bullet tuna (*Auxis rochei*). This hypothesis has yet to be confirmed.

Little tunny *Euthynnus alletteratus* (Rafinesque 1810), bullet tuna *Auxis rochei* (Risso 1810), and Atlantic bonito *Sarda sarda* (Bloch 1793) are the most abundant small tuna species in the Mediterranean Sea (Macías et al., 2006; Macías et al., 2014). These species are commercially exploited off the Spanish coast by fleets using a wide variety of fishing gear, and have significant commercial and ecological value given their important role in trophic chains.

Like the other two species, little tunny is a schooling and opportunistic predator species (Collette, 1986; El-Hawee et al., 2013), which is usually found in inshore waters (Valeiras and Abad, 2007). Although little is known about its migratory movements (Valeiras and Abad, 2007), Rodríguez-Roda (1966) observed seasonal movements of small tuna through the Strait of Gibraltar (which connects the Atlantic Ocean and Mediterranean Sea) for spawning purposes. *A. rochei* is a neritic

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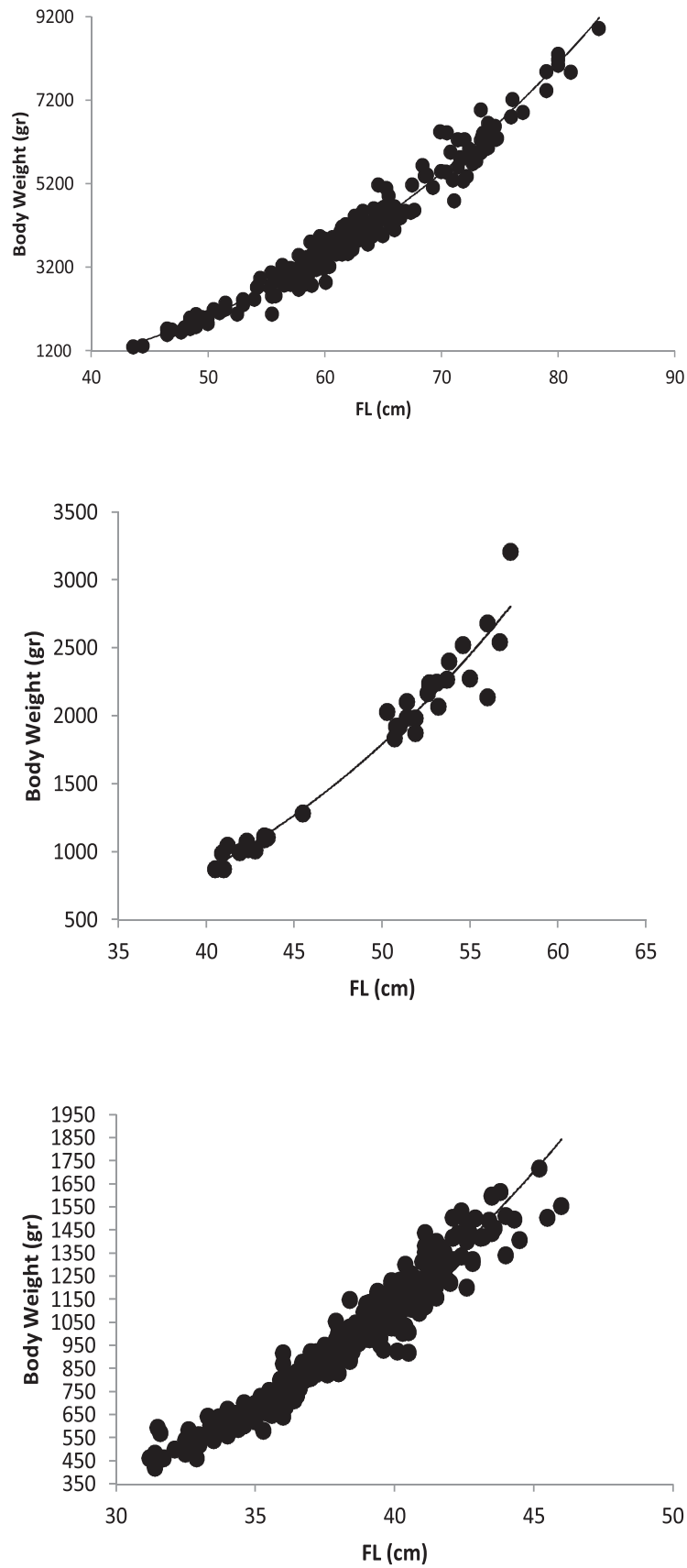


