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Indications of a climate effect on Mediterranean fisheries

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Abstract Using the Food and Agriculture Organization's (FAO) Mediterranean capture fisheries production dataset in conjunction with global and Mediterranean sea surface temperatures, we investigated trends in fisheries landings and landings per unit of effort of commercially important marine organisms, in relation to temperature oscillations. In addition to the overall warming trend, a temperature shift was detected in the Mediterranean Sea in the late 1990s. Fisheries landings fluctuations were examined for the most abundant commercial species (59 species) and showed significant year-to-year correlations with temperature for nearly 60 % of the cases. From these, the majority (~70 %) were negatively related and showed a reduction of 44 % on average. Increasing trends were found, mainly in the landings of species with short life spans, which seem to have benefited from the increase in water temperature. The effect of oceanic warming is apparent in most species or groups of species sharing ecological (e.g. small and medium pelagic, demersal fish) or taxonomic (e.g.

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cephalopods, crustaceans) traits. A landings-per-unit-of-effort (LPUE) proxy, using data from the seven Mediterranean European Union member states, also showed significant correlation with temperature fluctuations for six out of the eight species examined, indicating the persistence of temperature influence on landings when the fishing effect is accounted for. The speed of response of marine landings to the warming of the Mediterranean Sea possibly shows both the sensitivity and the vulnerable state of the fish stocks and indicates that climate should be examined together with fisheries as a factor shaping stock fluctuations.

1 Introduction

An increasing number of studies have been published on the effects of climate change on aquatic populations and fisheries resources (e.g. Brander 2007, 2010; Jennings and Brander 2010; Ottersen et al. 2006; Cheung et al. 2013). These document the fundamental role of water temperature fluctuations on fish stocks.

In the last 120 years or so, hemispheric and global temperature records are characterized by a low frequency signal known as global warming. This signal is evident in most areas of the planet including the Mediterranean Sea (IPCC 2007). Recently it has been documented that the Mediterranean Sea is warming in both shallow and deep waters (Vargas-Yáñez et al. 2008; Nykjaer 2009; Raitsos et al. 2010). The Mediterranean Sea is considered to be a ‘biodiversity hotspot’ (Myers et al. 2000) representing 4–18 % of the world marine species (Bianchi and Morri 2000). It is therefore an ideal location for undertaking studies on the effects of climate change on marine populations (Bethoux et al. 1999; Bethoux and Gentili 1999; Lejeusne et al. 2010).

The present study reports the link between fishing landings and landings per unit of effort (LPUE) with sea surface temperature oscillations in the Mediterranean Sea.

2 Methods

2.1 Landings data

The official FAO GFCM (General Fisheries Commission for the Mediterranean) capture production dataset on the fisheries landings of the Mediterranean countries ranging from 1985 to 2008 was used. FAO datasets have already been used in works linking fisheries trends with external factors or ecological change (e.g. Caddy and Rodhouse 1998; Fréon et al. 2003; Pauly et al. 2005). FAO offers fisheries statistics earlier than 1985, but those were excluded because: (a) Mediterranean landings data showed many inconsistencies with many species presenting zero/very low landings before 1980–1985. (b) Accurate remotely sensed datasets of sea surface temperature data with a consistent methodological approach (i.e. AVHRR [P5]) are available only since late 1981. Although earlier regional modeled SST data exist, they were avoided due to quality issues compared to the high resolution and accuracy of remote sensing ones (Nykjaer 2009). Inconsistencies in time (e.g., extirpation of the landings of a species for a certain year and increase of the landings of its genus) were treated by grouping accordingly to the highest taxon. Important Mediterranean aquaculture production species were excluded from the analysis, because abundance could be blurred by the catches of aquaculture escapees. Highly migratory large pelagics were also excluded, because of the possibility of Atlantic-Mediterranean migrations (additionally the landings of *Thunnus thynnus* are controlled through a Total Allowable Catches management scheme). For the full list of species/taxa see Supplementary Material A.

Landings were analyzed by (a) major category (group) and (b) species (or higher taxon). Seven categories were determined with regard to habitat or in relation to higher taxonomic groups (total landings, small pelagics, medium pelagics, demersal fish, crustaceans, bivalves and cephalopods). For the analysis at the species level the species/taxa (59 in total) with an average annual production higher than 1,000 t throughout the Mediterranean were selected (Supplementary Material B).

2.2 Fishing effort data

Data on fishing effort are not available for the entire Mediterranean. Yearly fleet size was extracted from the fleet register of the European Union (European Union 2010) for the seven Mediterranean EU member states (Spain, France, Italy, Slovenia, Greece, Malta and Cyprus). The vessels based in Mediterranean home ports were extracted and allocated to sectors, counting each vessel as: (a) a small-scale vessel if it wasn't registered for any industrial gear (trawl, purse seine), (b) "half" a purse seine/"half" a trawl if it was registered for both, (c) a trawl or purse seine if it was registered for one of them and any other small-scale gear. Fleet size per gear was used as a proxy of fishing effort.

