Chapter 1

Climate change impacts on marine ecosystems and resources

Chapter coordinator

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Abstract

The Mediterranean Sea is one of the biggest reservoirs of biodiversity in the world. Millions of people directly or indirectly depend on the ecosystem services it provides, in particular the provisioning of fisheries resources. Rather than a hot-spot of biodiversity, the Mediterranean Sea has now become a hot-spot of global change where climate change and other anthropogenic pressures (e.g., overfishing, pollution, habitat destruction) operate independently or synergistically to shape an altered Mediterranean Sea that may shift from the today picture. The set of physical-chemical changes triggered by climate change may disrupt the functioning of the biological components of ecosystems, from the individual up to the ecosystem scale, from the basis of the food webs (macrophytes, phytoplankton) up to the higher trophic levels (e.g., predator fish). Current research shows that the physiology and fish life history traits have changed, that fish distribution areas are moving northward and eastward, thus modifying the structure and the species composition of the communities. The dynamics of populations and food webs are modified as well, and species invasions increase at an unprecedented rate. Combined with fishing, climate change renders marine ecosystems more vulnerable to anthropogenic pressures, to natural hazards and to invasions by non-indigenous species. Although uncertainties remain with regard to the magnitude of expected ecological changes, the projections based on IPCC scenarios all confirm that climate change is a serious threat for the biodiversity and the sustainable exploitation of fishing resources in the Mediterranean Sea. This calls for the reinforcement of innovative and integrated research and assessment capacities to support an ecosystem-based management at the scale of the Mediterranean basin.

Résumé

La Méditerranée constitue l'un des plus grands réservoirs de biodiversité à l'échelle mondiale. Des millions de personnes dépendent directement ou indirectement des services écosystémiques rendus par celle-ci, notamment l'approvisionnement en ressources marines. Plus qu'un point chaud de biodiversité marine, la Méditerranée est désormais un point chaud du changement global où changement climatique et autres pressions d'origine anthropique (e.g. surexploitation, pollution, destruction d'habitat) peuvent agir indépendamment ou en synergie pour former une Méditerranée différente de celle que nous connaissons aujourd'hui. L'ensemble des modifications physico-chimiques induites par le changement climatique conduit à un bouleversement des composantes biologiques des écosystèmes, de l'échelle individuelle à l'échelle écosystémique, des producteurs primaires (algues, phytoplancton) aux plus hauts niveaux trophiques (e.g. poissons prédateurs). Les recherches actuelles démontrent que la physiologie et les traits de vie des poissons changent et que leurs distributions spatiales se sont décalées vers le nord et l'est, modifiant la structure et la composition des communautés. La dynamique des populations et des réseaux trophiques s'en trouve également modifiée et les invasions biologiques se multiplient à un rythme encore jamais observé. Avec la pêche, le changement climatique induit une fragilisation des écosystèmes marins, rendant ces derniers moins résilients et plus instables face aux activités anthropiques, aux aléas naturels et aux invasions d'espèces exotiques. Bien que des incertitudes demeurent quant à l'ampleur des changements biologiques en Méditerranée, les projections faites à partir des scénarios émis par le GIEC s'accordent pour affirmer que le changement climatique est une sérieuse menace pour la biodiversité marine et la production de ressources vivantes. Il s'agit alors d'appuyer des systèmes de recherche et d'évaluation innovants et intégrés afin d'adopter une gestion écosystémique à l'échelle du bassin méditerranéen.

Introduction

The Mediterranean Sea is a hotspot of biodiversity. It hosts 4% to 18% of all identified marine species, which is considerable given that the Mediterranean Sea only accounts for 0.82% of the global ocean surface (Coll et al. 2010). Considered as a "factory" designed to produce endemics, the unique geological history of the Mediterranean Sea and the variety of climatic and hydrological situations have led to the co-occurrence of cold, temperate and subtropical biota (Lejeusne et al. 2010). This biodiversity hot-spot is at risk today as a result of multiple pressures. Based on global climate change projection scenarios, the Mediterranean Sea has been classified as one of the most responsive regions to climate (Giorgi, 2006). The Mediterranean Sea is also known to be the biggest recipient of exotic species with the rate of species introduction peaking at two species per ten-day period in the 2000s (Ben Rais Lasram and Mouillot 2009, Zenetos et al. 2010). Combined with critical overfishing (more than 90% of assessed-stocks were overfished in 2015 (STECF 2016)), pollution and habitat destruction, climate change may result in the Mediterranean Sea becoming a hot-spot of global change (Micheli et al. 2013).

In this chapter, we describe how marine ecosystems and resources have shaped and, through interlinked mechanisms, may continue to shape future responses to climate change: (i) changes in primary production and in the structure of foodwebs, (ii) changes in population dynamics and life history traits, (iii) changes in species distribution range and habitats, and (iv) changes in the invasion rate of non-indigenous species. Examples are provided from different regions of the Mediterranean Sea and different biota (with a focus on fish communities), whereas marine top predators such as birds and marine mammals are not included in this review. Interactions between climate change, overfishing and habitat destruction are discussed throughout the chapter, but interactions with other direct anthropogenic pressures such as pollution, shipping, and oil spills are not addressed here.

References

Ben Rais Lasram F, Mouillot D (2009)
Increasing southern invasion enhances congruence between endemic and exotic Mediterranean fish fauna. Biol Invasions 11:697–711.

Coll M, Piroddi C, Steenbeek J, Kaschner K, Ben Rias Lasram F, Aguzzi J, Ballesteros E, Bianchi CN, Corbera J, Dailianis T, others (2010)
The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PloS One 5:e11842.

Giorgi F (2006)
Climate change hot-spots. Geophysical Research Letters 33(8): L08707.

Lejeusne C, Chevaldonné P, Pergent-Martini C, Boudouresque CF, Perez T (2010)
Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends Ecol Evol 25:250–260.

Micheli F, Halpern BS, Walbridge S, Ciriaco S, Ferretti F, Fraschetti S, Lewison R, Nykjaer L, Rosenberg AA (2013)
Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. PLoS One 8:e79889.

STECF (2016)
Reports of the Scientific, Technical and Economic Committee for Fisheries (STECF)-51st Plenary meeting Report (PLEN-16-01). 2016. Publications office of the European union, Luxembourg, EUR 27458 EN, JRC 101442, 95 pp.

Zenetos, A., Gofas, S., Verlaque, M., Cinar, M.E., Raso, G., Bianchi, C.N., Morri, C., Azzurro, E., Bilecenoglu, M., Froglia, C., Siokou, I., Violanti, D., Sfriso, A., San Martín, G., Giangrande, A., Katagan, T., Ballesteros, E., Ramos-Esplá, A., Mastrototaro, F., Ocaña, O., Zingone, A., Gambi, M.C., Streftaris, N. (2010)
Alien species in the Mediterranean Sea by 2010. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part I. Spatial distribution. Mediterranean Marine Science 11, 381-493.

Climate change impact on planktonic production in the Mediterranean Sea

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Primary production and plankton communities in the Mediterranean Sea

The Mediterranean Sea is characterized by a gradient of growing oligotrophy from the northwestern regions to the Levantine basin (Bosc et al. 2004). Nutrient availability is generally low, resulting in low phytoplankton biomass (less than 0.25 mg/mL). However, blooms and peaks in zooplankton biomass are recorded in areas of complex physical dynamics (winter convection, fronts, and gyres, Siokou-Frangou et al. 2010).

Seasonal hydrological regimes structure the phytoplankton community (Marty et al. 2002; Marty and Chiavérini 2010). Seasonal patterns are linked to variations in hydrological features and changes in nutrient concentrations: peaks in biomass occur in spring (March-April), after the replenishment of nutrients in surface waters owing to winter water mixing. After spring, the phytoplankton biomass decreases and goes deeper in the water column. Relying on satellite observations, D'Ortenzio and Ribera d'Alcalà (2009) defined a bioregionalization of the whole basin. Their classification provided a clear picture of the different phytoplankton trophic regimes in the Mediterranean. Nearly 60% of the basin's surface was described as « non-blooming » (mainly the eastern regions and the southwestern basin). Conversely, the northernmost regions, the Alboran, and the region of Rhodes were shown to be zones of « intermittent blooming » (gradual growth of biomass between September and February, linked to the deepening of the mixed layer). The locations of the different trophic regimes are clearly linked to convection and deep water formation processes (Millot and Taupier-Letage 2005). Primarily wind driven physical forcings favor the development of the phytoplankton by re-injecting nutrients (nitrates and phosphates) into the surface waters through mixing of the water column (Sverdrup 1953). This has a strong impact on the structure of the phytoplankton community.

Depending on the trophic regime, different phytoplankton taxa are likely to constitute the communities. Marty et al. (2002) analyzed algal pigment content to explore the relative contribution of different taxa to total phytoplankton biomass. These authors found that spring blooms were dominated by diatoms (large micro-algae characterized by silica shells), while stratifying conditions favor the development of nanoflagellates (nanophytoplankton), which are then replaced by cyanobacteria (picophytoplankton). The two latter phytoplankton size classes can be considered as markers of oligotrophic conditions, while microphytoplankton (diatoms) are opportunistic and burst after nutrient replenishment. Over the year, nanophytoplankton account for 43% to 50% of the total primary production of the Mediterranean Sea, which is largely dominated by Prymnesiophyta (Uitz et al. 2012). Even the blooming areas investigated by D'Ortenzio and Ribera d'Alcalà (2009) were dominated by nanophytoplankton, except in spring when they were replaced by microphytoplankton (up to 38% of total primary production). In non-blooming zones, picophytoplankton come after nanophytoplankton in order of abundance.

To date, offshore surveys of plankton distribution and communities have been dispersed not only in space and time, but have also used different methods (Siokou-Frangou et al. 2010). Consequently, regional and seasonal patterns of diversity and community composition are still poorly understood.

Concerning phytoplankton diversity, low biomass is linked to the dominance of the smallest plankton, which consist of picophytoplankton (mainly prochlorophytes), cyanobacteria (Synechococcus) and flagellates (Marty et al. 2002; Uitz et al. 2012). Non-colonial picodiatoms have occasionally been reported to be abundant, but cell size usually prevents their accurate identification. Nanophytoplankton, which are mainly composed of small flagellates, dinoflagellates, coccolithophores, and to a lesser extent of some small solitary diatoms, are also very abundant. Major increases in biomass are correlated with the growth of microphytoplankton, which are mainly composed of large colonies of diatoms (Marty et al. 2002; Marty and Chiavérini 2010). The main genera are *Asterionellopsis*, *Chaetoceros*, *Pseudo-nitzschia*, *Thalassionema* and *Thalassiosira* (Siokou-Frangou et al. 2010). These genera are unevenly distributed in the Mediterranean basin:

healthy colonies of *Chaetoceros* and *Pseudo-nitzschia* have been observed in areas of deep convection while colonies of *Chaetoceros*, in association with *Thalassiosira*, *Proboscia*, *Rhizosolenia* and *Leptocylindrus* have been found across fronts and gyres (circular oceanic surface currents). Although among the less abundant microplankton, dinoflagellates show significant diversity in the Mediterranean; like nanoplankton, they are associated with stratified and nutrient-depleted conditions. These taxa exhibit wide trophic modes: some are heterotrophic, while others are mixotrophic (*Neoceratium spp*.) or host endosymbiotic cyanobacteria. To summarize, Mediterranean phytoplankton comprise very diverse taxa with diverse ecological preferences.

Regarding zooplankton, the world dominance of copepods in the water column also applies to the Mediterranean. Like micro-algae, smaller species (< 2 mm) prevail in the communities, whatever the trophic regime (Siokou-Frangou et al. 2010). The bulk of zooplankton comprises very diverse genera of calanoids and cyclopoids. The relative contribution of the smaller cyclopoids is thought to increase with the increasing west-east gradient of oligotrophy, while larger species are more abundant in colder and more productive areas (Siokou-Frangou et al. 1997).

Other zooplankton taxa should not be overlooked. Cladocerans are found in large numbers in summer in coastal environments (Riandey et al., 2005). Gelatinous filter-feeders, like salps, frequently produce spectacular blooms in warm waters. Outbursts of jellyfish in summer have become a public concern. Gelatinous-wise, chaetognaths and siphonophores are carnivorous species frequently encountered in the Mediterranean Sea that prey on copepods and other smaller planktonic organisms.

Climate variability influences plankton distribution and community composition

Plankton abundance and distribution are strongly controlled by hydrological features and water mass advection. The tight coupling between their population dynamics and climate makes them optimal indicators to monitor the impact of climate variability on ecosystems (Hays et al. 2005). Tunin-Ley et al. (2009) assembled time series to investigate the effects of increasing temperatures on the distribution of 46 *Ceratium* species (Dinoflagellates) over the 20th century (1908-2005). Irrespective of the location, species composition showed a clear seasonal cycle, but phenologies differed according to the species and the sites surveyed. Although *Ceratium* assemblages did vary with changing temperatures, contrary to expectations, thermophilic species did not show increasing trends. As no new species were detected during the 20th century, the disappearance of species that prefer colder conditions could not be balanced, and warming has resulted in a loss of biodiversity.