Fig. 1. Length-Weight Relationship per Species. Key: FL, Fork length.

Table 1
Length/Weight Parameters per Species.

Species	Function	R ²
Little tunny (N = 256)	Weight = 0.0205*Length ^{2.94}	0.97
Bullet tuna (N = 325)	Weight = 0.0019*Length ^{3.6}	0.95
Atlantic bonito (N = 361)	Weight = 0.0045*Length ^{3.3}	0.97

pelagic species that exhibits seasonal movements through the Strait of Gibraltar, although such movements tend to take place over the continental shelf (Muñoz-Expósito et al., 2017). Thus, every year between April to June these species move across Cabo Tiñoso (Azohía, South-Eastern Spain), where they are caught in tuna traps. The Atlantic bonito migrates along the coast for large distances, as proven by the existence of tagged-recaptured fish in the Alboran Sea; thus, it has been shown that there is genetic migration from the Atlantic Ocean to the Alboran Sea during spring (Rey et al., 1984). After the spawning season, this species migrates again through the Strait to the Atlantic Ocean.

The main aim of the present study was to investigate the effect of the NAO on the physical condition and gonadosomatic index of migrating small tuna (i.e. little tunny, bullet tuna, and Atlantic bonito) caught in the western Mediterranean Sea, and hence to assess the biological effect of the NAO on tuna species.

2. Material and methods

During the period 2003–2016, the three species (i.e. little tunny, bullet tuna, and Atlantic bonito) were sampled between April and June each year. In the case of Atlantic bonito the study period considered was 2003–2015 because the samples from 2016 could not be analysed due to a lack of available data. A total of 1916 individuals were caught during annual scientific surveys conducted in the La Azohía trap (Murcia, South-Eastern Iberian Peninsula). The study only used female tuna.

The number of females sampled per species differed depending on availability. Thus, a total of 258 little tunny and 325 bullet tuna were sampled. The final sample of Atlantic bonito comprised 361 individuals. Each specimen was measured to the nearest millimetre (fork length) and weighed to the nearest 10 g. Gonads were removed from the gut cavity, each individual was sexed by visual exploration of the gonad, and gonads were measured to the nearest gram.

Subsequently, the length-weight relationship (LWR) was calculated for each species using the following function (Ricker, 1973; Froese, 2006):

$$\text{Weight} = a * \text{Length}^b; \tag{1}$$

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 centimetres (cm), respectively. Aberrant points were retired according to Froese et al. (2011).

To assess the physical condition of the individual fish at a specific time, where physical condition is represented by the body mass of a fish of a given length, the Le Cren (LC) condition index was estimated using the regression coefficients previously obtained for the LWR:

$$\text{LC} = \text{Wobserved}/\text{Westimated}; \tag{2}$$

Where Wobserved is the observed weight expressed in grams, and Westimated is the fitted weight as a function of length based on the LWR equation. Thus, these expressions represent the deviation of an individual of a given length from the expected weight for that length (Le Cren, 1951).

In a second step, the gonadosomatic index (GSI) was estimated for each sampled as: (Gonad Weight/Eviscerated Weight)*100

2.1. Atmospheric data

The National Oceanic and Atmospheric Administration (NOAA) provided monthly NAO values for the study period (2003–2016) (data available at: <http://www.noaa.gov>). Given that climatic variability is at its highest during the winter months (i.e. from November of the previous year to March of the current year) (Hurrell, 1995), the average value of the winter months (NAOw) was also used in the models. Furthermore, the NAOw was also included to identify temporal lags between the prevailing atmospheric conditions and the biological effect they trigger.