Variability in the targeting of species renders the estimation of species-specific effort difficult and the effort between different gears should be standardized; thus we analysed species mainly targeted/caught by a single gear using the corresponding fleet sector size. We calculated a proxy of landings per unit of effort (hereafter LPUE) using the trawler fleet size for *Merluccius merluccius* and *Melicertus kerathurus*, the purse-seiner fleet size for *Boops boops, Engraulis encrasicolus* and *Sardina pilchardus* and the small-scale fleet size for *Dentex dentex, Epinephelus marginatus* and *Diplodus sargus*. The landings of the seven Mediterranean EU member-states were pooled by species and divided by the corresponding fleet sizes.

2.3 Temperature data

The Advanced Very High Resolution Radiometer (AVHRR) Sea Surface Temperature (SST) product was acquired from the NASA PO.DAAC. The AVHRR Pathfinder 5 (P5) monthly mean products of a 4×4 km^2 spatial resolution were used (1985–2008). The SST data were spatially averaged for the area of study. In order to avoid potential bias related to solar radiation during the day-time from surface heating, the night-time SST products were used (Raitsos et al. 2006).

Northern Hemisphere Temperature (NHT) anomalies were obtained for 1985–2008 and were expressed as anomalies relative to the 1961–90 reference period means. NHT data were produced by the Climatic Research Unit (CRU) and Hadley Centre (Jones et al. 2008). Detailed analysis of combining those two temperature products (SST and NHT), to support the fact that the regional temperature trends are part of global patterns, can be seen elsewhere (Raitsos et al. 2010).

2.4 Analysis

Pearson cross-correlation (r) analysis was used to examine the relationships between the landings and temperature, using either no lag or a 1-year lag between them. The probability of significance of the correlation was adjusted to correct for temporal autocorrelation (PACF) using the Chelton method (Pyper and Peterman 1998). This method calculates an "effective" number of degrees of freedom, penalizing for autocorrelation found at different

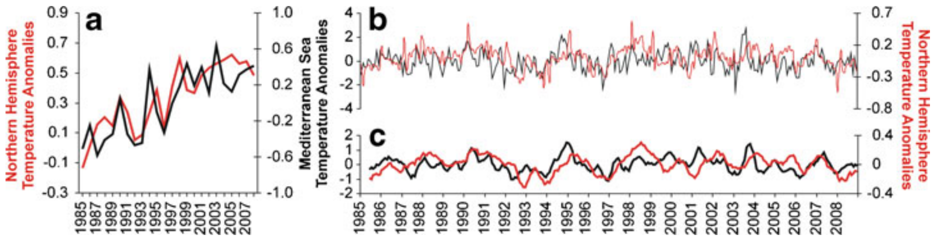


Fig. 1 Mediterranean sea surface temperature (SST) anomalies (*black line*) against the Northern Hemisphere Temperatures anomalies (*red line*). **a** Year to year changes, **b** Monthly averages of the de-seasonalized and detrended datasets, **c** Moving averages at 6 months

time-lag levels. When both time series are positively autocorrelated, the effective degrees of freedom result in more conservative rejections of the null hypothesis (Pyper and Peterman 1998).

In addition, a regime shift index (RSI) combined with an automatic sequential algorithm (Rodionov 2004) was used to examine statistically the existence, timing and significance (α=0.05) of abrupt changes in fisheries and temperature data. This is a sequential processing technique and for each new observation the test examines the validity of a null hypothesis being the existence of a regime shift. The absolute value of RSI represents the magnitude of the shift(s) while its sign indicates increase/decrease between regimes (Rodionov 2004).