Marty and Chiavérini (2010) monitored hydrological changes in the Ligurian basin and their biogeochemical consequences during the period 1995-2007. These authors revealed an increase in phytoplankton biomass (+1.5 mgChla/ m^2.yr) paralleling increases in temperature and salinity in the northwestern Mediterranean Sea. Furthermore, the fraction of biomass attributed to diatoms also increased. Thus, the increases in biomass were due to generalized growth of phytoplankton, not only to the growth of the smaller size classes that usually dominate in warmer conditions. Marty and Chiavérini (2010) reported an increase in the frequency of mixing events, rather than longer stratification periods.

Long time series provide ideal material to study plankton dynamics under climate change. Several multidecadal surveys have been conducted in the Mediterranean Sea (Berline et al. 2012), all of which evidenced strong seasonal patterns in phytoplankton and zooplankton communities (Ribera d'Alcalà et al. 2004). In the Gulf of Naples for instance, a time series from 1984 to 2000 revealed an over decadal decrease in phytoplankton (Ribera d'Alcalà et al. 2004), together with an increase in a rare copepod species and a weak decrease in zooplankton biomass. These authors suggested that biological rhythms regulate the temporal dynamics while the climate modulates the amplitude of the growth periods. This hypothesis was later invalidated by Mazzocchi et al. (2011) using the same time series, by providing evidence for phenological changes in Mediterranean mesozooplankton: the copepod assemblage characterizing spring and summer conditions declined over the study period as its typical high production season became shorter and started earlier in the year. By contrast, the communities that depend on summer and fall conditions remained stable phenology-wise, and were quite resilient to decreases in phytoplankton biomass. From these results, Mazzocchi et al. (2011) concluded that the zooplankton composition does not vary according to phytoplankton variability, and that zooplankton communities are resilient to climate change. This conclusion was challenged by Conversi et al. (2009), who demonstrated a dramatic shift across the copepod community between the late 1980s and the early 1990s. Warming combined with changes in circulation in the Ionian Sea (Civitarese et al. 2010) have been identified as the principal causes. The link between climatic variability and phytoplankton dynamics is consequently not well understood yet.

To summarize, plankton assemblages in the Mediterranean have proved to be good indicators of environmental changes. The variety of trophic regimes and the diversity of biological communities offer great opportunities to test hypotheses concerning climate change and its impacts on plankton. The Mediterranean Sea contains a wide range of plankton whose environmental preferences and functional roles remain to be fully determined. The patterns described above suggest differences between the ecological traits and environmental preferences of species. By altering the pelagic environment, anthropogenic climate change could alter plankton distribution, as well as their importance in the food web.

How will anthropogenic climate change impact Mediterranean plankton?

Despite the importance of plankton for both food webs and biogeochemical cycles, very few studies have attempted to forecast the impact of climate change on primary production and community composition in the Mediterranean Sea (Lazzari et al. 2013; Herrmann et al. 2014). There are projections at the global scale, but the corresponding models do not adequately resolve the peculiar regional processes of the Mediterranean, and regional coupled models thus need to be implemented.

Focusing on the northwestern areas of the basin (Gulf of Lion and Ligurian Sea), Herrmann et al. (2014) investigated the response of the pelagic plankton ecosystem and associated carbon cycle, to long term changes in oceanic and atmospheric circulation. Their predictions suggest that climate change will not modify the seasonal dynamics and variability of the planktonic ecosystem at a first order, compared to what is modeled for the contemporary period. Microphytoplankton and nanophytoplankton biomasses are not expected to increase by the end of the 21st century. Meanwhile, their model forecasts an increase in zooplankton biomass, due to a gain in the smaller size fractions (nanozooplankton), and in picophytoplankton biomass. Their study suggests that climate change in the northwestern Mediterranean will favour the smallest components of the plankton, and strengthen the microbial loop activity.

Lazzari et al. (2013) used a different model that covered the entire Mediterranean Sea to assess the impact of climate change on the carbon cycle in a plankton ecosystem model. Like Herrmann et al. (2014), their model predicts a strengthening of the microbial pathway in the plankton ecosystem with reduced nutrient availability and phytoplankton biomass.

In contrast to higher trophic levels (Ben Rais Lasram 2010; Albouy et al. 2012), the potential impact of rising temperatures and salinity on plankton species composition has never been assessed. This will be crucial to better understand how climate change could reshape plankton in the Mediterranean Sea, as not all species share similar traits and functions in the ecosystems (Benedetti et al. 2016). In the future, more modeling studies are needed to better constrain the predicted impacts of climate change on primary production and plankton size structure. Models should also focus on resolving taxonomic and ecological complexity by accounting for differences in plankton species traits. Finally, multi-trophic models should be developed to estimate how climate change may impact the structure of the food web and ecosystem services provision.

References

Albouy, C., F. Guilhaumon, M. B. Araújo, D. Mouillot, F. Leprieur (2012)
Combining projected changes in species richness and composition reveals climate change impacts on coastal Mediterranean fish assemblages, *Global Change Biology*, *18*(10), 2995-3003.

Benedetti, F., S. Gasparini, S.-D. Ayata (2016)
Identifying copepod functional groups from species functional traits, Journal of Plankton Research, 38(1), 159-166.

Ben Rais Lasram, F., F. Guilhaumon, C. Albouy, S. Somot, W. Thuiller, D. Mouillot (2010)
The Mediterranean Sea as a "cul de sac" for endemic fishes facing climate change, *Global Change Biology*, *16*(12), 3233-3245.

Berline, L., I. Siokou-Frangou, I. Marasović, O. Vidjak, M. L. Fernández de Puelles, M. G. Mazzocchi, G. Assimakopoulou, S. Zervoudaki, S. Fonda-Umani, A. Conversi (2012)
Intercomparison of six Mediterranean zooplankton time series, *Progress in Oceanography*, *97*, 76-91.

Bosc, E., A. Bricaud, D. Antoine (2004)
Seasonal and interannual variability in algal biomass and primary production in the Mediterranean Sea, as derived from 4 years of SeaWiFS observations, *Global Biogeochemical Cycles*, *18*(1).

Civitarese, G., M. Gačić, M. Lipizer, G. Eusebi Borzelli (2010)
On the impact of the Bimodal Oscillating System (BiOS) on the biogeochemistry and biology of the Adriatic and Ionian Seas (Eastern Mediterranean), *Biogeosciences Discussions*, *7*(5), 6971-6995.

Conversi, A., T. Peluso, S. Fonda-Umani (2009)
Gulf of Trieste: A changing ecosystem, *Journal of Geophysical Research: Oceans (1978-2012)*, *114*(C3).

D'Ortenzio, F., M. Ribera d'Alcala (2009)
On the trophic regimes of the Mediterranean Sea: a satellite analysis, *Biogeosciences*, *6*(2), 139-148.

Hays, G. C., A. J. Richardson, C. Robinson (2005)
Climate change and marine plankton, *Trends in Ecology & Evolution*, *20*(6), 337-344.

Herrmann, M., C. Estournel, F. Adloff, F. Diaz (2014)
Impact of climate change on the northwestern Mediterranean Sea pelagic planktonic ecosystem and associated carbon cycle, *Journal of Geophysical Research: Oceans*, *119*(9), 5815-5836.

Lazzari, P., G. Mattia, C. Solidoro, S. Salon, A. Crise, M. Zavatarelli, P. Oddo, M. Vichi (2013)
The impacts of climate change and environmental management policies on the trophic regimes in the Mediterranean Sea: Scenario analyses, *Journal of Marine Systems*, *135*, 137-149.

Marty, J.-C., J. Chiavérini, M.-D. Pizay, B. Avril (2002)
Seasonal and interannual dynamics of nutrients and phytoplankton pigments in the western Mediterranean Sea at the DYFAMED time-series station (1991-1999), *Deep Sea Research Part II: Topical Studies in Oceanography*, *49*(11), 1965-1985.

Marty, J., J. Chiavérini (2010)
Hydrological changes in the Ligurian Sea (NW Mediterranean, DYFAMED site) during 1995-

2007 and biogeochemical consequences, *Biogeosciences*, *7*(7).

Mazzocchi, M. G., P. Licandro, L. Dubroca, I. Di Capua, V. Saggiomo (2011)
Zooplankton associations in a Mediterranean long-term time-series, *Journal of Plankton Research*, *33*(8), 1163-1181.

Millot, C., I. Taupier-Letage (2005),
Circulation in the Mediterranean sea, in *The Mediterranean Sea*, edited, pp. 29-66, Springer.

Ribera d'Alcalà, M., F. Conversano, F. Corato, P. Licandro, O. Mangoni, D. Marino, M. Mazzocchi, M. Modigh, M. Montresor, M. Nardella (2004)
Seasonal patterns in plankton communities in a pluriannual time series at a coastal Mediterranean site (Gulf of Naples): an attempt to discern recurrences and trends, *Scientia Marina (Barcelona)*, *68*(Suppl. 1).

Siokou-Frangou, I., E. Christou, N. Fragopoulu, M. Mazzocchi (1997)
Mesozooplankton distribution from Sicily to Cyprus (Eastern Mediterranean). 2. Copepod assemblages, *Oceanolica Acta*, *20*(3), 537-548.

Siokou-Frangou, I., U. Christaki, M. Mazzocchi, M. Montresor, M. R. d'Alcala, D. Vaqué, A. Zingone (2010),
Plankton in the open Mediterranean Sea: a review, *Biogeosciences*, *7*(5), 1543-1586.

Sverdrup, H. (1953)
On conditions for the vernal blooming of phytoplankton, *Journal du Conseil*, *18*(3), 287-295.

Tunin-Ley, A., F. Ibañez, J.-P. Labat, A. Zingone, R. Lemée (2009)
Phytoplankton biodiversity and NW Mediterranean Sea warming: changes in the dinoflagellate genus *Ceratium* in the 20th century, *Mar Ecol Prog Ser*, *375*, 85-99.

Uitz, J., D. Stramski, B. Gentili, F. D'Ortenzio, H. Claustre (2012)
Estimates of phytoplankton class-specific and total primary production in the Mediterranean Sea from satellite ocean color observations, *Global Biogeochemical Cycles*, *26*(2).

Climate change induces bottom-up changes in the food webs of the Mediterranean Sea

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At the global scale, one of the main effects of climate change on marine ecosystems is changing the rate and patterns of primary production (Brown et al. 2010). In the Mediterranean Sea, although there is no consensus and no clear trends have emerged, several studies expect that, by increasing the vertical stability of the water column and by decreasing nutrient replenishment, seawater warming will cause changes in phytoplankton bloom phenology, biomass and community structure (Goffart et al. 2002, Bosc et al. 2004, Tunin-Ley et al. 2009). What has been clearly demonstrated is that seawater warming will lead to a shift in dominant species towards smaller species (picophytoplankton and nanoflagellates) and a decrease in diatoms (The MerMex Group 2011). Moreover, acidification in the Mediterranean Sea will strengthen the expected impacts, with an expected decrease in the biomass of calcifying organisms such as coccolithophorids, which are important plankton primary producers (Dias et al. 2010, The MerMex Group 2011). Primary and secondary production (i.e. the production of phytoplankton and zooplankton, respectively) play a key role in biogeochemical cycles, as well as in the structure and functioning of food webs and in global productivity of marine ecosystems. Through bottom-up or wasp-waist trophic controls (Cury et al. 2003), changes at the base of the food webs may transfer from low to high trophic levels, with potential impacts on the production of living resources and fisheries. Moreover, since the Mediterranean is a semi-enclosed sea, expected impacts of climate change on phytoplankton communities and their dynamics could affect ecosystems much more rapidly than in other oceanic regions (Lejeusne et al. 2010, Siokou-Frangou et al. 2010). In this chapter, we describe how climate change could affect the functioning of marine systems, and more specifically, the production of living resources by bottom-up control. We use a few typical recent examples to show how the strength of the bottom-up control and the base of the food web in the Mediterranean Sea could be affected by several hydrological changes and how these changes could affect food web dynamics, catch potential, and conservation of the marine biodiversity in the future.

Changes in primary and secondary production affect food web dynamics and recruitment

At the global scale, under the IPCC SRES (Intergovernmental Panel on Climate Change Special Report on Emission Scenarios) A2 scenario, and based on the output of four global coupled carbon cycle-climate models, Steinacher et al. (2010) suggest that global mean primary production may decrease by 2% to 20% by 2100 relative to preindustrial conditions. In the Mediterranean Sea, by increasing the strength of the vertical stratification, warming could affect the turbulent nutrient supply to the photic layer and hence could reduce primary production (Marbà et al. 2015), as well as reduce the relative contribution of larger cells (The MerMex Group 2011). There are still many uncertainties on the level of impact of sea warming and of acidification on primary production in the basin, but it is clear that physical-chemical changes will affect the magnitude, timing and composition of phytoplankton blooms, with associated changes in the seasonal distribution of zooplankton (see sub-chapter 2.1.1 for more details).