2.2. Data analysis

The NAO index can be positive or negative. It is widely known that the positive phases of NAO induce higher than average westerly winds across northern mid-latitudes with a dry climate in southern Europe, while the negative phases of NAO induce major precipitation. Thereby, positive or negative NAO phases produce differential effect on weather and oceanography (Báez et al., 2013a,b). For this reason, the associations between the mean positive NAOw phases versus the mean negative NAOw phases for both the LC index and the GSI were investigated using the Mann-Whitney U test. We also used non-parametric Spearman correlation.

3. Results

Fig. 1 and Table 1 show the LWR obtained per species and regression coefficients, respectively. Table 2 shows the LC and GSI mean per year and species. We plotted the time series of biological indices respect to NAO index, using box-plots (Fig. 2a–f).

In the case of the 256 little tunny (before removed aberrant points), significant differences (U = 6397, P = 0.027) were found between the mean LC index during negative NAOw phases (0.993) and positive NAOw phases (1.013). Quasi-significant differences (U = 6880, P = 0.057) were also found between the mean GSI mean during negative NAOw phases (1.49) and positive NAOw phases (1.89).

Furthermore, a significant positive non-parametric correlation was found between the GSI and the LC index (Rho = 0.35, P < .0001). Thus, females with the highest LC had the highest GSI index. Moreover, significant positive non-parametric correlations were found between the GSI and the NAOw (Rho = 0.234, P < .0001), but it did not found between the LC index and the NAOw (Rho = 0.119, P = 0.058).

In the case of the 325 bullet tuna, no significant differences (U = 11,986.5, P = 0.595) were found between the mean LC index during negative NAOw phases (0.996) and positive NAOw phases (1.003). However, significant differences (U = 9157, P < .0001) were

Table 2
Observed average of biological data per year.

Year	Little tunny		Atlantic bonito		Bullet tuna		
	LC	GSI	LC	GSI	LC	GSI	NAOw
2003	0.95	0.844	0.979	4.727	1.0094	5.25	-0.033
2004	0.997	1.105	0.982	4.376	1.058	1.89	0.54
2005	0.996	1.074	1.051	3.463	0.96	1.746	0.212
2006	0.982	1.514	0.997	4.959	0.985	1.574	-0.005
2007	0.994	0.971	0.954	1.6006	1.044	1.0496	0.523
2008	1.012	1.89	1.0179	6.25	1.066	1.6056	0.258
2009	0.987	1.821	0.999	1.898	0.978	1.516	-0.03
2010	0.999	1.272	0.997	3.72	0.957	1.355	-1.107
2011	0.983	2.215	0.9905	2.679	1.035	1.483	-0.0933
2012	1.034	1.682	1	5.351	0.957	1.418	1.2017
2013	1.012	1.084	0.977	2.153	1.00093	1.55	-0.238
2014	1.038	1.75	0.98	3.79	0.992	1.455	0.765
2015	1.027	4.1619	0.988	3.92	0.962	1.494	1.305
2016	0.955	1.011			1.025	1.94	1.132