2.5 Potential biases

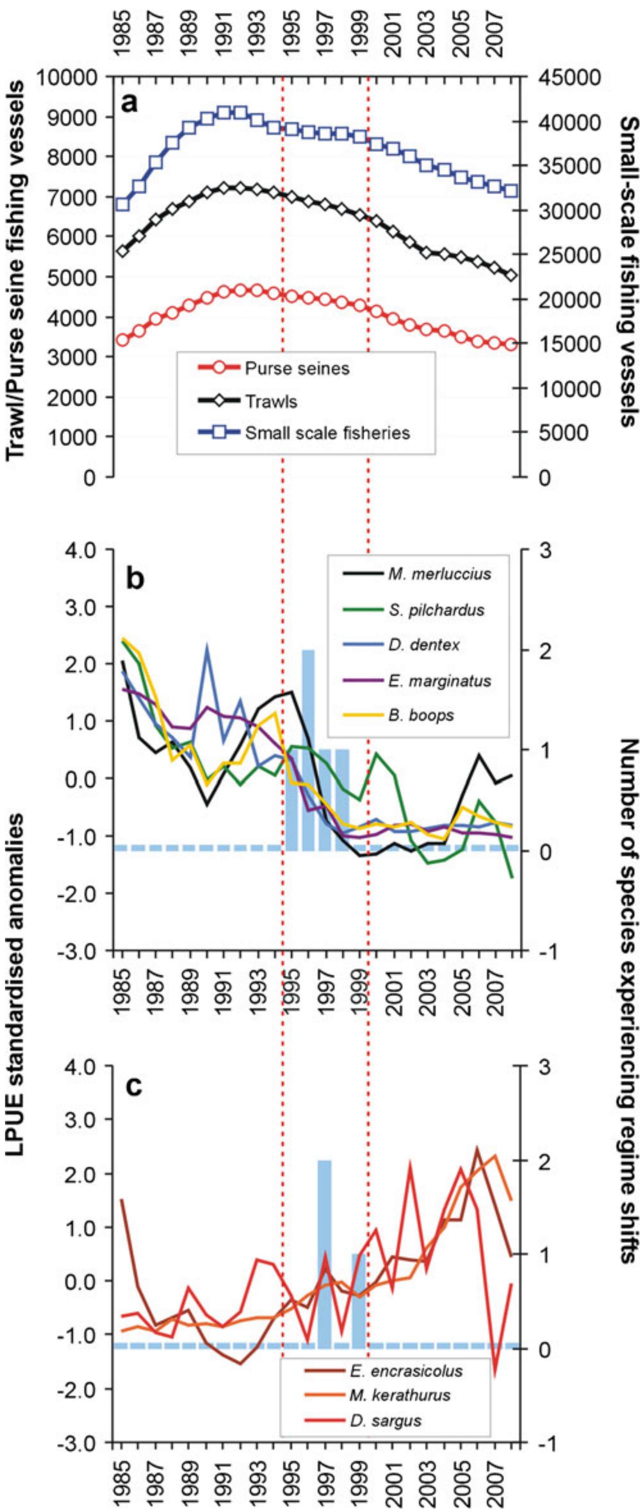
Trends in stock abundances are usually detected by analyzing catch or landings per unit of effort rather than pure catch or landings data (Watson and Pauly 2001). However, it has been argued that trends in catch data are consistent with biomass trends (Froese et al. 2012). The use of landings data from all the Mediterranean countries guarantees that the patterns detected are not an artifact produced by the sampling scheme or changes in recording of a specific country. Regarding fishing effort, our analysis includes the assumption that there have not been significant interannual changes in species targeting within the respective fleets.

3 Results and discussion

3.1 Northern hemispheric warming and its relation to the regional sea temperatures

The annual NHT and the regional remotely-sensed SST (Fig. 1a) were significantly correlated (r= 0.804, p= 0.0001) In Fig. 1b the monthly data of both datasets are de-seasonalized and de-trended. The 6-months moving average was also plotted to reduce the data noise (Fig. 1c). A clear relationship between the de-trended datasets is still evident, while they parallel each other at a significant level (r= 0.3, p= 0.0001). The above indicate that the documented Mediterranean Sea warming is part of global climate trends and not a regional phenomenon. Evidently in the late 1990s (Fig. 1a) the warming observed during

Fig. 2 **a** Number of EU fishing vessels attributed to trawl, purse seine and small-scale gears, **b** Negative LPUE anomalies, **c** Positive LPUE anomalies. The *blue vertical bars* represent the timing and number of species experiencing regime shifts. The *red dotted lines* denote the time frame when the regime shifts occurred ▶


a
Trawl/Purse seine fishing vessels
Small-scale fishing vessels
Purse seines
Trawls
Small scale fisheries
b
M. merluccius
S. pilchardus
D. dentex
E. marginatus
B. boops
c
E. encrasicolus
M. kerathurus
D. sargus
LPUE standardised anomalies
Number of species experiencing regime shifts