It is now recognized that primary production is critical to maintain biodiversity and support fishery catches in the world's oceans (Brown et al. 2010). Indeed, more than 90% of ocean productivity is ensured by phytoplankton, which is then transferred throughout the food webs by grazing and predation and lost through metabolism (Lindeman 1942, Gascuel et al. 2008). Few studies have tried to forecast potential changes in primary and secondary production and the ensuing impacts on food webs and on the functioning of Mediterranean ecosystems. Many uncertainties remain concerning the magnitude of the expected climate-induced changes. Nevertheless, based on studies of other ecosystems in the world, it is possible to extrapolate the consequences of changes in primary production in this region. For instance, Chassot et al. (2010) showed that phytoplankton primary production influences global fisheries production at the scale of Large Marine Ecosystems (LME). This assumption was confirmed by Blanchard et al. (2012), who showed that, in 11 large regional shelf seas, potential marine fisheries production is primarily determined by available primary production. Similarly, using an ecosystem model, Brown et al. (2010) demonstrated that changes in primary production affect fisheries catch and value and have major implications for the conservation of marine biodiversity. Finally, at local, regional and global scales, several authors have established that fluctuations in fishery yields are linked to fluctuations in phytoplankton, zooplankton and benthic communities (e.g. Darnaude et al. 2004, Edwards & Richardson 2004, Cheung et al. 2010, Barange et al. 2014).

In the Mediterranean Sea, previous observations already suggested that a reduction in primary production linked to an increase of sea surface temperature could have negative impacts on fisheries catch and could exacerbate current trends of overfishing. This hypothesis was confirmed by Cheung et al. (2011) whose models predict that if phytoplankton communities shift towards smaller size cells, energy transfer from primary production to higher trophic levels may decline in the future, with an associated reduction in catch potential (see sub-chapter 2.1.4). Moreover, a decrease in primary production could be detrimental for the conservation of taxa of interest and for overall biodiversity in a context of global change, with potential synergies with overfishing, habitat degradation and biological invasions.

In marine ecosystems, environmental conditions play an important role in fish recruitment (i.e. the number of fish that survive from the early larval stage to reach the recruitment stage that can be targeted by fisheries). As fish larvae are very vulnerable to starvation, their survival strongly depends on prey availability, meaning the mean size of prey, their seasonal timing and abundance (Beaugrand et al. 2003) are crucial. The match-mismatch hypothesis (Cushing 1990) emphasizes that the production of first feeding larvae must match the production of planktonic food. Thus, by affecting primary and secondary production and timing, climate change may disrupt the distribution and phenology of fish larvae, affect recruitment and production of fish stocks, with indirect effects on food web structures and ecosystem-level changes (Edwards & Richardson 2004, Brander 2010). In the Mediterranean Sea, projected changes in primary and secondary productions suggest that trophic mismatches between fish pre-recruits and their prey could increase in the future, with negative consequences for recruitment success, sustainable fisheries and conservation of biodiversity (Lejeusne et al. 2010, Stergiou et al. 2015).

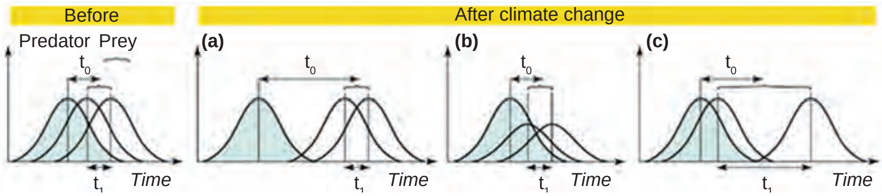

Figure 1
Match-mismatch hypothesis and three possible effects of climate change:
(a) Change in the timing of prey peak production; (b) Change in the level of prey abundance;
(c) Change in the amplitude of year-to-year variations in prey timing in regions where inter-annual variability in temperature is expected to increase. t_0 is the degree of time mismatch,
t_1 is the inter-annual variability in the timing of prey population.
From Cury et al. (2008).

In addition to impacts on plankton production and timing, climate change can also lead to changes in the composition of species that form the base of marine food webs. In the Mediterranean Sea, the increase in water temperature has already modified jellyfish population dynamics (Coll et al. 2010). For several decades, the extent and intensity of jellyfish outbreaks have increased, in particular outbreaks of *Pelagia noctiluca*, a planktonic predator of fish larvae and of their zooplankton prey (Licandro et al. 2010). In the western Mediterranean, the increasing frequency of these outbreaks can be explained by the alteration of the trophic structure of ecosystems due to overfishing and/or eutrophication on the one hand, and by sea warming and changes in surface hydrography on the other (Licandro et al. 2010, Canepa et al. 2014). As already shown in the Black Sea, outbreaks can affect fisheries by bottom-up and top-down controls on fish larvae survival (Daskalov et al. 2007). In fact, jellyfish can affect fish recruitment negatively and as they can be venomous, outbreaks can also be detrimental to aquaculture and have strong ecological and socio-economic impacts. Considering the current IPCC projections, Licandro et al. (2010) suggested that outbreaks of *P.noctiluca*, along with other jellyfish species, may become more frequent in the Mediterranean basin and extend over a longer period of the year than previously, causing alteration of the pelagic food web and thereby reducing fishery production. For instance, in the northwestern Mediterranean Sea, Molinero et al. (2005) found that the increase in jellyfish outbreaks during the 1980s was largely favored by high positive temperature anomalies. They highlighted the trophic cascade that took place during the mid-late 1980s, with the high abundance of jellyfish and a marked drop in the abundance of copepods. However, the variability of copepods has direct implications for pelagic fish populations and for the biological pump of carbon into the deep ocean (Ohman & Hirche 2001, Calbet 2008). Thus, the Mediterranean pelagic ecosystem could shift towards an alternative state with less organic matter exported and prone to the risk of high trophic level predators (exploited by fisheries) being replaced by jellyfish (Gros 2011).

Another consequence of climate change in the Mediterranean Sea, which, at first sight, has less impact on fisheries, is the increase in the mucilage phenomenon. Indeed, surface water warming and the associated increase in water column stability can favor the coalescence of marine snow (i.e. small amorphous aggregates with colloidal properties) into marine mucilage (Danovaro et al. 2009). Danovaro et al. (2009) have shown that the majority of mucilage spreading is linked to climate-driven sea surface warming. The occurrence of mucilage events is increasing and spreading to several regions beyond the Adriatic Sea. Mucilage can act as a controlling factor for microbial diversity and could act as a carrier of specific microorganisms, thereby increasing the spread of pathogenic bacteria (Danovaro et al. 2009). According to these authors, if the mucilage phenomenon continues to increase in frequency and duration and to extend its range in the region, the increased frequency and extension of some marine diseases may have consequences for human health; "a warmer world would be a sicker world" (Harvell et al. 2009). Mucilage, in turn, can induce hypoxic phenomena, extensive anoxia and may reduce the provision of ecosystem services and ecosystem resilience. Indeed, hypoxia or anoxia events can cause the suffocation of benthic and epibenthic organisms on the sea bottom, which, in turn, could result in severe fishery and sanitary problems (Danovaro et al. 2005). Moreover, because of mucilage's properties, the phenomena may clog fishing nets causing serious socio-economic damage for fisheries (Rinaldi et al. 1995).

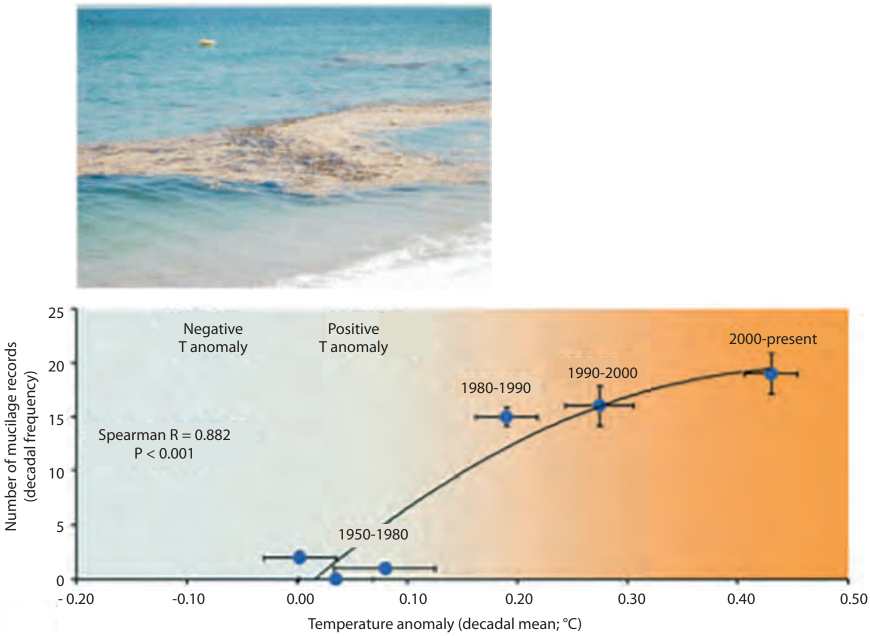

Figure 2
Relationships between mucilage occurrence in the Mediterranean Sea and climate change (as magnitude of the thermal anomalies) on a decadal basis. Photo of mucilage in surface off-shore waters. Adapted from Danovaro et al. (2009).

Climate change drives commercial fish production

Because of their short life span, their nutrition relying on short plankton-based food chains and their recruitment controlled by the environment, pelagic fish stocks are excellent sentinel species for analysis of the effects of climate change on ecosystems (Checkley et al. 2009). This is not surprising, given that these species have a very high growth and population turnover rate, making them more susceptible to changes in the environment. For example, in the western Mediterranean, a significant relationship was found between round sardinella (*Sardinella aurita*) landings and temperature anomalies (Sabates et al. 2006). Indeed, a gradual northward increase in the abundance of this warm water species was observed along the Mediterranean Iberian coast. Consequently, an overall increase in landings of round sardinella has been observed over the last 30 years (around 35 000 t), while landings remained below 5000 t year^{-1} until the early 1980s. This increase is linked to the successful reproduction of the species, marked by an increase in larval abundance, in the northwestern Mediterranean. At the same time and in the same area, landings of two other pelagic species, sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*), have declined in recent decades. Sprat (*Sprattus sprattus*), a cold water small pelagic species, has virtually disappeared from commercial catches of the northwestern Mediterranean (Sabates et al. 2006). Using a 3-D full life cycle population model at the Mediterranean Sea LME (large marine ecosystem) scale, under the SRES IPCC A1B scenario, Stergiou et al. (2015) determined that the anchovy biomass would decrease significantly (by around -28 %) in 2080-2100 compared to 1980-2000. This prediction is linked to a decrease in zooplankton biomass and rising temperatures that affect fish metabolic rates (i.e. an increase in maintenance cost). In their study, sea warming was shown to affect net fish somatic growth and to indirectly affect egg production, which is weight dependent. Moreover, with warmer temperatures, fish early life stages could be subject to higher starvation mortalities due to the increased energy required to meet maintenance costs (Stergiou et al. 2015). As a result, anchovy stock biomass is predicted to decrease by 33% in the Adriatic sub-area, by 18% in the north Aegean sub-area and by 15% in the Catalan Sea/Gulf of Lions sub-area.

In the northwestern Mediterranean, numerous changes in environmental conditions such as riverine input or wind mixing can explain fluctuations in the productivity of small pelagic fish (Lloret et al. 2004). For instance, a significant relationship between monthly landings of anchovy and freshwater inputs of the Ebre River during the spawning season of anchovy has been found (Lloret et al. 2004). For sardine, monthly landings were positively correlated with wind mixing during its spawning season (Lloret et al. 2004). Thus, in a context in which climate change is expected to increase variance in rainfall regimes, with increased frequency of droughts paralleled by unusual amounts of rainfall and floods, increasing temperature and changing wind mixing, pelagic fish stocks in the Mediterranean are likely to be strongly impacted (Lloret et al. 2001). In the northwestern Mediterranean, in contrast to anchovy, sardine abundance was found to be negatively correlated with sea surface temperature, and the warming trend may have contributed both to the decrease in sardine abundance and to the extension of the distribution area of the round sardinella (Palomera et al. 2007, Rijnsdorp et al. 2010). In addition to climate change impacts, fluctuations in small pelagic populations have also been shown to be associated with interdecadal variability of climate indices, such as the well-known Atlantic Multidecadal Oscillation (AMO) and the more local Western Mediterranean Oscillation (WeMO) indices (Martín et al. 2012, Alheit et al. 2014).

Pelagic fish are essential trophic compartments of marine ecosystems due to their high biomass at intermediate levels of the food web, and therefore their key role in the transfer of organic matter from lower to higher trophic levels (Cury et al. 2000, Palomera et al. 2007). Hence, variability in small pelagic fish due to climate change or other anthropogenic disturbances will modify both the structure and functioning of ecosystems (Cury et al. 2000). Pelagic stocks are not the only stocks to be impacted by changes in river discharge. Salen-Picard et al. (2002) showed that the Rhone river flow in the Gulf of Lion also influenced abundances of *Solea solea* by causing pulses of organic matter that are followed by peaks of polychaetes density. Indeed, a positive correlation was found between the mean annual commercial landings of *S. solea*, with a time lag of five years, in two fishing harbors close to the Rhone delta (Salen-Picard et al. 2002). The authors of the study concluded that fluctuations in sole fishery yield in the Gulf of Lion can be influenced by climate, as the Rhone river flow is related to the North Atlantic Oscillation, which drives precipitation over Western Europe. In fact, a decrease in run-off into the Mediterranean Sea could reduce the productivity of sole and other demersal fish in this region (Salen-Picard et al. 2002, Darnaude et al. 2004). By coupling a hydrodynamic model to the food web model Ecopath with Ecosim, Libralato & Solidoro (2009) showed that changes in river run-off are the major environmental driver of ecosystem dynamics in coastal areas in the Adriatic, especially the Lagoon of Venice.