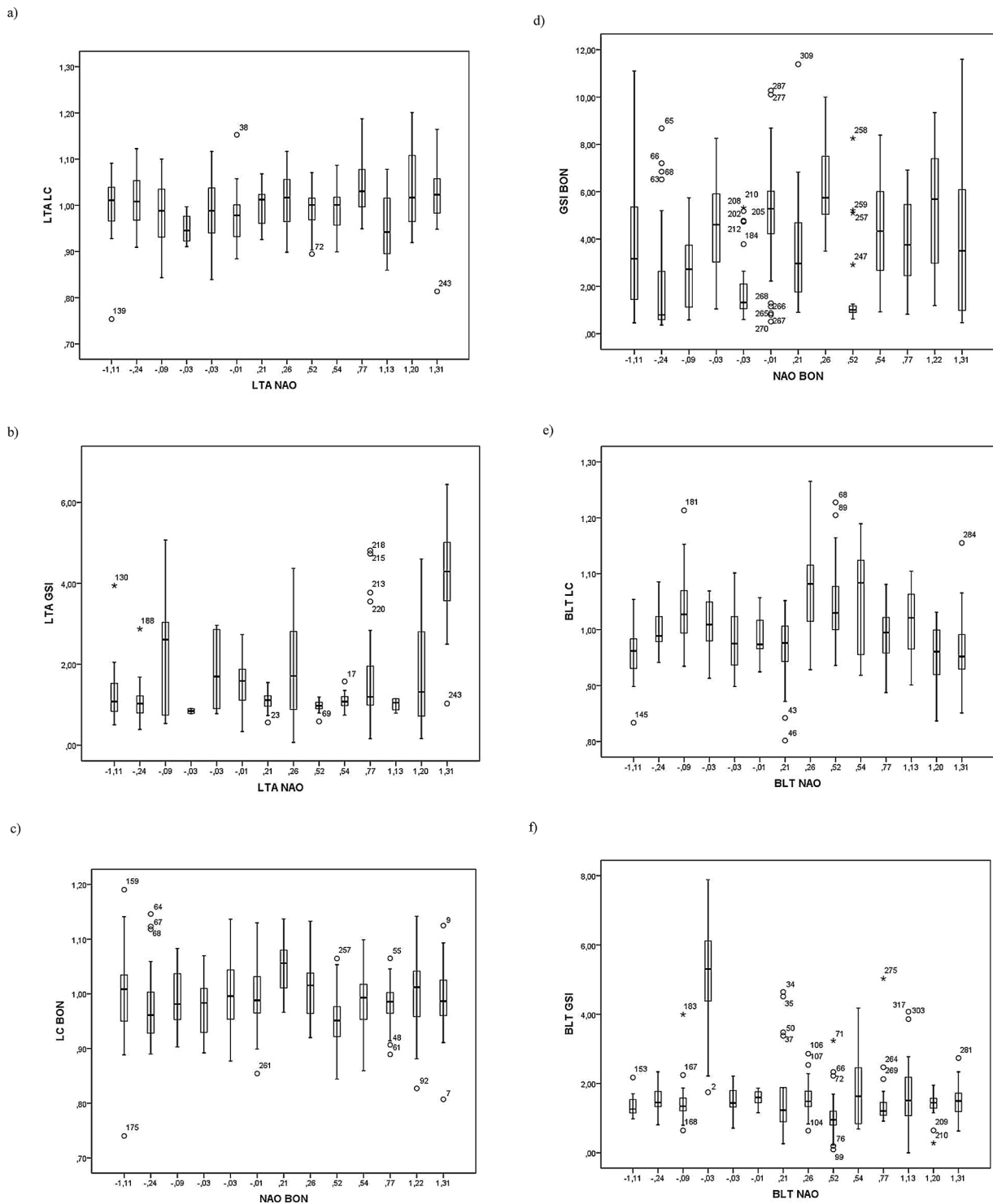


Fig. 2. Box plots of the time series of biological indices respect to NAOw index. a) Le Cren (LC) condition index versus North Atlantic Oscillation in winter (NAOw) for the little tunny (LTA); b) gonadosomatic index (GSI) versus NAOw for LTA; c) LC versus NAOw for the Atlantic bonito (BON); d) GSI versus NAOw for BON; e) LC versus NAOw for the bullet tuna (BLT); f) GSI versus NAOw for BLT.

found between the mean GSI during negative NAOw phases (2.02) and positive NAOw phases (1.5).

In addition, a significant negative non-parametric correlation was found between the GSI and the LC index ($Rho = -0.202, P < .0001$). Thus, females with the highest LC had the lowest GSI index. Moreover, no conclusive significant negative non-parametric correlations were found between the LC index and the NAOw ($Rho = -0.11, P = 0.048$).