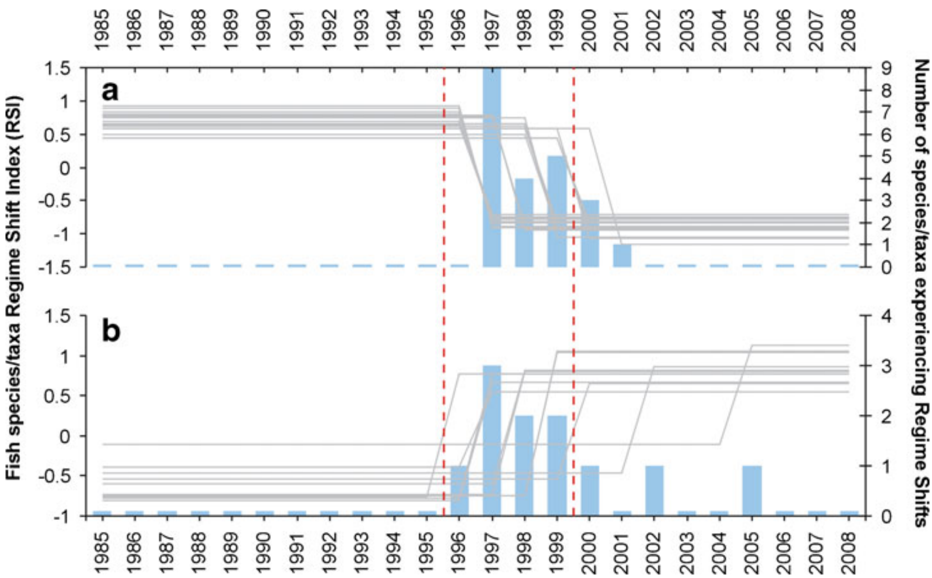


Fig. 3 Significant ($p>0.05$) abrupt changes of fisheries landings indicated by Rodionov's Regime Shift Index (RSI). **a** Negative regime shifts of landings anomalies, and **b** Positive shifts of landings anomalies. The *grey lines* indicate the RSI values of the species/taxa experiencing regime shifts. The *blue vertical bars* represent the timing and number of species/taxa experiencing regime shifts. The red dotted lines denote the time frame when more than 75 % of the total regime shifts in species/taxa landings (18/22 negative and 8/11 positive) occurred

the 80s– 90s has leveled off (stabilized). This change in temperature is apparent worldwide (Swanson and Tsonis 2009; Reid and Beaugrand 2012).

Most of the global oceans display overall positive SST trends (Ting et al. 2009; Large and Yeager 2012). Recently, it was reported that an intensification of the phenomenon is apparent after the 1976/1977, 1986/1987 and 1997/1998 El Niño events (Reid and Beaugrand 2012). The relationship between the NHT and Mediterranean SST reported here, is in accordance with the global synchrony of accelerating rise in SSTs.

3.2 Linking the landings and LPUE with the Mediterranean warming

During this temperature change, the European fishing fleet showed a progressive increase (1985–1991), followed by a progressive decrease (until 2008) for all fleet segments (Fig. 2a). The LPUE annual timeseries of five species out of eight (Fig. 2b) showed an overall decreasing trend and the RSI revealed significant changes circa 1997. Three species illustrated an increasing trend, while the RSI indicated significant shifts in 1997 and 1999 (Fig 2c). Additionally, the investigation of shifts in the landings of the most important 59 species/taxa indicated that most of them went through a significant abrupt change in the mid-late 90s (Fig. 3a and b). Correlations of LPUE and SST (Fig. 4) indicated that five species out of eight were negatively paralleling the SST changes and three positively ($p<0.05$), however when the autocorrelation function was applied, the significance level was reduced ($p<0.10$ for five species or slightly higher for the rest).

The investigation at group level indicated that the interannual variability of the Mediterranean SST and landings anomalies (Fig. 5) demonstrate opposite trends with the exception of the