To summarize, many uncertainties remain on future change in primary production and more data are needed to carefully assess possible impacts on marine biodiversity and on fisheries production. With this synthesis, we highlight a possible change in the strength of the bottom-up control in the Mediterranean ecosystems. Small pelagics are influenced by a plethora of factors, each of which can be altered by climate change, so that they can have additive, synergistic or antagonistic effects on small pelagics. Climate change is expected to reduce primary production rates at basin scale, to alter the phenology of phytoplankton and zooplankton blooms and to cause shifts in community structures. All these changes will have dramatic impacts on the structure and functioning of ecosystems, and especially on food web dynamics. For fisheries, the change in primary production will likely result in a reduction of catches and/or an exacerbation of the effects of overfishing. Finally, by affecting rainfall regimes, and therefore river outflows, climate change could affect the overall food web and fishery production on the continental shelf.

References

Alheit J, Licandro P, Coombs S, Garcia A, Giráldez A, Santamaría MTG, Slotte A, Tsikliras AC (2014)
Reprint of "Atlantic Multidecadal Oscillation (AMO) modulates dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic." J Mar Syst 133:88–102

Barange M, Merino G, Blanchard JL, Scholtens J, Harle J, Allison EH, Allen JI, Holt J, Jennings S, others (2014)
Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat Clim Change 4:211–216

Beaugrand G, Brander KM, Lindley JA, Souissi S, Reid PC (2003)
Plankton effect on cod recruitment in the North Sea. Nature 426:661–664

Blanchard JL, Jennings S, Holmes R, Harle J, Merino G, Allen JI, Holt J, Dulvy NK, Barange M (2012)
Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philos Trans R Soc Lond B Biol Sci 367:2979–2989

Bosc E, Bricaud A, Antoine D (2004)
Seasonal and interannual variability in algal biomass and primary production in the Mediterranean Sea, as derived from 4 years of SeaWiFS observations.
Glob Biogeochem Cycles 18

Brander K (2010)
Impacts of climate change on fisheries. J Mar Syst 79:389–402

Brown CJ, Fulton EA, Hobday AJ, Matear RJ, Possingham HP, Bulman C, Christensen V, Forrest RE, Gehrke PC, Gribble NA, others (2010)
Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. Glob Change Biol 16:1194–1212

Calbet A (2008)
The trophic roles of microzooplankton in marine systems. ICES J Mar Sci J Cons 65:325–331

Canepa A, Fuentes V, Sabatés A, Piraino S, Boero F, Gili J-M (2014)
Pelagia noctiluca in the Mediterranean Sea. In: Jellyfish Blooms. Springer, p 237–266

Chassot E, Bonhommeau S, Dulvy NK, Mélin F, Watson R, Gascuel D, Le Pape O (2010)
Global marine primary production constrains fisheries catches. Ecol Lett 13:495–505

Checkley D, Alheit J, Oozeki Y, Roy C (2009)
Climate change and small pelagic fish. Cambridge University Press Cambridge

Cheung WW, Dunne J, Sarmiento JL, Pauly D (2011)
Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J Mar Sci J Cons:fsr012

Cheung WW, Lam VW, Sarmiento JL, Kearney K, Watson REG, Zeller D, Pauly D (2010)
Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob Change Biol 16:24–35

Coll M, Piroddi C, Steenbeek J, Kaschner K, Ben Rias Lasram F, Aguzzi J, Ballesteros E, Bianchi CN, Corbera J, Dailianis T, others (2010)
The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PloS One 5:e11842

Cury P, Bakun A, Crawford RJ, Jarre A, Quiñones RA, Shannon LJ, Verheye HM (2000)
Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES J Mar Sci J Cons 57:603–618

Cury PM, Shin Y-J, Planque B, Durant JM, Fromentin J-M, Kramer-Schadt S, Stenseth NC, Travers M, Grimm V (2008)
Ecosystem oceanography for global change in fisheries. Trends Ecol Evol 23:338–346

Cushing DH (1990)
Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Adv Mar Biol 26:249–293

Danovaro R, Armeni M, Luna GM, Corinaldesi C, Dell'Anno A, Ferrari CR, Fiordelmondo C, Gambi C, Gismondi M, Manini E, others (2005)
Exo-enzymatic activities and dissolved organic pools in relation with mucilage development in the Northern Adriatic Sea. Sci Total Environ 353:189–203

Danovaro R, Umani SF, Pusceddu A (2009)
Climate change and the potential spreading of marine mucilage and microbial pathogens in the Mediterranean Sea. PLoS One 4:e7006

Darnaude AM, Salen-Picard C, Polunin NV, Harmelin-Vivien ML (2004)
Trophodynamic linkage between river runoff and coastal fishery yield elucidated by stable isotope data in the Gulf of Lions (NW Mediterranean). Oecologia 138:325–332

Daskalov GM, Grishin AN, Rodionov S, Mihneva V (2007)
Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. Proc Natl Acad Sci 104:10518–10523

Dias BB, Hart MB, Smart CW, Hall-Spencer JM (2010)
Modern seawater acidification: the response of foraminifera to high-CO2 conditions in the Mediterranean Sea. J Geol Soc 167:843–846

Edwards M, Richardson AJ (2004)
Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430:881–884

Gascuel D, Morissette L, Palomares MLD, Christensen V (2008)
Trophic flow kinetics in marine ecosystems: toward a theoretical approach to ecosystem functioning. Ecol Model 217:33–47

Goffart A, Hecq J-H, Legendre L (2002)
Changes in the development of the winter-spring phytoplankton bloom in the Bay of Calvi (NW Mediterranean) over the last two decades: a response to changing climate? Mar Ecol Prog Ser 236:45–60

Gros P (2011)
Ecosystèmes marins (Chapitre 5). In: Connaissance des impacts du changement climatique sur la biodiversité en France métropolitaine synthèse de la bibliographie.

Harvell D, Altizer S, Cattadori IM, Harrington L, Weil E (2009)
Climate change and wildlife diseases: when does the host matter the most? Ecology 90:912–920

Lejeusne C, Chevaldonné P, Pergent-Martini C, Boudouresque CF, Perez T (2010)
Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends Ecol Evol 25:250–260

Libralato S, Solidoro C (2009)
Bridging biogeochemical and food web models for an End-to-End representation of marine ecosystem dynamics: The Venice lagoon case study. Ecol Model 220:2960–2971

Licandro P, Conway DVP, Yahia MD, De Puelles MF, Gasparini S, Hecq J-H, Tranter P, Kirby RR (2010)
A blooming jellyfish in the northeast Atlantic and Mediterranean. Biol Lett:rsbl20100150

Lindeman RL (1942)
The trophic-dynamic aspect of ecology. Ecology 23:399–417

Lloret J, Lleonart J, Solé I, Fromentin J-M (2001)
Fluctuations of landings and environmental conditions in the north-western Mediterranean Sea. Fish Oceanogr 10:33–50

Lloret J, Palomera I, Salat J, Sole I (2004)
Impact of freshwater input and wind on landings of anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus) in shelf waters surrounding the Ebre (Ebro) River delta (north-western Mediterranean). Fish Oceanogr 13:102–110

Marbà N, Jordà G, Agustí S, Girard C, Duarte CM (2015)
Footprints of climate change on Mediterranean Sea biota. Front Mar Sci

Martín P, Sabatés A, Lloret J, Martin-Vide J (2012)
Climate modulation of fish populations: the role of the Western Mediterranean Oscillation (WeMO) in sardine (Sardina pilchardus) and

anchovy (Engraulis encrasicolus) production in the north-western Mediterranean. Clim Change 110:925–939

Molinero JC, Ibanez F, Nival P, Buecher E, Souissi S (2005)
North Atlantic climate and northwestern Mediterranean plankton variability. Limnol Oceanogr 50:1213–1220

Ohman MD, Hirche H-J (2001)
Density-dependent mortality in an oceanic copepod population. Nature 412:638–641

Palomera I, Olivar MP, Salat J, Sabatés A, Coll M, Garcia A, Morales-Nin B (2007)
Small pelagic fish in the NW Mediterranean Sea: an ecological review. Prog Oceanogr 74:377–396

Rijnsdorp AD, Peck MA, Engelhard GH, Möllmann C, Pinnegar JK (2010)
Resolving climate impacts on fish stocks. International Council for the Exploration of the Sea

Rinaldi A, Vollenweider RA, Montanari G, Ferrari CR, Ghetti A (1995)
Mucilages in Italian seas: the Adriatic and Tyrrhenian seas, 1988–1991. Sci Total Environ 165:165–183

Sabates A, Martín P, Lloret J, Raya V (2006)
Sea warming and fish distribution: the case of the small pelagic fish, Sardinella aurita, in the western Mediterranean. Glob Change Biol 12:2209–2219

Salen-Picard C, Darnaude AM, Arlhac D, Harmelin-Vivien ML (2002)
Fluctuations of macrobenthic populations: a link between climate-driven river run-off and sole fishery yields in the Gulf of Lions. Oecologia 133:380–388

Siokou-Frangou I, Christaki U, Mazzocchi MG, Montresor M, Ribera d'Alcalá M, Vaqué D, Zingone A (2010)
Plankton in the open Mediterranean Sea: a review. Biogeosciences 7:1543–1586

Steinacher M, Joos F, Frolicher TL, Bopp L, Cadule P, Cocco V, Doney SC, Gehlen M, Lindsay K, Moore JK, others (2010)
Projected 21st century decrease in marine productivity: a multi-model analysis. Biogeosciences 7

Stergiou KI, Somarakis S, Triantafyllou G, Tsiaras KP, Giannoulaki M, Petihakis G, Machias A, Tsikliras AC (2015)
Trends in productivity and biomass yields in the Mediterranean Sea Large Marine Ecosystem during climate change. Environ Dev

The MerMex Group, Madron XD de, Guieu C, Sempéré R, Conan P, Cossa D, D'Ortenzio F, Estournel C, Gazeau F, Rabouille C, others (2011)
Marine ecosystems' responses to climatic and anthropogenic forcings in the Mediterranean. Prog Oceanogr 91:97–166

Tunin-Ley A, Ibañez F, Labat J-P, Zingone A, Lemée R (2009)
Phytoplankton biodiversity and NW Mediterranean Sea warming: changes in the dinoflagellate genus Ceratium in the 20th century. Mar Ecol Prog Ser 375:85–99

Sub-chapter 2.1.3

Climate change impacts on marine resources

From individual to ecosystem responses

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Temperature has a major direct effect on the physiology, growth, reproduction, recruitment and behavior of poikilothermic organisms such as fish. It affects many physiological processes ranging from damaging proteins to disrupting organ function. Environmental changes, especially climate warming, may thus strongly influence the abundance and biogeography of fish through species-specific physiological thresholds of temperature tolerance, or through responses to changes in other trophic levels (Perry et al. 2005, Sabates et al. 2006, Rijnsdorp et al. 2009). Organisms tend to adapt to local environmental temperatures, with optimal physiological responses matching temperatures that are close to the environmental average (Hoegh-Guldberg & Bruno 2010). In this context, shifts in the spatial distribution range of marine organisms are among the most perceptible consequences of climate change at the world scale, with potentially significant impacts on commercial fisheries (Perry et al. 2005), on food webs and ecosystem functioning (Doney et al. 2012, Albouy et al. 2014), and on biodiversity as a whole (Harley 2011, Bellard et al. 2012).

The warming of the Mediterranean Sea affects the fitness of marine biota as already shown by records of changes in abundance, survival and fertility, phenology and species migration (Marbà et al. 2015). Population abundance and survival are the biological variables are the most frequently reported impacts of Mediterranean warming, followed by migration of native and introduced species (Marbà et al. 2015). However, the sensitivity of Mediterranean biota to warming varies across taxonomic groups (Marbà et al. 2015), from primary producers to high trophic levels, with possible synergistic effects with other anthropogenic impacts such as high exploitation (Harley et al. 2006). In this chapter, we use examples to analyze the expected impacts of climate change on marine organisms in the Mediterranean Sea, with a focus on fish, and to investigate possible responses from individual to ecosystem level. It is important to bear in mind that in the Mediterranean Sea, the effects of climate change occur in parallel with other human-driven effects such as overfishing, pollution, and habitat degradation (Coll et al. 2010), and can have cumulative effects, frequently of synergistic nature (Calvo et al. 2011).