Finally, in the case of the 361 Atlantic bonito sampled between

2003 and 2015, no significant differences ($U = 15,406.5, P = 0.44$) were found between the mean LC index during negative NAOw phases (0.991) and positive NAOw phases (0.994). However, significant differences ($U = 12,777.5, P = 0.001$) were found between the mean GSI during negative NAOw phases (3.142) and positive NAOw phases (4.039).

Moreover, a significant positive non-parametric correlation was found between the GSI and the LC index ($Rho = 0.39, P < .0001$).

Thus, females with the highest LC had the highest GSI index. Significant positive non-parametric correlations were found between the GSI and the NAOw (Rho = 0.217, $P < .001$), and between the LC and the NAOw.

4. Discussion

Our results indicate a correlation between LC and GSI. However, we do not observe a common pattern for the three species. Thus, for little tunny (LTA) and Atlantic bonito (BON) the correlation was positive, while for the bullet tuna (BLT) the correlation was negative. According to Sabatés and Recasens (2001) small tunas could exhibit different spawning behaviours in the Western Mediterranean, as a strategy to avoid competition between them, because they spawn at the same time.

The positive correlation between GSI and a proxy of body condition (as in the cases of LTA and BON), is a common finding in fish (for example Hossain et al., 2012, and Mozsár et al., 2015, in freshwater species). A better body condition could induce highest energetic investment in gonad growth and development. Indeed, according to Roff (1983) the surplus energy from somatic grows is channelled into either somatic or gonad growth. So BON and LTA increase the gonads weight from surplus body reserves. However, in the case of BLT the active growth of the gonads could be based on direct investment of energy. Thus bullet tuna follow a different strategy to that of the other two species in the use of energy and in gonad development. This difference could be due to three different factors: 1) the spawning period is longer than that of the other two species (Sabatés and Recasens, 2001; Valeiras and Abad, 2007); 2) their smaller body size leads to the decreased retention of fat, which is consumed more rapidly before the reproductive period; and 3) there is a sampling bias, because between April and June the other two species have not yet entered the spawning period (Valeiras and Abad, 2007).

Regarding to the effect of NAOw on the GSI and LC index; we suggest that the NAOw affects in two different ways: 1) affecting the availability of food resources during their genetic migration towards the Mediterranean Sea; or 2) affecting the oceanographic conditions that activate the maturation.

We hypothesize that a positive NAOw phases result in stronger-than-average westerly winds across northern mid-latitudes (Hurrell, 1995; Visbeck et al., 2001) and could lead to improvements in the physical condition of tuna migrating to the Spanish Mediterranean Sea. Thus, changes in the dominant winds could favour pre-spawning migration by reducing the energy demand during this process and increasing the availability of nutrients, thereby guaranteeing their recovery after the spawning period. This hypothesis is supported by the results, which suggest that during positive NAOw phases the little tunny were in better physical condition.

The NAO lead to the oceanography condition (Báez et al., 2013a,b). We hypothesize that NAOw could affect oceanography conditions which activate the maturation of BLT and BON, for example Sea Surface Temperature.

Several studies in tuna species indicate that a major gonad weight implicated major batch fecundity (i.e. Zudaire et al., 2013; Saber et al., 2016). Studies on *Thunnus alalunga* in the Mediterranean Sea conclude gonadal weight was the most powerful predictor for batch fecundity. GAM analysis showed that not only large females but also small ones (with large ovaries) are capable of spawning large eggs bath. Moreover, relative batch fecundity (batch fecundity/body weight) was only significantly related to gonad weight (Saber et al., 2016). So changes in GSI induced by NAO could affect the reproductive potential of small tuna species.

Thereby, the NAO could determine the reproductive potential of migrating tuna. Many authors have predicted that in a climate change scenario, the NAO will alternate between extreme positive phases and extreme negative phases (e.g., Vicente-Serrano et al., 2011). In the light of the results, climate change could have a negative effect on the

reproductive potential of the species by affecting recruitment in such a way that it could be very low after extreme negative NAO phases, thereby putting the stock at risk. This situation is particular concern in the case of bullet tuna and Atlantic bonito because their fisheries mainly focus on one or two age classes. In this setting, the passage of just 2 or 3 years with a very low recruitment rate could lead to the depletion of the biomass of reproductive stock. For this reason, future management measures need to be developed according to any such changes in climatic conditions.