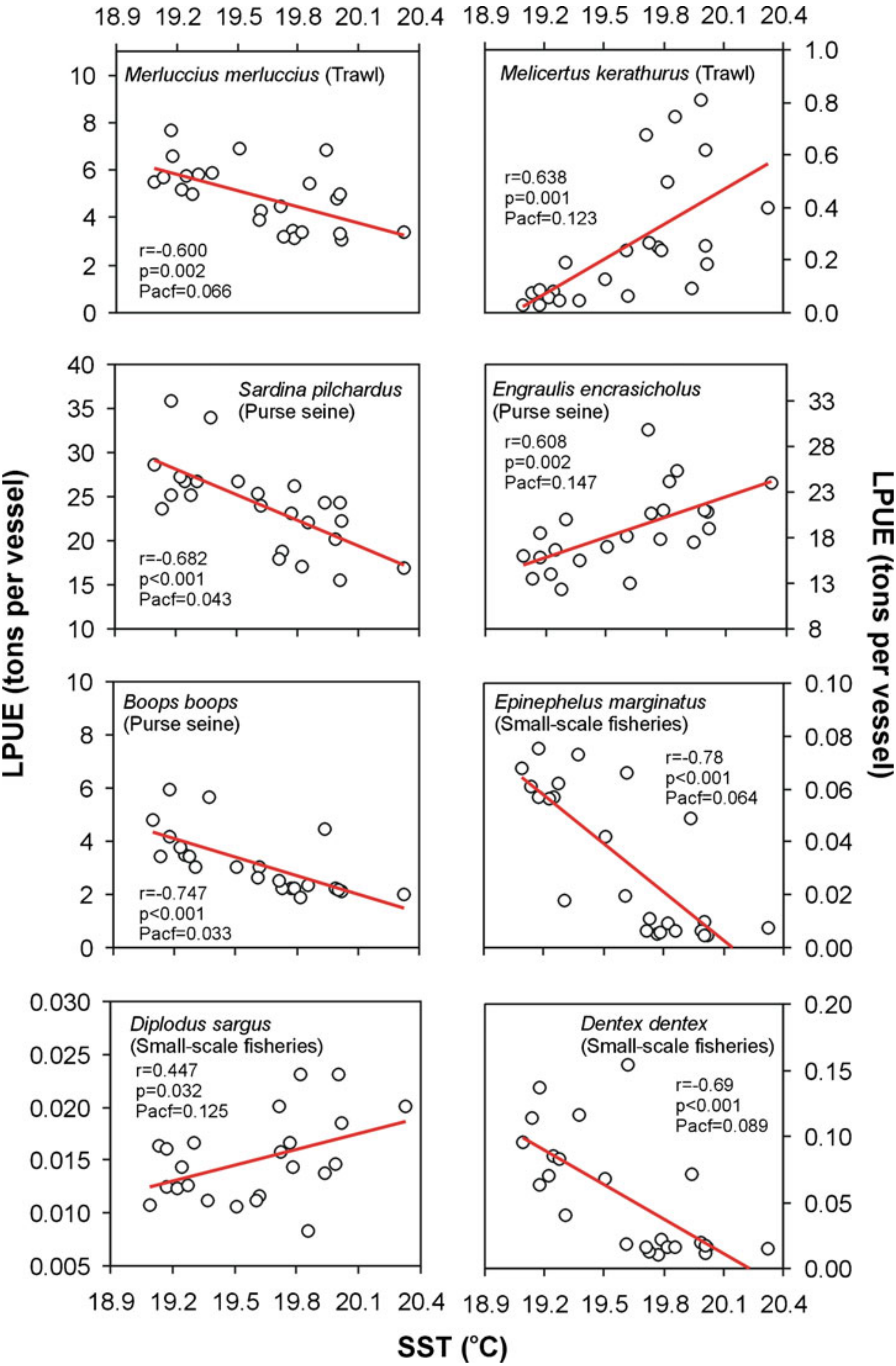


Fig. 4 Landings per Unit of Effort (LPUE) of the eight selected species, derived from the EU Mediterranean countries, against SST. The fishing gear is shown in parenthesis, and the correlation coefficients are indicated for each species. The *red line* represents the linear regression

Fig. 5 Mediterranean sea surface temperature (SST) anomalies against the interannual variation of Mediterranean capture fisheries anomalies. The *black solid line* represents the SST, while the *red solid line* the fisheries anomalies. Negative SST values represent colder periods while positive anomalies warmer ones. Highly significant negative relationships revealed in every category except the medium pelagic case where a significant positive one was found. The significance level has been adjusted to account for temporal autocorrelation (ACF)

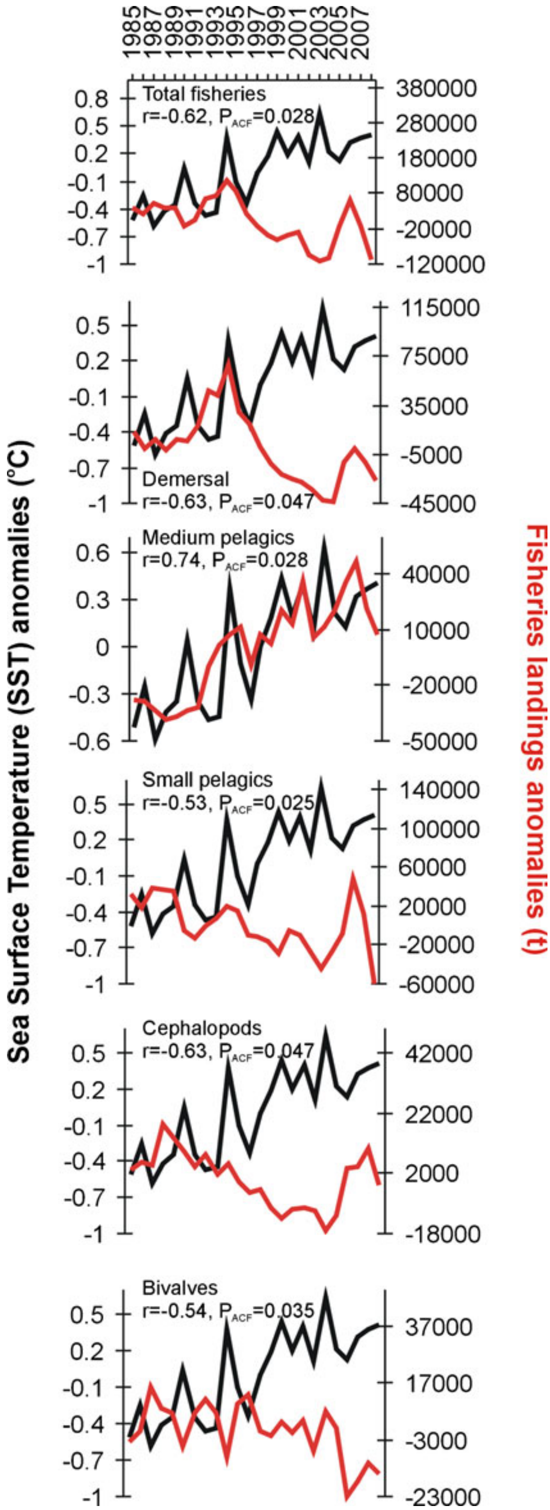
medium pelagics (positive correlation) and crustaceans (no correlation, not shown). In all significant cases, the statistical probability was highly reduced with autocorrelation removal, but still remained above the 95 % significance level. The highest cross-correlations occurred with a 1-year time lag (with temperature leading) except from the pelagics and bivalves (where no lag achieved higher correlation). This lag could be the minimum time needed to observe the effects of temperature fluctuations on marine populations. Many Mediterranean commercial fisheries are largely based on juveniles (Lleonart and Maynou 2003); thus, the abundance of a year-class in any specific year, could determine the level of landings for the subsequent year. Examination of year-to-year changes revealed declines in the last 10 years ranging from 9 % (small pelagic fish) to 20 % (bivalves), whereas the medium pelagics increased by 36 %.