Climate change affects functional traits of fishes

Several studies have shown that changes in temperature and in ocean chemistry affect the growth, reproduction and physiology of marine organisms (Pörtner & Knust 2007, Sumaila et al. 2011). It was recently shown that fish body size may be reduced due to climate change, especially in response to warming, reduction in oxygen, and resource availability (Daufresne et al. 2009, Sheridan & Bickford 2011, Cheung et al. 2013) (Figure 1). In a meta-analysis of the effect of climate on fish body size, Daufresne et al. (2009) showed a significant increase in the proportion of small-sized species and young age classes and a decrease in size-at-age, in accordance with Bergmann's rule concerning temperature vs. size. According to the IPCC (Intergovernmental Panel on Climate Change), oceans are projected to become warmer and less oxygenated (IPCC 2014). As a consequence, in the Mediterranean Sea, the average maximum body weight of fish is expected to shrink by 4% to 49% from 2000 to 2050 (Cheung et al. 2013).

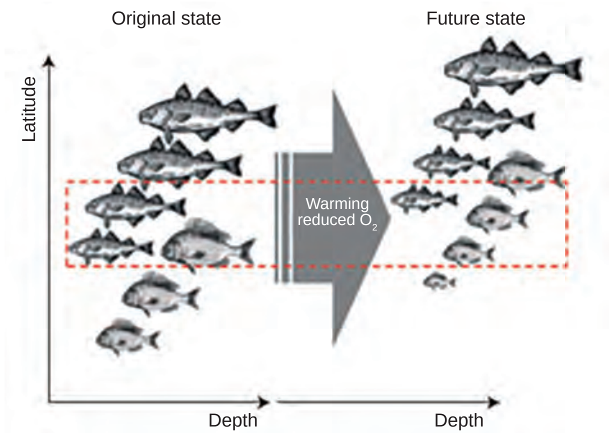


Figure 1
Expected changes in body size at individual and assemblage levels. According to Cheung et al. (2013), due to the invasion/increased abundance of smaller-bodied species and local extinction/decreased abundance of larger-bodied species, the mean maximum body weight is expected to decrease at the assemblage level, with a vertical distribution shift of species.

Despite relative local heterogeneity, the projected decrease in fish size is largest in the western Mediterranean (20%-49%). In contrast, the mean assemblage body weight is expected to increase in the Gulf of Lion likely due to the northward migration of large exploited species. However, interpreting global scale simulation results at a regional scale can be hazardous and more dedicated fine scale regional studies are needed. Nonetheless, changes in assemblage-level body size structure suggest that climate and ocean changes will cause dramatic modifications of food web dynamics (predator-prey interactions are strongly dependent on size as well as on food consumption rates), the natural mortality rate of fish populations (negatively correlated with maximum body weight) and size at maturity (positively correlated with maximum body weight) (Pauly 1980, Palomares & Pauly 1998, Cheung et al. 2013). Fishes in warmer waters are expected to have a smaller maximum body size and smaller size at first maturity with possible higher natural mortality rates (Sumaila et al. 2011). All these key population parameters determine population dynamics and productivity.

Sea warming changes fish distribution and associated assemblages

In the Mediterranean Sea, the increasing abundance of thermophilic biota can be described by two major processes of change involving both indigenous and non-indigenous species (Boero et al. 2008): the northward extension and enhancement of native thermophilic species (i.e. meridionalization) and the increasing introductions and range extension of thermophilic non-indigenous species (i.e. tropicalization).

Due to seawater warming, numerous native thermophilic species have greatly extended their distribution range and are becoming more abundant especially in the northwestern part of the basin (box 1). One of the best studied case is the ornate wrasse *Thalassoma pavo*, a species once confined to the southern parts of the Mediterranean Sea, which penetrated into the Ligurian Sea in the 1980s, where it is now able to reproduce, thereby becoming "naturalized" (Sara et al. 2005, Bianchi 2007). *Sparisoma cretense*, a parrotfish species, is considered to be a clear indicator of meridionalization because of its increasing abundance over the last two decades (Azzurro et al. 2011). Originally, this parrotfish was thought to be common in the strait of Sicily (i.e. chiefly distributed along the southern and eastern coasts) but absent from northern Sicily. Several recent studies confirmed the increase in the populations of *Sparisoma cretense* over the last 10 years. Currently, the species is well established along the coast of France and in the central and northern Adriatic (Azzurro et al. 2011).

Box 1
The effects of climate change on the Catalan Sea ecosystem

The Catalan Sea represents a portion of the Western Mediterranean region and is located between the Balearic Islands to the east and the eastern Iberian Peninsula to the west (Figure B1a).

The region has shown clear signs of climate change, including an increase in sea surface temperature (SST) of approximately 1.1 °C in the last 40 years (Figure B1b), an increase in salinization of the intermediate and deep waters, a rise in sea level over the last century, and strengthening of seasonal stratification in summer (Calvo et al. 2011). A decrease in rainfall and wind, warmer surface waters and hence a longer stratification period is foreseen (Calvo et al. 2011).

The effects of climate change can be clearly seen in all the compartments of the marine ecosystem in the region. There has been an increase in thermophilic species, which are favored by increasing temperatures, in contrast to temperate species. These increases include algal, invertebrate and vertebrate species. For example, an increase in the SST has been linked with the expansion of round sardinella (*Sardinella aurita*) (Sabates et al. 2006), and with the decline of sardine (*Sardina pilchardus*) (Palomera et al. 2007). Declines in freshwater inputs and winds may have had an impact on pelagic fish species (Lloret et al. 2004).

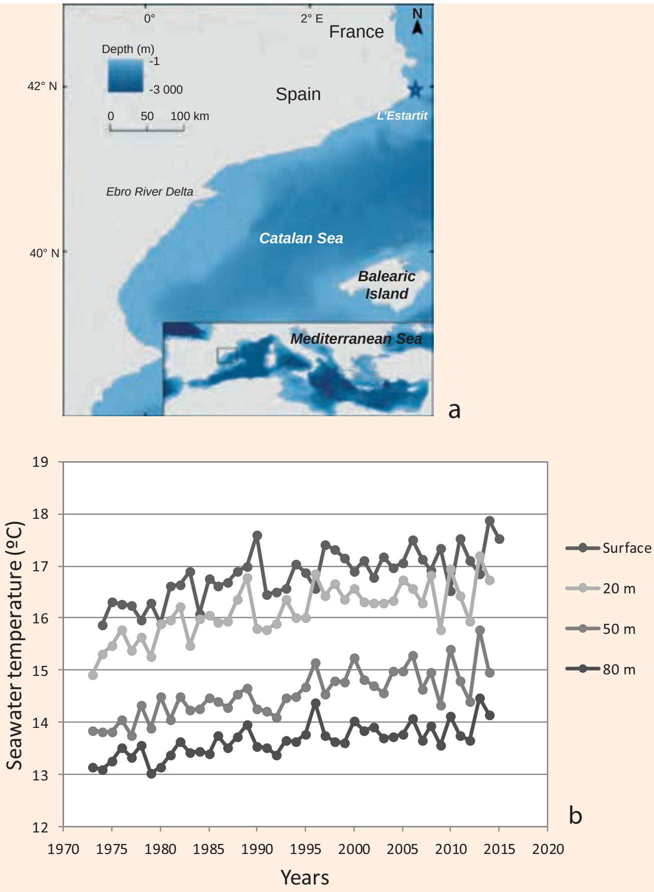


Figure B1

a) The Catalan Sea region in the western Mediterranean Sea. Star: Estartit oceanographic station.
b) Evolution of the mean annual sea temperature at Estartit station from 1974 to 2015.
The curves present data at the surface, 20, 50 and 80 m depth, respectively.
Data source: Josep Pasqual in collaboration with the Institut de Ciències del Mar (ICM-CSIC), Barcelona, and Parc Natural del Montgrí, Les Illes Medes i el Baix Ter.

Mass mortality events of sessile invertebrate species have been linked with anomalous warm waters in specific hot years with longer stratification periods (Coma et al. 2009). Significant mortality episodes have been documented for gorgonian and sponge species, which are long-lived and slow growing vulnerable organisms (Garrabou et al. 2009). In addition, the capacity of the ocean to absorb atmospheric CO2 has been linked with increased acidification of the seawater, which can have negative impacts on many pelagic and benthic organisms with calcareous body parts such as corals, mussels, pteropods and coccolithophores (CIESM 2008).

The strengthening of the stratification period of the water column has been linked with changes in primary productivity and with the increase in the smallest phytoplankton species (Calvo et al. 2011). The longer stratification period and the high SST has also been linked with more frequent and abundant proliferations of gelatinous species, including jellyfish (Molinero et al. 2008).

These effects have had marked impacts on food webs in the Catalan Sea, which occur simultaneously with other coastal anthropogenic effects such as overfishing, habitat degradation and pollution (Coll et al. 2010) and can have synergistic impacts (Calvo et al. 2011).

The barracuda *Sphyraena viridensis* and the dolphinfish *Coryphaena hippurus* are two other good examples of the meridionalization process. These two top predator species have greatly extended their natural distribution range over the last 30 years (Lejeusne et al. 2010, Azzurro et al. 2011). Due to the range expansion of these species, besides changes in fish species richness, a recent study predicts that under climate change the mean body size of fish assemblages will increase on the continental shelf with potential effects on trophic functioning (Albouy et al. 2013). However, this study only took distribution range shifts into account, but not the climate-induced physiological changes.

Most of the non-indigenous species in the Mediterranean Sea are thermophilic species originating from the tropical Indo-Pacific region (i.e. Lessespsian migrations). In total, more than 900 alien species have been recorded (Zenetos et al. 2012) and the introduction of warm and tropical alien species has been exacerbated by the warming of the eastern Mediterranean (Raitsos et al. 2010), which creates maritime corridors (box 2). Since 2011, the number of alien macrophyte, mollusk and polychaetes species has increased by two to three species per year, by three to four species per year of crustaceans, and by six species per year of fish (Zenetos et al. 2012). At the same time, the diversity of alien species is largely underestimated due to a "shifting baseline syndrome" (i.e. cultural traditions tend to embrace newly introduced organisms progressively, by attributing to them the values originally associated with native species. The new species are therefore included in the assumed normal or desirable state of a natural system) (Clavero 2014). Thus, the tropicalization of the Mediterranean Sea (i.e. the increased occurrence of warm-water biota), particularly in the eastern Mediterranean, seems inevitable (Bianchi & Morri 2003, Ben Rais Lasram & Mouillot 2009). This phenomenon may locally and temporally increase species richness but several studies demonstrated that warming and aquatic invasions can lead to the decline and even collapse of several marine populations (Bianchi & Morri 2003, Occhipinti-Ambrogi 2007). In the short to medium term, invasive aliens may cause major shifts in community composition and lead to a significant loss in Mediterranean biodiversity and, possibly, to cascade effects on food webs (Galil 2000, Streftaris & Zenetos 2006, Molnar et al. 2008, Lejeusne et al. 2010, Zenetos et al. 2012). Evidence for geographical extension is particularly abundant for species coming from the Red Sea (Azzurro et al. 2008). For instance, the bluespotted cornetfish, *Fistularia commersonii*, which was observed for the first time in 2000 in Israel, was soon afterwards recorded all over the eastern and central Mediterranean coasts, up to the proximity of the Strait of Gibraltar (Golani 2000, Bilecenoglu et al. 2002, Pais et al. 2007, Azzurro et al. 2008, Dulčić et al. 2008). Today, it is one of the most successful invaders of the Mediterranean Sea and can have strong potential impacts on food web dynamics by preying upon commercially important fish such as the bogue (*Boops boops*) and the red mullet (*Mullus barbatus*) and by competing for food with native piscivorous fish (Kalogirou et al. 2007).

Box 2
Climate change and exotic fish invasions

Does climate play a key role in the dispersal success of exotic fish species?
The invasion success of some exotic species has been shown to be positively related to the match between native and colonized environments (Duncan et al. 2001). In particular, a species that is introduced in similar thermal conditions is more likely to establish successfully. This is called the "climate match" hypothesis, and it appears to play a key role in the invasion rate in the Mediterranean Sea. The greater dispersal success of Lessepsian species was associated with thermal conditions prior to 1980 (Ben Rais Lasram et al. 2008); crossing the Suez Canal does not necessarily guarantee successful invasion and widespread dispersal of fish populations.

Is the Mediterranean Sea experiencing increasing southern invasions?
Many species have shifted their distribution area by extending northward as a response to climate warming (Cheung et al. 2009). Southern invasions are an indicator of the impact of climate change on biodiversity. Lessepsian species migrating through the Suez Canal inevitably originate from more southern latitudes than the Mediterranean Sea, so their dynamics can be easily correlated to climate warming.

In contrast to the Lessepsian species, Atlantic species do not come necessarily from lower latitudes. Their introduction rate assessed by the number of species that migrated to the Mediterranean Sea, does not therefore indicate whether southern migrations are accelerating during a period of global warming. The original latitude of introduced Atlantic species rather than their abundance can be used as an indicator of the rate of southern invasions. Ben Rais Lasram and Mouillot (2009) showed that the Lessepsian invasion rate and the latitude of Atlantic species entering the Mediterranean Sea both significantly correlated to the Mediterranean SST, positively and negatively respectively. These analyses suggest that southern invasions from the Red Sea and from the Atlantic accelerate with global warming (Figure B2).