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References

- Báez, J.C., Ortiz De Urbina, J.M., Real, R., Macías, D., 2011. Cumulative effect of the north Atlantic oscillation on age-class abundance of albacore (*Thunnus alalunga*). *J. Appl. Ichthyol.* 27 (6), 1356–1359.
- Báez, J.C., Gimeno, L., Gómez-Gesteira, M., Ferri-Yáñez, F., Real, R., 2013a. Combined effects of the North Atlantic Oscillation and the Arctic Oscillation on sea surface temperature in the Alboran Sea. *PLoS One* 8 (4), e62201. <https://doi.org/10.1371/journal.pone.0062201>.
- Báez, J.C., Macías, D., De Castro, M., Gómez-Gesteira, M., Gimeno, L., Real, R., 2013b. Analysis of the effect of atmospheric oscillations on physical condition of pre-reproductive bluefin tuna from the Strait of Gibraltar. *Anim. Biodivers. Conserv.* 36, 225–233.
- Borja, A., Santiago, J., 2002. Does the North Atlantic Oscillation control some processes influencing recruitment of temperate tunas? *ICCAT Col. Vol. Sci. Pap.* 54, 964–984.
- Brander, K., Mohn, R.K., 2011. Effect of North Atlantic Oscillation (NAO) on recruitment of Atlantic cod (*Gadus morhua*). *Can. J. Fish. Aquat. Sci.* 61, 1558–1564.
- Collette, B., 1986. Scombridae (including Thunnidae, Scomberomoridae, Gasterochismatidae and Sardiidae). In: Whitehead, P.J.P., Bauchot, M.L., Hureau, J.C., Nielsen, J., Tortonese, E. (Eds.), *Fishes of the North-Eastern Atlantic and the Mediterranean*, 2nd ed. Unesco, pp. 981–997.
- El-Hawee, A.R., Sabry, E., Mohamed, H., 2013. Fishery and population characteristics of *Euthynnus alletteratus* (Rafinesque 1810) in the Eastern Coast of Alexandria, Egypt. *Turk. J. Fish. Aquat. Sci.* 13, 629–638.
- Forchhammer, M., Post, E., Stenseth, N.C., 2002. North Atlantic Oscillation timing of long- and short-distance migration. *J. Anim. Ecol.* 71, 1002–1014.
- Froese, R., 2006. Cube law, condition factor and weight-length relationships: history, meta-analysis and recommendations. *J. Appl. Ichthyol.* 22 (44), 241–253.
- Froese, R., Tsikliras, A.C., Stergiou, K.I., 2011. Cube law, condition factor and weight-length relationships: history, meta-analysis and recommendations. *Acta Ichthyol. Piscat.* 41 (4), 261–263.
- Graham, C.T., Harrod, C., 2009. Implications of climate change for the fishes of the British Isles. *J. Fish Biol.* 74, 1143–1205.
- Hossain, Y., Rahman, M., Abdallah, E.M., 2012. Relationships between body size, weight, condition and fecundity of the threatened fish *Puntius ticto* (Hamilton, 1822) in the Ganges River, Northwestern Bangladesh. *Sains Malays.* 41 (7), 803–814.
- Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269, 676–679.
- Hurrell, J.W., Deser, C., 2009. North Atlantic climate variability: the role of the North Atlantic Oscillation. *J. Mar. Syst.* 78, 28–41.
- Macías, D., Lema, L., Gómez-Vives, M.J., Ortiz de Urbina, J.M., de la Serna, J.M., 2006. Some biological aspects of small tunas (*Euthynnus alletteratus*, *Sarda sarda* and *Auxis rochei*) from the South Western Spanish Mediterranean traps. *ICCAT Col. Vol. Sci. Pap.* 59, 579–589.
- Macías, D., Saber, S., Osuna, A.M., Cruz-Castán, R.M., Gómez-Vives, M.J., Báez, J.C., 2014. First record of intersexuality in *Euthynnus alletteratus* in the Mediterranean Sea: histological description. *Mar. Biodivers.* 7, e3. <https://doi.org/10.1017/S1755267213001152>.
- Mejuto, J., 2003. Recruit indices of the North Atlantic swordfish (*Xiphias gladius*) and their possible link to atmospheric and oceanographic indicators during the 1982–2000 period. *ICCAT Col. Vol. Sci. Pap.* 55, 1506–1515.
- Mozsár, A., Boros, G., Sály, P., Antal, L., Nagy, S.A., 2015. Relationship between Fulton's condition factor and proximate body composition in three freshwater fish species. *J. Appl. Ichthyol.* 31 (2), 315–320.
- Muñoz-Expósito, P., Macías, D., Ortíz De Urbina, J.M., García-Barcelona, S., Gómez-Vives, M.J., Báez, J.C., 2017. North Atlantic oscillation affects the physical condition of migrating bullet tuna *Auxis rochei* (Risso, 1810) from the Western Mediterranean Sea. *Fish. Res.* 194, 84–88.
- Rey, J.C., Alot, E., Ramos, A., 1984. Sinopsis biológica del bonito, *Sarda sarda* (Bloch) del Mediterráneo y Atlántico Este. *ICCAT Col. Vol. Sci. Pap.* 20 (2), 469–502.