The most abundant commercial cases (59 species) were examined individually against SST (for the correlation results see Supplementary material B). Approximately 64 % were correlated with SST, with 66 % of these negatively influenced. In the last decade of the time-series, landings decreased on average by 44 %. Figure 6 highlights a few species/taxa examples (from a variety of environments and covering a large taxonomic spectrum) that were negatively related to temperature oscillations. Examples of species/taxa positively correlated with the marine warming are shown in Fig. 7.

Individual species abundances moderated by temperature have already been reported in the Mediterranean Sea at local scales (Tsikliras 2008; Martín et al. 2012). In our study, we report two different findings that indicate an evident relationship between landings and temperature: (a) the relationship between the interannual SST variability and landings, and (b) relatively synchronized temporal shifts in SST and fisheries landings (RSI).

The reason why the landings of some species have increased or decreased with temperature oscillations may be related to stock spawning periods. For instance, the two most important small pelagic species (purse seine targets) have different spawning period peaks: *Engraulis encrasicolus* in summer, *Sardina pilchardus* in winter. The warming may have resulted into opposing modifications of the spawning success or period duration similar to their Pacific relatives (Takasuka et al. 2008). *D. sargus* and *D. dentex* (demersal species of the family Sparidae - targeted by small-scale fisheries) also showed opposing trends and have different spawning periods (winter-spring and late spring, respectively). Other biological traits can render species thermophilic/psychrophilic and even interspecific relationships (competition, predation) may shape stock dynamics.

An indirect effect of warming could also be related to food availability. In the global oceans, surface stratification increases plankton in illuminated surface waters at higher latitudes (light-limited), whereas the opposite occurs at mid-latitudes where the reduction of the nutrient supplies decreases phytoplankton (Gregg et al. 2003; Behrenfeld et al. 2006; Doney 2006). These effects are also pertinent in the relatively oligotrophic and warmer Mediterranean Sea. In fact, it has been reported that positive SST trends reduce the vertical mixing of the water column, leading to nutrient depleted surface areas and consequently reducing primary production and phytoplankton biomass (Barale et al. 2008; Tsiaras et al. 2012; Volpe et al. 2012). These conditions resonate upwards through the food web, and may affect fisheries (Verity and Smetacek 1996; Bopp et al. 2005). In the Mediterranean Sea, the monthly satellite derived chlorophyll-a data from SeaWiFS (SeaWiFS 2013)


1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
Total fisheries
r=-0.62, P_ACF=0.028
Demersal
r=-0.63, P_ACF=0.047
Medium pelagics
r=0.74, P_ACF=0.028
Small pelagics
r=-0.53, P_ACF=0.025
Cephalopods
r=-0.63, P_ACF=0.047
Bivalves
r=-0.54, P_ACF=0.035
Sea Surface Temperature (SST) anomalies (°C)
Fisheries landings anomalies (t)