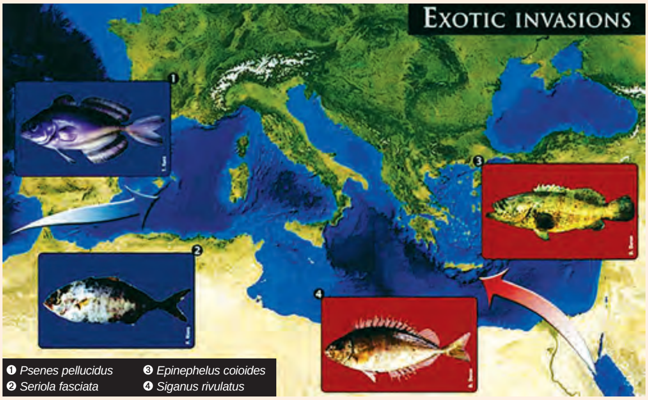


Figure B2
The Mediterranean Sea under southern invasions.

Is there an increasing spatial overlap between exotic and endemic Mediterranean fish fauna?
Spatial overlap is an indicator of the intensity of interaction between species and the potential hazards coming from exotic species. By comparing the distributions of endemic and exotic species, it appeared that between 1980 and 2006, major exotic species have moved northwards in the Mediterranean Sea by approximately 300 km (Ben Rais Lasram and Mouillot 2009). After the 1980s, some exotic fish species reached the coldest areas of the Mediterranean Sea (western basin), for example the Adriatic Sea, which is a major hotspot of endemism. The number of exotic species in the Mediterranean is now 98.4% higher than it was 20 years ago (Ben Rais Lasram and Mouillot 2009).

What can we learn from the spread of Lessepsian species?
Species move to keep pace with changing climates, but can they move at the required speed? The spread rates of native species may underestimate how fast species can move. The exceptional spread rates of Lessepsian species can give upper estimates to the rate at which native species could spread to colonize suitable habitats under climate change. Hiddink et al. (2012) estimated that about 20% of Lessepsian species could not spread fast enough to keep pace with climate change in about 20% of the global seas, thus suggesting that climate change may lead to biodiversity loss.

Can we predict invasion risk in the Mediterranean Sea?
Species Distribution Models (SDM) have been used intensively to predict range shifts of marine species in the context of climate change (Cheung et al. 2009; Albouy et al. 2013). Parravicini et al. (2015) showed that Lessepsian fish species may spread far beyond their native niches and that SDMs do not predict their new distributions better than null models. This suggests that SDMs may underestimate the potential spread of Lessepsian species.

References

Albouy, C., Guilhaumon, F., Leprieur, F.,
Ben Rais Lasram, F., Somot, S., Aznar, R., Velez, L. (2013)
Projected climate change and the changing biogeography of coastal Mediterranean fishes. Journal of Biogeography, 40, 534-547.

Ben Rais Lasram, F., Tomasini, J.A.,
Guilhaumon, F., Romdhane, M.S., Do Chi, T., Mouillot, D. (2008)
Ecological correlates of dispersal success of Lessepsian fishes. Marine Ecology Progress Series, 363, 273-286.

Ben Rais Lasram, F., Mouillot, D. (2009)
Increasing southern invasion enhances congruence between endemic and exotic Mediterranean fish fauna. Biological Invasions, 11, 697-711.

Cheung, W.W., Lam, V.W., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D. (2009)
Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 10, 235-251.

Duncan, R.P., Bomford, M., Forsyth, D.M., Conibear, L. (2001)
High predictability in introduction outcomes and the geographical range size of introduced Australian birds: a role for climate. Journal of Animal Ecology, 70, 621-632.

Hiddink, J., Ben Rais Lasram, F., Cantrill, J., Davies, A. (2012)
Keeping pace with climate change: what can we learn from the spread of Lessepsian migrants? Global Change Biology, 18, 2161–2172.

Parravicini, V., Azzurro, E., Michel, Kulbicki M., Belmaker, J. (2015)
Niche shift can impair the ability to predict invasion risk in the marine realm: an illustration using Mediterranean fish invaders. Ecology Letters, 18(3), 246-253.

In the Mediterranean Sea, the history of the invasive of the rabbitfish species *Siganus luridus* and *Siganus rivulatus*, two herbivorous fishes, is probably the best example of impacts caused by invasive alien species on the whole ecosystem, from primary producers to top predators (Galil 2007). For instance, a survey conducted along around 1,000 km of coastline (temperate reefs) in the eastern Mediterranean demonstrated that, in regions with abundant rabbitfish, canopy algae were 65% less abundant, there was a 60% reduction in overall benthic biomass (algae and invertebrates) and a 40% reduction in total species richness (Vergés et al. 2014) (Figure 2).

Therefore, climate warming produces "winners" and "losers" among fish assemblages. Winner species may enjoy higher survival, growth and reproduction

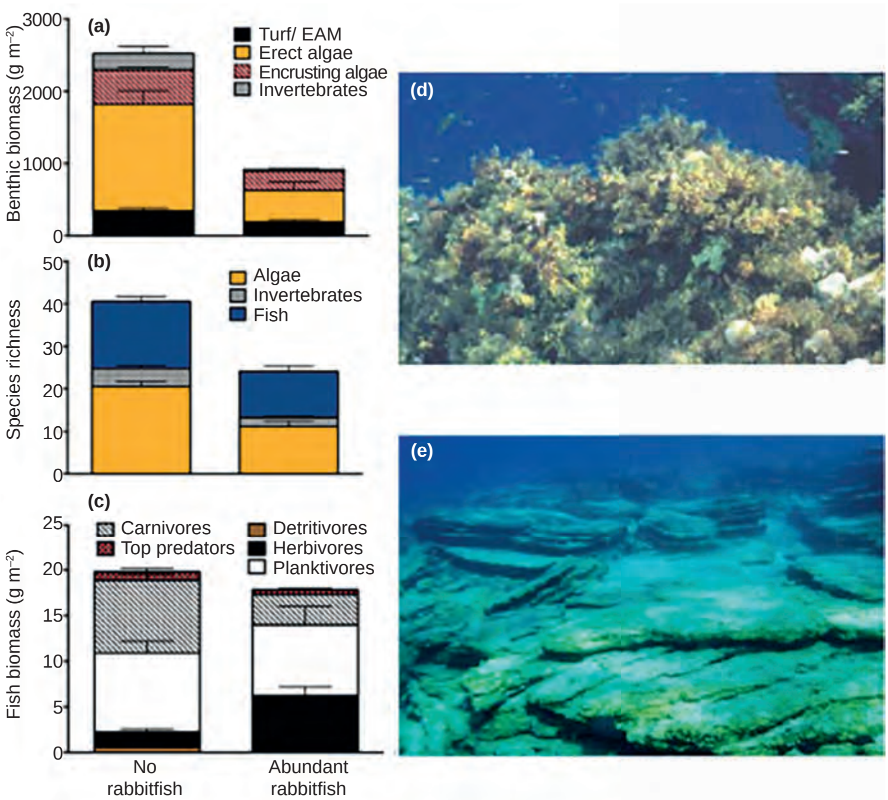


Figure 2

Benthic biomass and species richness patterns in Mediterranean regions with or without rabbitfish. (a) Total biomass of dominant benthic organisms; (b) Total species richness of algae, invertebrates and fish; (c) Fish biomass of major trophic groups; (d) Photo of a Cystoseira spp. forest where tropical rabbitfishes are absent; (e) Barren area typical of the eastern Mediterranean sites where range-shifting tropical rabbitfish are abundant.

From Vergés et al. (2014).

rates in a changing Mediterranean while for losers, more stressful conditions may lead to higher mortality rates, reduced growth, smaller size and reduced reproduction (Doney et al. 2012). For winners, climate warming is synonymous with geographic range extensions (e.g. ornate wrasse has increased its range by about 1,000 km in recent decades) while for others it is synonymous with range contraction. This is particularly true for cold-water species. Projecting the potential future distributions of 75 Mediterranean endemic fish species based on a global warming scenario implemented with the OPAMED8 model and Ecological Niche Models (ENMs), Ben Rais Lasram et al. (2010) showed that, by 2041-2060, 25 species would qualify for the IUCN (International Union for the Conservation of Nature and Natural Resources) Red List and six species would become extinct (for example, starry sturgeon *Acipenser stellatus* and European sturgeon *Huso huso*). For "narrow" endemic species (i.e. endemic species found strictly in the Mediterranean Sea that do not reach the neighboring Atlantic Ocean and Black Sea) their extinction would be irreversible.

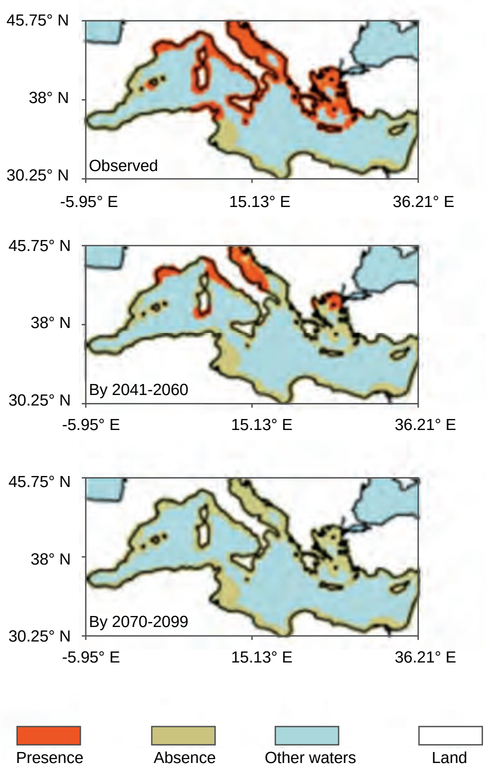


Figure 3
Observed distribution areas of the endemic Mediterranean fish Gobius geniporus *(1980s, top) and projected potential future thermal habitats (by 2040-2060 middle; 2070-2099, bottom). The "cul-de-sac" effect is clearly visible for this species. From Ben Rais Lasram et al. (2010).*

Box 3

Climate change impacts on the Gulf of Gabes ecosystem

The Gulf of Gabes is located in southern Tunisia, at the junction of the eastern and the western basins. It is the second largest continental shelf in the Mediterranean Sea (36 000 km²) after the Adriatic Sea. The seabed is covered by an extensive *Posidonia oceanica* meadow, the largest in the Mediterranean Sea and one of the largest in the world (Batisse & Jeudy de Grissac 1998). The meadow is a spawning ground for marine organisms and an important nursery for juvenile fish of the region (Hattour et al. 1995), it hosts 247 of the 327 marine fish species of Tunisia of which 44 species have only been recorded in the Gulf of Gabes (Bradai et al. 2004).

The high diversity and production of the Gulf of Gabes and its accessibility (very shallow slope of the continental shelf, soft bottom suitable for bottom trawling) have contributed to a considerable increase in the number of fishing fleets. The Gulf of Gabes has become the main fishing area in Tunisia.

Like the rest of the Mediterranean Sea, the Gulf of Gabes has been undergoing warming: sea surface temperature and salinity have increased by respectively 2 °C and 0.5 over the last 100 years. The warming of the surface layer has resulted in intensification of the thermohaline circulation, and variations in water density have led to a rise in sea level of 1 cm over the last century (Ben Mahmoud & Harzallah 2009).

Climate change has likely caused the observed shifts of the distribution areas of some fish species usually encountered in northern Tunisia: *Brama brama*, *Trachinotus ovatus*, *Ariosoma balearicum* and *Oblada melanura* currently inhabit the Gulf of Gabes (Bradai & Capapé 2001). In parallel, the colonization of the waters by some exotic thermophilic species has also been attributed to climate change (e.g. Missaoui & Zaouali 1995, Bradai et al. 2004). The fish species exploited in this coastal region of Tunisia are also strongly impacted by climate change. Species distribution models that include habitat selection processes and the physiological temperature tolerance of exploited marine species, project a decline in species prevalence by an average of 56% by the end of the 21st century (figure B3). The models suggest that the magnitude of the changes caused by climate will be greater than that caused by the loss of the *Posidonia* meadow. This suggests that climate, and particularly temperature, is a key driver of marine species distribution even at a small spatial scale like the Gulf of Gabes (Hattab et al. 2014).

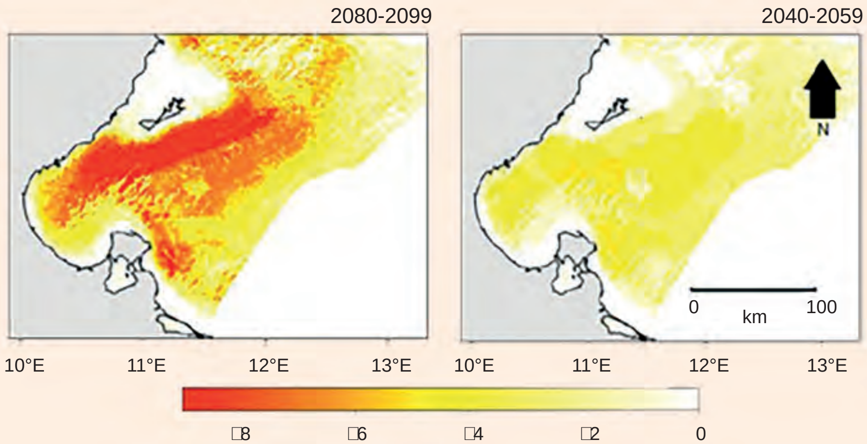


Figure B3 Differences between species richness predicted under current climate conditions (1982-2009, baseline scenario) and values predicted under a mid-century climate scenario (2040-2059, right panel) and an end-century climate scenario (2080-2099, left panel) (Hattab et al. 2014).

