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Climate effects on historic bluefin tuna captures in the Gibraltar Strait and Western Mediterranean

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ABSTRACT

Historical capture records of bluefin tuna (*Thunnus thynnus*; BFT hereafter) from the Gibraltar Strait and Western Mediterranean show pronounced short- and long-term fluctuations. Some of these fluctuations are believed to be associated with biological and ecological process, as well as distinct climate factors. For the period of study (1700–1936) of this work, we found a long-term increasing trend in the BFT captures and in the climate variables. After applying a statistical time series analysis of relevant climate variables and long-term tuna capture records, it is highlighted the role played by sea-surface temperature (SST) on bluefin population variations. The most relevant result of this study is the strong correlation found between the total solar irradiance (TSI) — an external component of the climate system — and bluefin captures. The solar irradiance could have affected storminess during the period under study, mainly during the time interval 1700–1810. We suggest physico-biological mechanisms that explain the BFT catch fluctuations in two consecutive time intervals. In the first period, from 1700 to 1810, this mechanism could be high storm and wind activity, which would have made the BFT fisheries activities more difficult by reducing their efficacy. In contrast, during the interval from 1810 to 1907, the effects of wind and storms could be on spawning behaviour and larval ecology, and hence on year class strength, rather than on fish or fisherman's behaviour. These findings open up a range of new lines of enquiry that are relevant for both, fisheries and climate change research.

1. Introduction

The Atlantic Bluefin Tuna (*Thunnus thynnus*, Linné 1758) has been historically relevant since Phoenician times (ca. 900 years BC) because of its commercial importance (López-Capont, 1997; Pairman-Brown, 2002). Its capture has become one of the oldest fisheries organized on an industrial scale (Lemos and Gomes, 2004). Fishermen have noticed for a long time that schools of this species regularly appear near the coast, keeping the shore on their right side while performing a cyclonic movement around the Western Mediterranean Sea. Therefore, centuries ago they developed a unique catching technique, involving special trapnets set up along the Western Mediterranean coast, which could guide hundreds or even thousands of fish into the gear (Sará, 1980). Since this ancestral technique has lasted until the 1960s without significant structural changes (Doumenge, 1998; Ravier and Fromentin, 2001), it is reasonable to assume that all these trap fisheries in the region of study had been exploiting essentially the same population, and accordingly their fishing yields had experienced similar long-term fluctuations (Ravier and Fromentin, 2001).

In spite of all the information that can be extracted from BFT historical data, there are today some questions that still remain unsolved (Fromentin, 2003). In particular, it is important to identify the fluctuations that exist in the historical capture records and the factors that have caused them, especially those that could have been environmentally forced (Cushing, 1982; Lemos and Gomes, 2004; Fromentin and Powers, 2005). This knowledge would be invaluable for predicting the future of BFT populations and devising policies to manage them, especially in an era of fishery overexploitation and anthropogenic climate change.

Literature about the relation between BFT historical data and climate variables in the Eastern Atlantic and Western Mediterranean is scarce. Ravier and Fromentin (2004) found that long-term fluctuations in the

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BFT capture series from trap fisheries located around the Mediterranean and the East Atlantic appeared to be negatively correlated with long-term trends in the North Atlantic sea-surface temperatures. Ganzedo et al. (2009) found a relation between BFT captures (from 1525 to 1756) from several almadrabas located in southern Europe and climate variables, such as air and sea temperatures and atmospheric concentration of greenhouse gases (GHG). They also suggested a potential connection between BFT captures and solar irradiance (Ganzedo et al., 2009). More recently, Caballero-Alfonso (2011) presented a detailed analysis of the effect of surface temperature and solar irradiance on the North Atlantic BFT captures between 1525 and 1936.

The present study aims to shed new light on the roots of the fluctuations and evolution of BFT populations. In particular, it tries to elucidate the causes of the observed variations in the historical (1700–1936) BFT capture records from Gibraltar and Western Mediterranean, by showing that they could be related to changes in solar irradiance and natural climate variability. In this line of research, there are numerous previous works where a relationship has been found between diverse solar activity variables (e.g. number of sunspots or total solar irradiance) and another fisheries around the world; for instance, anchovy (Yousef, 2006; Guiñez et al., 2014) or sardine (Jayaprakash, 2002; Santos et al., 2012). The solar irradiance, the primary source of energy into the climate system and vital to all life processes on Earth, could have affected directly or indirectly the BFT populations (larval ecology, recruitment, etc.) and the fisheries. Paleoclimatic studies show that solar activity could have driven the storminess in the NW Mediterranean for the last 2700 years (Degeai et al., 2015). We suggest that a physico-biological mechanism might have affected the BFT fishing performance through an increase in storm and wind activity (magnitude and frequency of storm events), which could have increased the effort and reduced the efficacy of BFT catches. On the other hand, this high storm and wind activity could also have affected the spawning behaviour and larval ecology, and hence year class strength.