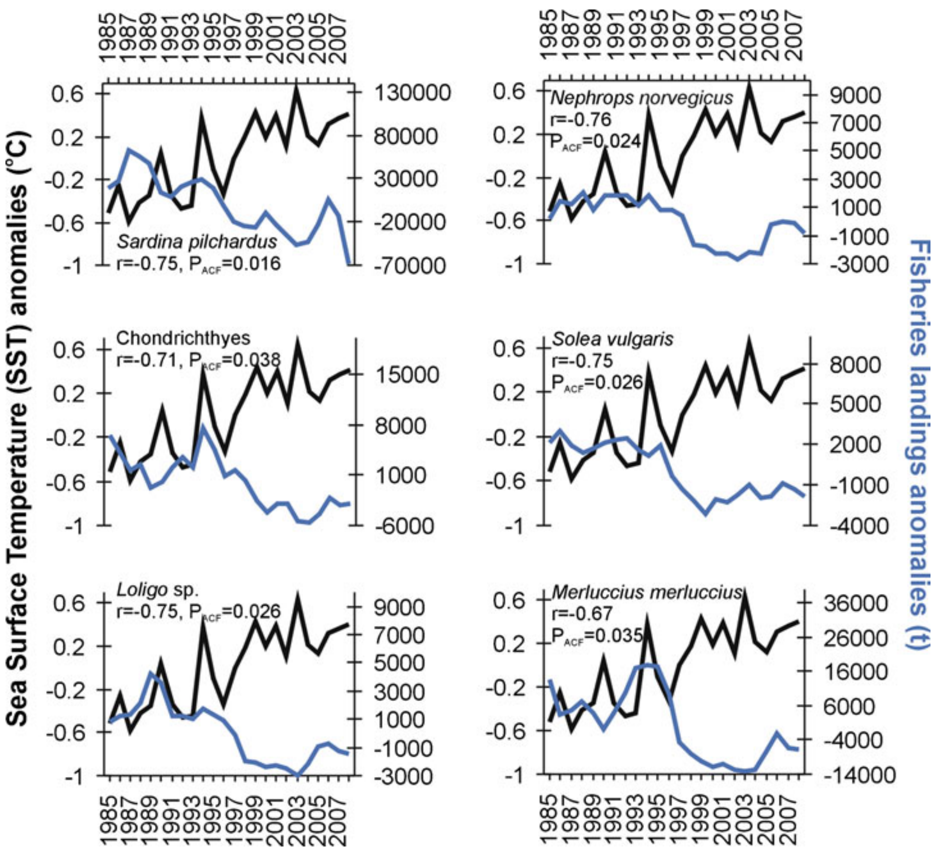


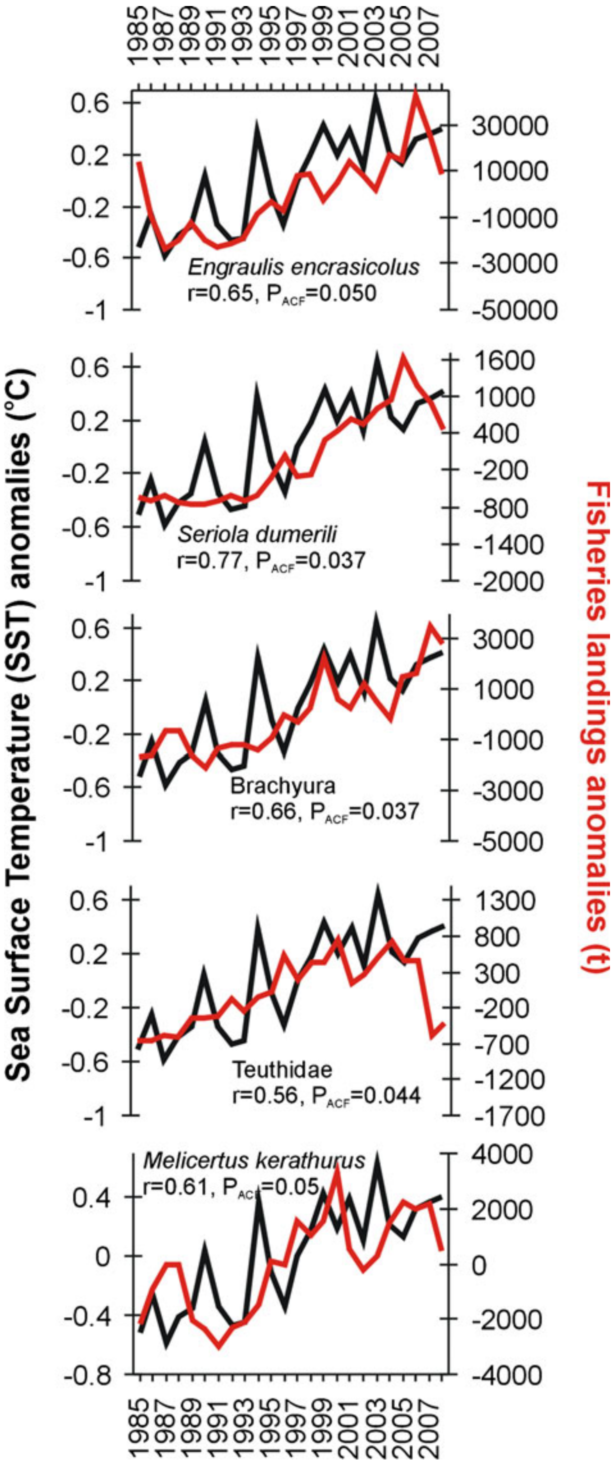
Fig. 6 Mediterranean sea surface temperature anomalies versus interannual variation of Mediterranean capture fisheries data. The *black solid line* represents the SST anomalies, while the *solid blue* the fisheries data. These examples show individual species/taxa that negatively parallel the observed warming. The correlation coefficient and its significance are indicated

were significantly negatively correlated with SST ($r=-0.89$, $p=0.0001$, during the period of 1997–2008 corresponding approximately to half our dataset). Modelling studies (Blanchard et al. 2012; Woodworth-Jefcoats et al. 2013) have also demonstrated the potential modification of fish abundance by climate change through fluctuations in plankton abundance.