In addition, the ENMs showed that by the middle of the 21st century, the coldest areas of the Mediterranean Sea (i.e. Adriatic Sea and Gulf of Lion) would act as a refuge for cold water species. However, by the end of the century, those areas are projected to become a "cul-de-sac" that would drive these species towards extinction. By 2041-2060, 31 species were projected to extend their geographic range, whereas the geographic range of 44 species was projected to contract (e.g. the slender goby *Gobius geniporus*) (Figure 3). The Gulf of Gabes, one of the largest continental shelves in the Mediterranean Sea and a major area of fishing activities is also undergoing a warming phase with marked consequences for the distribution of exploited species (box 3).

Overall, 25% of the Mediterranean continental shelf is predicted to be subject to a total modification of endemic assemblages by the end of the 21st century (Ben Rais Lasram et al. 2010). This projection are likely to be conservative. A more recent study based on the SRES IPCC A2 ("*business as usual*") scenario suggested that at the end of the century, 54 species (mainly gobiidae) will have lost their climatically suitable habitat (Albouy et al. 2013); species richness is predicted to decrease across 70.4% of the continental shelf area (Figure 4) and mean fish body size to increase over 74.8% of the area. Thus, by reducing the geographic range size of small-bodied species, climate change may contribute to the loss of small and low trophic level fishes, which may have ecosystem-wide impacts (Albouy et al. 2013). This last projection disagrees with projections of Cheung et al. (2013) who rather suggested that maximum body weight will decrease at the scale of the Mediterranean basin. However, contrary to Cheung et al. (2013), Albouy et al. (2013) only considered distribution shifts caused by climate warming and not the resulting physiological changes, thus introducing a source of structural uncertainty.

For two exploited species, the allis shad *Alosa alosa* and *Microchirus azevian*, projections highlight possible extinction strengthened by exploitation by fisheries. Other commercially important species such as the European flounder (*Platichtys flesus*), the Danube sturgeon (*Acipenser gueldenstaedtii*) and the starry sturgeon (*Acipenser stellatus*) are likely to be affected by climatic change both in fresh-water and marine habitats. Because marine species track their climate niches from the different parts of the Mediterranean, Albouy et al. (2012) showed that most of the Aegean and Adriatic Sea will be subject to a high rate of species replacement and an increase in species richness by the mid-21st century, as a result of a northward and eastward shift in species ranges. However, by the end of 21st century, with increasing temperature, these same areas, along with the Gulf of Lion, are expected to undergo a net decrease in species richness. The "cul-de-sac effect" described by Ben Rais Lasram (2010) suggests that for many fish species, the loss of their thermal niche may not be compensated for by the arrival of other species from the south (Albouy et al. 2012).

Beyond consequences at the level of individual species, changes in fish distributional range may result in dramatic changes in the structure of the community and of the food web, with potential consequences for ecosystem

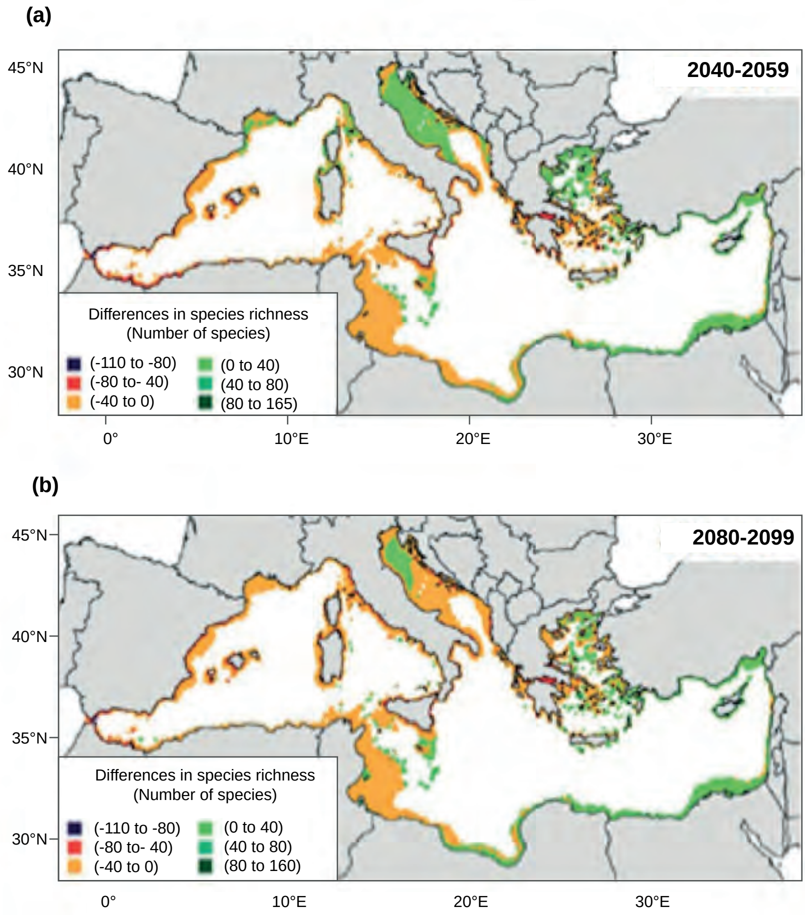


Figure 4
Differences in species richness between a baseline scenario (1961-1980) and two time periods (a: 2040-2059 ; b: 2080-2099) predicted for the continental shelf of the Mediterranean Sea (all fish species of the continental shelf are represented) according to the SRES IPCC A2 scenario. Adapted from Albouy et al. (2013).

functioning. To capture this phenonemon, Albouy et al. (2014) built a trophic size-based model coupled with current and projected future distributions of Mediterranean fish species. These authors showed that by 2080-2099, 54 fish species among 256 coastal endemic and native species included in the model, would disappear from the Mediterranean continental shelf, resulting in a widespread decrease in local species richness. These disappearances will likely be accompanied by a decrease in the number of trophic links between the fish species (in the order of 70%) of the continental shelf. Moreover, fish prey abundance is expected to be lower at the end of the 21st century compared to the baseline period (1961-1980), which may further increase the probability of extinction of fish species (Albouy et al. 2014). Projecting species distribution in the future is a simple way to address the effects of climate change on fish communities, but ignores changes in substrates and in physical habitats, for example. The potential impact of climate change on some essential habitats could severely affect the life cycle and the spatial distribution or redistribution of numerous marine species whether indigenous or not (box 4).

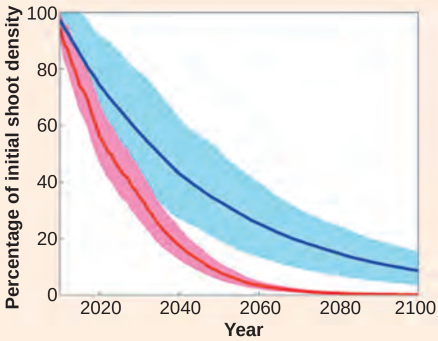
Climate Change affects migration patterns and phenologies

Climate influences a variety of ecological processes such as migration patterns and phenologies (Stenseth et al. 2002). Several studies have shown that climate driven changes in temperature modify or will modify the phenology of annual migrations to feeding and/or spawning grounds (e.g. Sims et al. 2004, Huse & Ellingsen 2008, Rijnsdorp et al. 2009). For instance, based on a review of published data in the northeast Atlantic, Rijnsdorp et al. (2009) reported that pelagic species exhibit clear changes in seasonal migration related to climate-induced changes in secondary production. In the Mediterranean Sea, climate change and variability are critical to the seasonal spawning and migration behaviors of the Atlantic Bluefin tuna *Thunnus thynnus*, a large migratory fish species of high economic and ecological importance (Ravier & Fromentin 2004, Muhling et al. 2011). Indeed, it has been suggested that water temperature triggers the spawning activity of the species (Muhling et al. 2011). If the Mediterranean Sea warms up earlier in the year, spawning may also start earlier, with a potential mismatch between favorable feeding conditions and tuna reproduction. In addition, the migration patterns and spatial distribution of highly mobile large pelagic fish, such as bluefin tuna, may be indirectly altered by climate-induced changes in prey abundance (Walther et al. 2002). Historical data from the Mediterranean Sea suggest that bluefin tuna may change their migration routes and spawning behaviors in association with long-term fluctuations in temperature (Ravier & Fromentin 2004). As a result, the migration routes of bluefin tuna may vary and adapt to climate change and potentially explore new spawning grounds in the Atlantic. However, some authors have also warned that overfishing has likely reduced the genetic diversity of the bluefin tuna, so its ability to adapt to climate change may also be affected (Perry et al. 2010, Planque et al. 2010, Muhling et al. 2011). Moreover, the energy cost and potential reduced fitness resulting from adaptation to a changing climate may reduce the surplus production of exploited stocks and make them more vulnerable to previously sustainable fishing levels (Brander 2010). This assumption applies to all exploited fish populations that experience high and prolonged fishing mortality and consequently a selective pressure of several alleles and genotypes. In fact, the loss of sub-populations may reduce the ability of marine species to adapt to climate change (Brander

Box 4

Climate change will impact essential fish habitats

Climate change reduces habitat complexity and has likely the most pronounced influence on habitat-forming species such as seagrass (Hoegh-Guldberg & Bruno 2010). A recent study projected the trajectory of *Posidonia oceanica* meadows under expected sea warming in the western Mediterranean over the 21st century and concluded that warming could lead to the functional extinction of *P. oceanica* meadows by the middle of this century even under a low greenhouse-gas emissions scenario (Jordà et al. 2012) (Figure B4).



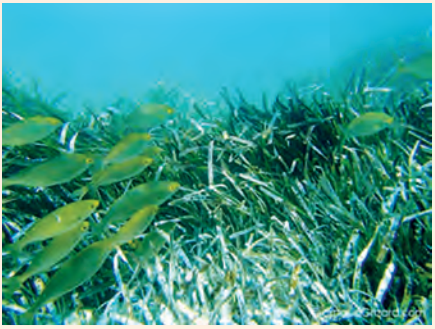


Figure B4
***Left*: percentage of P. oceanica shoot density in the twenty-first century. The pink line represents the projected percentage of shoot density under warming and local impacts, and the blue line represents the projected trend in the absence of warming. From Jordà et al. (2012). *Right*: photo of P. oceanica. Source www.arnaudgrizard.com.**

Given the importance of the functional role of seagrass meadows in the ecosystem (as an essential habitat for commercially and recreationally important fishery species, coastal protection from erosion, as a food source for megaherbivores such as sea turtles, nutrient recycling, etc.), the degradation of this key habitat may have dramatic consequences for regional biodiversity, food web dynamics and *de facto* for human welfare (Beck et al. 2001, Orth et al. 2006, Waycott et al. 2009, Jordà et al. 2012). In addition, Hattab et al. (2014) showed that the habitat loss of *P. oceanica* in the Gulf of Gabes, replaced by muddy sand, combined with climate change, triggered a high level of species replacement and a significant reduction in the geographical range of several species including the bluespotted seabream *Pagrus caeruleostictus*, the speckled shrimp *Metapenaeus Monoceros* and the brown comber *Serranus hepatus*, and that these species might be replaced by other commercial species such as the black goby (*Gobius niger*), the European hake (*Merluccius merluccius*), and the musky octopus (*Eledone moschata*) (Hattab, et al. 2014). Organisms typically respond to climate change by shifting their biogeographic ranges to maintain their thermal regime (Parmesan & Yohe 2003). However, a recent analysis of the velocity of climate change, as the rate of poleward migration of isotherms with climate change, identified the Mediterranean Sea as a region of concern because the northward displacement of the biogeographic ranges of endemic species, such as *P. oceanica*, is bounded by the presence of the European continent (Burrows et al. 2011).

In addition to sea warming, ocean acidification (OA) is considered as a major threat to the marine environment in the coming years. Calcifying organisms can be affected by increased seawater acidification, which both reduces the growth of calcareous skeletons and tends to dissolve them (Bramanti et al. 2013). Habitat-forming species such as *Lithophyllum cabiochae* (a crustose coralline alga which constitutes marl beds) could be severely affected by OA. As marl beds are spatially complex habitats that provide shelter for numerous species and trophic groups (Barbera et al. 2003), OA could have major consequences for the biodiversity and biogeochemistry of coralligenous communities (Martin & Gattuso 2009).

2010, Planque et al. 2010). By influencing food abundance and age structure, climate and fishing may also have significant effects on migration route fidelity, population resilience, and colonization of new habitats (Perry et al. 2010).