- Ricker, W.E., 1973. Linear regressions in fishery research. *Fish. Res. Board Can.* 30, 409–434.
- Rodríguez-Roda, J., 1966. Estudio de la bacoreta, *Euthynnus alletteratus* (Raf.), bonito, *Sarda sarda* (Bloch) y melva *Auxis thazard* (Lac.), capturados por las almadrabas españolas. *Investigación Pesquera* 30, 247–292.
- Roff, D.R., 1983. An allocation model of growth and reproduction in fish. *Can. J. Fish. Aquat. Sci.* 40 (9), 1395–1404.
- Rubio, C.J., Macías, D., Camiñas, J.A., Fernández, I.L., Báez, J.C., 2016. Effects of North Atlantic Oscillation (NAO) on Spanish catches of albacore (*Thunnus alalunga*) and yellowfin tuna (*Thunnus albacares*) in the north-east Atlantic Ocean. *Anim. Biodiv. Conserv.* 39 (2), 195–198.
- Sabatés, A., Recasens, L., 2001. Seasonal distribution and spawning of small tunas, *Auxis rochei* (Risso) and *Sarda sarda* (Bloch) in the northwestern Mediterranean. *Sci. Mar.* 65 (2), 95–100.
- Saber, S., Macías, D., Ortiz de Urbina, J.M., Kjesbu, O.S., 2016. Contrasting batch fecundity estimates of albacore (*Thunnus alalunga*), an indeterminate spawner, by different laboratory techniques. *Fish. Res.* 176, 76–85.
- Valeiras, J., Abad, E., 2007. In: *Small tuna: ICCAT Field Manual* (Ed.), International Commission for the Conservation of Atlantic Tuna, Available from: <https://www.iccat.int/en/>.
- Vicente-Serrano, S.M., Trigo, R.M., López-Moreno, J.I., Liberato, M.L.R., Lorenzo-Lacruz, J., Beguería, S., Morán-Tejeda, E., Kenawy, A., 2011. The 2010 extreme winter north hemisphere atmospheric variability in Iberian precipitation: anomalies, driving mechanisms and future projections. *Clim. Res.* 46, 51–65.
- Visbeck, M.H., Hurrell, J.W., Polvani, L., Cullen, H.M., 2001. The North Atlantic oscillation: past, present, and future. *Proc. Natl. Acad. Sci. U. S. A.* 98, 12876–12877.
- Zudaire, I., Murua, H., Grande, M., Bodin, N., 2013. Reproductive potential of yellowfin tuna (*Thunnus albacares*) in the western Indian Ocean. *Fish. Bull.* 111, 252–264.