Fishing effort and landings can be affected by fishing strategy and tactics, legislation, market demands and fuel prices (for a description of the heterogeneity of Mediterranean fisheries see Tzanatos et al. 2013). The formation of the EU has affected northern Mediterranean fleet dynamics initially with funding schemes for fleet construction/upgrade (in the EEC of the '80s) and later through subsidies to have fishing vessels scrapped. Technological improvements during these years must have also led to more efficient harvesting.

Fisheries modify species communities, geographic distribution and stock structure alterating the size and age of fish populations, which may lead to highly variable annual

Fig. 7 Year to year changes in regional SST and Mediterranean capture fisheries data. The *black solid line* ▶ represents the SST anomalies, while the *solid red* the fisheries data. These examples show individual species/taxa that parallel the observed warming. The correlation coefficient and its significance are indicated


Sea Surface Temperature (SST) anomalies (°C)
Fisheries landings anomalies (t)
Engraulis encrasicolus
r=0.65, P_ACF=0.050
Seriola dumerili
r=0.77, P_ACF=0.037
Brachyura
r=0.66, P_ACF=0.037
Teuthidae
r=0.56, P_ACF=0.044
Melicertus kerathurus
r=0.61, P_ACF=0.05
1985 1987 1989 1991 1993 1995 1997 1999 2001 2003 2005 2007

stock recruitment (Hsieh et al. 2006). This renders fish populations more vulnerable and sensitive to a degree that prevents them from being able to adapt quickly enough to climatic changes (Ottersen et al. 2006). Thus, climate change may influence fish stocks in several direct and indirect ways, e.g. acting on physiology, reproduction or modifying food abundance and habitats (Brander 2007). The speed of response of marine landings to temperature fluctuations of the Mediterranean Sea possibly shows the sensitivity and the vulnerable state of the fish stocks. The multiannual time needed for international coordination, formulation and implementation of management actions indicates a temporal incompatibility between the problem and the management response. Consequently climate should be examined as a factor shaping stock fluctuations within the context of the Ecosystem Approach to Fisheries Management (Worm and Myers 2004; Jennings and Rice 2011).

Other parameters apart from SST can also affect fish stocks, but were not analyzed due to incontinuous time-series in the area. In the Mediterranean, sea surface salinity (Rixen et al. 2005), deep water temperature and salinity (Manca et al. 2004) have also shown increasing trends. No significant regional oxygen concentration changes have been reported, except for a 0.2 % annual decrease in the deep Alboran Sea (El Boukhary et al. 2002). Ludwig et al. (2009) relate a 20 % decrease in river runoff (1960–2000) to both the climatic change and dam construction. Nutrient runoff could have significant effects on landings regionally (Adriatic Sea, Gulf of Lions and Aegean Sea) according to Caddy et al. (1995). Other anthropogenic effects may also have entered the food web: e.g. aquaculture nutrients have increased chlorophyll around Sicily (Sara et al. 2011). In general, the ecosystem status being the resultant of a number of components, it is difficult to identify the effect of each one separately. Additionally, the fluctuations of some components (e.g. river runoff) can be climatically-driven and may have acted independently or synergistically with SST.

The present work reports that yearly landings/LPUE follow marine temperature fluctuations in a pan-Mediterranean scale. Landings/effort data on fine spatial scales do not exist, but are available only at a Geographical Sub-Areas (GSA) level concerning the EU countries. The need for an improved, standardized and geographically referenced sampling system at a Mediterranean level is evident. Possibly this should involve organizations such as the International Commission for the Scientific Exploration of the Mediterranean (CIESM) and the EU Mediterranean Regional Advisory Council. Even with the presently available datasets, a natural next step would be to investigate differences between GSAs in order to attempt the detection of shifts in species ranges.

Here we provide only speculations upon the ways temperature could have affected stock abundance, as the exact mechanism is tentative (and could even be different between species). Thus, more research should be done in the mechanisms that shape the effects of temperature on fish stocks under a holistic approach. Nevertheless, the fact that landings/LPUE interannual fluctuations and regimes seem to respond to temperature oscillation and changes, strengthens the claim that temperature has played a key role in regulating fish abundance.

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