2. Materials and methods

2.1. Capture data

BFT capture records (Fig. 1) from eleven traps localized along the Gibraltar Strait and the Western Mediterranean (Fig. 2) were collected for this study from different sources (López-Capont, 1997; Ravier and Fromentin, 2001; Ravier, 2003; Lemos and Gomes, 2004). Each BFT capture time series spans more than 100 years within the period 1525–1936. After a preliminary inspection, we decided to limit our analysis to the time interval from 1700 to 1936, due to the scarcity and inhomogeneity of the two oldest capture time series (Conil and Zahara; Fig. 1 and Fig. S1). As a consequence of these drawbacks, we removed Conil and Zahara in our analysis. The year 1936 was selected as the last year of the time series in order to avoid distortions of the analysis caused by the impact of BFT fishing technology changes after World War II (e.g., fishing capacity of bait boats, purse seiners and long liner fleets) and the possible effects of overfishing. In addition, the Sicily series was considered only after 1700 (although the earliest records date back to 1602) because several geological events (e.g. earthquakes), depopulation, and social instability occurred in that region during the XVII century (Russo-Adams, 2008), causing great variability in captures by the Sicilian traps.

Qualitatively, data from different sites show very similar variations within overlapping time periods. Moreover, previous studies using similar BFT capture data (Ravier and Fromentin, 2001; Caballero-Alfonso, 2011; Ganzedo et al., 2009) have shown that long-term fluctuations in trap catches are synchronous all around the Gibraltar and Western Mediterranean. These long-term fluctuations can be considered as a proxy of true abundance (Ravier and Fromentin, 2001).

Taking into account the fact that, during the historical period covered by in this study, all these traps were built and operated in the same way, we opted for reconstructing the missing data using the Data INterpolating Empirical Orthogonal Functions technique (DINEOF; Alvera-Azcárate et al., 2005; Ganzedo et al., 2011, 2013). This statistical technique of data reconstruction is based on the decomposition of the time series into Empirical Orthogonal Functions (EOF), and it was first applied to fisheries by Ganzedo et al. (2013). In order to reduce the dimensionality of the 9 reconstructed BFT captures, we applied the Empirical Orthogonal Functions (EOF). We used in our analysis only the first principal component (EOF1; Fig. 3), as the EOF1 alone can explain 65.51% of the total variance. It should be noticed that the EOF1 is equivalent to the synthetic time series built by Ravier and Fromentin (2001) to represent the long-term fluctuations of BFT capture data sets, which is a proxy of BFT abundance (Sella, 1929; Fromentin et al., 2000; Ravier and Fromentin, 2001).

2.2. Climate data

Paleoclimate proxy reconstructions were preferred in this study, because there are no observed climate data available for the whole time period. Time series from General Circulation Models (GCMs) were avoided, because they would require data assimilation. Paleoclimate reconstructions reveal long-term trends of the climate system and, to a certain extent, also higher-frequency variations.

One climate variable that has a clear relationship with tuna fisheries is the sea surface temperature (SST) (Polovina, 1996; Korsmeyer and Dewar, 2001; Schaefer, 2001; Graham and Dickson, 2004). We used reconstructed annual SST data from Mann et al. (2009) covering the time interval 1700–1936. Three of these SST data sets were analysed: global (SST1), Northern Hemisphere (SST2) and averaged (SST3) over the region 35°N–45°N, −10°W–15°E (Fig. 4). Lastly, as external climate forcings, we included three independent Total Solar Irradiance (TSI) reconstructions: Lean (2000); TSI1; Krivova et al. (2010); TSI2 and Velasco-Herrera et al. (2015); TSI3 for the interval of study (Fig. 5).

2.3. Statistical data analyses

In order to verify whether the data sets under study (captures and environmental data) contain statistically significant trends, we applied the Mann–Kendall test (Libiseller and Grimvall, 2002; Hipel and McLeod, 1994), as implemented in the R package "trend" (Pohlert, 2015). We chose this technique because it is a non-parametric test, that is, it does not require the time series to be normally distributed. Furthermore, it has a low sensitivity to abrupt breaks due to inhomogeneous time series (Jaagus, 2006). Once we had verified the existence of statistically significant trends in each time series, we studied and verified whether the trend in the dependent variable (EOF1 of the reconstructed BFT captures) was determined by the trend in the independent variables (SSTs and TSIs). Therefore, we had performed a partial Mann–Kendall test (Libiseller and Grimvall, 2002; Hipel and McLeod, 1994), also implemented in the R package "trend" (Pohlert, 2015). Potential relations between the independent variables and the EOF1 were investigated using the "PearsonT" software (Mudelsee, 2003a), in which the linear trend was removed and the bootstrap confidence interval from serially dependent time series was take into account (Mudelsee, 2003b).

3. Results and discussion

3.1. The BFT long-term trend analysis

The EOF1 of the reconstructed BFT captures (dashed line in Fig. 3) shows a slightly increasing trend, something that is confirmed by the Mann–Kendall test (Table 1). On the other hand, our EOF1 of the reconstructed BFT captures is very similar to the synthetic time series of the BFT historical captures obtained (practically from the same data documentation sources) for the Mediterranean Sea and Eastern Atlantic by Ravier and Fromentin (2001); thin line in Fig. 8 of this reference).