With this synthesis, we highlight the observed and potential consequences of climate change at different levels, from the individual to the ecosystem level. Climate change is expected to affect the physiology of individuals with consequences for community assemblages and population dynamics. Meridionalization and tropicalization processes have already taken place but appear to have accelerated in recent years with dramatic consequences for the Mediterranean biodiversity in the medium and long term. For several species, in particular those of commercial interest, climate change is expected to modify migration patterns and periodicities with consequences for population dynamics and fisheries management. All these changes are shaping a different Mediterranean Sea in which living resources and human activities will need to adapt in a sustainable way.

References

Albouy C, Guilhaumon F, Araújo MB, Mouillot D, Leprieur F (2012)
Combining projected changes in species richness and composition reveals climate change impacts on coastal Mediterranean fish assemblages.
Glob Change Biol 18:2995–3003.

Albouy C, Guilhaumon F, Leprieur F, Ben rais Lasram F, Somot S, Aznar R, Velez L, Le Loc'h F, Mouillot D (2013)
Projected climate change and the changing biogeography of coastal Mediterranean fishes.
J Biogeogr 40:534–547.

Albouy C, Velez L, Coll M, Colloca F, Le Loc'h F, Mouillot D, Gravel D (2014)
From projected species distribution to food-web structure under climate change.
Glob Change Biol 20:730–741.

Azzurro E, Commission Internationale pour l'Exploration Scientifique de la Mer Mediterranee- CIESM M, Briand F (2008)
The advance of thermophilic fishes in the Mediterranean sea: overview and methodological questions.
In: CIESM workshop monographs.
CIESM, Monaco, p 39–46.

Azzurro E, Moschella P, Maynou F (2011)
Tracking signals of change in Mediterranean fish diversity based on local ecological knowledge.
PLoS One 6:e24885.

Barbera C, Bordehore C, Borg JA, Glémarec M, Grall J, Hall-Spencer JM, De La Huz CH, Lanfranco E, Lastra M, Moore PG, others (2003)
Conservation and management of northeast Atlantic and Mediterranean maerl beds. Aquat Conserv Mar Freshw Ecosyst 13:S65–S76.

Batisse A, Jeudy de Grissac A (1998)
A global representative system of marine protected areas. Volume 1; marine region 3: Mediterranean in www.environment.gov.au/library/pubs /mpa/03medit.html. 33pp.

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, Halpern B, Hays CG, Hoshino K, Minello TJ, others (2001)
The Identification, Conservation, and Management of Estuarine and Marine Nurseries for Fish and Invertebrates A better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve

conservation and management of these areas. Bioscience 51:633–641.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012)
Impacts of climate change on the future of biodiversity. Ecol Lett 15:365–377.

Ben Mahmoud R, Harzallah A (2009)
Effet des changements climatique sur la température et la salinité des eaux tunisiennes. Mémoire de master. Institut national des Sciences et Technologies de la mer Salammbô, Ecole nationale d'ingénieurs de Tunis. Tunisie. 51pp.

Ben Rais Lasram F, Guilhaumon F, Albouy C, Somot S, Thuiller W, Mouillot D (2010)
The Mediterranean Sea as a "cul-de-sac"for endemic fishes facing climate change. Glob Change Biol 16:3233–3245.

Ben Rais Lasram F, Mouillot D (2009)
Increasing southern invasion enhances congruence between endemic and exotic Mediterranean fish fauna. Biol Invasions 11:697–711.

Bianchi CN (2007)
Biodiversity issues for the forthcoming tropical Mediterranean Sea. In: Biodiversity in Enclosed Seas and Artificial Marine Habitats. Springer, p 7–21.

Bianchi CN, Morri C (2003)
Global sea warming and" tropicalization" of the Mediterranean Sea: biogeographic and ecological aspects. Biogeographia 24:319–328.

Bilecenoglu M, Taskavak E, Kunt KB (2002)
Range extension of three lessepsian migrant fish (Fistularia commersoni, Sphyraena flavicauda, Lagocephalus suezensis) in the Mediterranean Sea. J Mar Biol Assoc UK 82:525–526.

Boero F, Féral J-P, Azzurro E, Cardin V, Riedel B, Despalatović M, Munda I, Moschella P, Zaouali J, Umani SF, others (2008)
Executive summary of CIESM Workshop 35 "Climate warming and related changes in Mediterranean marine biota." In: CIESM workshop monographs.p 5–21.

Bradai MN, Capapé C (2001)
Captures du diable de mer, Mobula mobular, dans le golfe de Gabès (Tunisie méridionale, Méditerranée centrale). Cybium 25:389–391.

Bradai MN, Quignard J-P, Bouain A, Jarboui O, Ouannes-Ghorbel A, Ben Abdallah L, Zaouali J, Ben Salem S (2004)
Ichtyofaune autochtone et exotique des côtes tunisiennes: recensement et biogéographie. Cybium 28:315–328.

Bramanti L, Movilla J, Guron M, Calvo E, Gori A, Dominguez-Carrió C, Grinyó J, Lopez-Sanz A, Martinez-Quintana A, Pelejero C, others (2013)
Detrimental effects of ocean acidification on the economically important Mediterranean red coral (Corallium rubrum). Glob Change Biol 19:1897–1908.

Brander K (2010)
Impacts of climate change on fisheries. J Mar Syst 79:389–402.

Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, Brander KM, Brown C, Bruno JF, Duarte CM, Halpern BS, others (2011)
The pace of shifting climate in marine and terrestrial ecosystems. Science 334:652–655.

Calvo EM, Simó R, Coma R, Ribes M, Pascual J, Sabatés A, Gili JM, Pelejero C (2011)
Effects of climate change on Mediterranean marine ecosystems: the case of the Catalan Sea.

Cheung WW, Sarmiento JL, Dunne J, Frölicher TL, Lam VW, Palomares MD, Watson R, Pauly D (2013)
Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat Clim Change 3:254–258.

CIESM (2008)
Impacts of acidification on biological, chemical and physical systems in the Mediterranean and Black Seas. In: Briand F (ed) CIESM workshop monograph 36. CIESM, Monaco.

Clavero M (2014)
Shifting baselines and the conservation of non-native species. Conserv Biol 28:1434–6.

Coll M, Piroddi C, Steenbeek J, Kaschner K, Ben Rias Lasram F,

Aguzzi J, Ballesteros E, Bianchi CN, Corbera J, Dailianis T, others (2010)
The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PloS One 5:e11842.

Coma R, Ribes M, Serrano E, Jiménez E, Salat J, Pascual J (2009)
Global warming-enhanced stratification and mass mortality events in the Mediterranean. Proc Natl Acad Sci 106:6176–6181.

Daufresne M, Lengfellner K, Sommer U (2009)
Global warming benefits the small in aquatic ecosystems. Proc Natl Acad Sci 106:12788–12793.

Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, Galindo HM, Grebmeier JM, Hollowed AB, Knowlton N, others (2012)
Climate change impacts on marine ecosystems. Mar Sci 4.

Dulčić J, Scordella G, Guidetti P (2008)
On the record of the Lessepsian migrant Fistularia commersonii (Rüppell, 1835) from the Adriatic Sea. J Appl Ichthyol 24:101–102.

Galil BS (2000)
A sea under siege–alien species in the Mediterranean. Biol Invasions 2:177–186.

Galil BS (2007)
Loss or gain? Invasive aliens and biodiversity in the Mediterranean Sea. Mar Pollut Bull 55:314–322.

Garrabou J, Coma R, Bensoussan N, Bally M, Chevaldonné P, Cigliano M, Díaz D, Harmelin J-G, Gambi MC, Kersting DK, others (2009)
Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. Glob Change Biol 15:1090–1103.

Golani D (2000)
First record of the bluespotted cornetfish from the Mediterranean Sea. J Fish Biol 56:1545–1547.

Harley CD (2011)
Climate change, keystone predation, and biodiversity loss. Science 334:1124–1127.

Harley CD, Randall Hughes A, Hultgren KM, Miner BG, Sorte CJ, Thornber CS, Rodriguez LF, Tomanek L, Williams SL (2006)
The impacts of climate change in coastal marine systems. Ecol Lett 9:228–241.

Hattab T, Albouy C, Ben Rais Lasram F, Somot S, Loc'h L, Leprieur F, others (2014)
Towards a better understanding of potential impacts of climate change on marine species distribution: a multiscale modelling approach. Glob Ecol Biogeogr 23:1417–1429.

Hattour A, Ben Mustapha K, Turki B, Mhetli M, Tritar B (1995)
L'écosystème du golfe de Gabès: dégradation de son couvert végétal et de sa pêcherie benthique. Rapp. Comm. Int. Mer. Médit 34: 33pp.

Hoegh-Guldberg O, Bruno JF (2010)
The impact of climate change on the world's marine ecosystems. Science 328:1523–1528.

Huse G, Ellingsen I (2008)
Capelin migrations and climate change–a modelling analysis. Clim Change 87:177–197.

Jordà G, Marbà N, Duarte CM (2012)
Mediterranean seagrass vulnerable to regional climate warming. Nat Clim Change 2:821–824.

Kalogirou S, Corsini M, Kondilatos G, Wennhage H akan (2007)
Diet of the invasive piscivorous fish Fistularia commersonii in a recently colonized area of the eastern Mediterranean. Biol Invasions 9:887–896.

Lejeusne C, Chevaldonné P, Pergent-Martini C, Boudouresque CF, Perez T (2010)
Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends Ecol Evol 25:250–260.

Lloret J, Palomera I, Salat J, Sole I (2004)
Impact of freshwater input and wind on landings of anchovy (Engraulis encrasicolus) and sardine (Sardina pilchardus) in shelf waters surrounding the Ebre (Ebro) River delta (north-western Mediterranean). Fish Oceanogr 13:102–110.

Marbà N, Jordà G, Agustí S, Girard C, Duarte CM (2015)
Footprints of climate change on Mediterranean Sea biota. Front Mar Sci.

Martin S, Gattuso J-P (2009)
Response of Mediterranean coralline algae to ocean acidification and elevated temperature. Glob Change Biol 15:2089–2100.

Missaoui H, Zaouali J (1995)
Apparition de nouveaux Crustacés dans les pêches crevettières du golfe de Gabès, Tunisie. Mar Life 5:27–34.

Molinero JC, Casini M, Buecher E (2008)
The influence of the Atlantic and regional climate variability on the long-term changes in gelatinous carnivore populations in the northwestern Mediterranean. Limnol Oceanogr 53:1456–1467.

Molnar JL, Gamboa RL, Revenga C, Spalding MD (2008)
Assessing the global threat of invasive species to marine biodiversity. Front Ecol Environ 6:485–492.

Muhling BA, Lee S-K, Lamkin JT, Liu Y (2011)
Predicting the effects of climate change on bluefin tuna (Thunnus thynnus) spawning habitat in the Gulf of Mexico. ICES J Mar Sci J Cons:fsr008.

Occhipinti-Ambrogi A (2007)
Global change and marine communities: alien species and climate change. Mar Pollut Bull 55:342–352.

Orth RJ, Carruthers TJ, Dennison WC, Duarte CM, Fourqurean JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Olyarnik S, others (2006)
A global crisis for seagrass ecosystems. Bioscience 56:987–996.

Pais A, Merella P, Follesa MC, Garippa G (2007)
Westward range expansion of the Lessepsian migrant Fistularia commersonii (Fistulariidae) in the Mediterranean Sea, with notes on its parasites. J Fish Biol 70:269–277.

Palomares MLD, Pauly D (1998)
Predicting food consumption of fish populations as functions of mortality, food type, morphometrics, temperature and salinity. Mar Freshw Res 49:447–453.

Palomera I, Olivar MP, Salat J, Sabatés A, Coll M, Garcia A, Morales-Nin B (2007)
Small pelagic fish in the NW Mediterranean Sea: an ecological review. Prog Oceanogr 74:377–396.

Parmesan C, Yohe G (2003)
A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37–42.

Pauly D (1980)
On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J Cons 39:175–192.

Perry RI, Cury P, Brander K, Jennings S, Möllmann C, Planque B (2010)
Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. J Mar Syst 79:427–435.

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005)
Climate change and distribution shifts in marine fishes. science 308:1912–1915.

Planque B, Fromentin J-M, Cury P, Drinkwater KF, Jennings S, Perry RI, Kifani S (2010)
How does fishing alter marine populations and ecosystems sensitivity to climate? J Mar Syst 79:403–417.

Pörtner HO, Knust R (2007)
Climate change affects marine fishes through the oxygen limitation of thermal tolerance. science 315:95–97.

Raitsos DE, Beaugrand G, Georgopoulos D, Zenetos A, Pancucci-Papadopoulou AM, Theocharis A, Papathanassiou E (2010)
Global climate change amplifies the entry of tropical species into the Eastern Mediterranean Sea. Limnol Oceanogr 55:1478–1484.

Ravier C, Fromentin J-M (2004)
Are the long-term fluctuations in Atlantic bluefin tuna (Thunnus thynnus) population related to environmental changes? Fish Oceanogr 13:145–160.

Rijnsdorp AD, Peck MA, Engelhard GH, Möllmann C, Pinnegar JK (2009)
Resolving the effect of climate change on fish populations. ICES J Mar Sci J Cons:fsp056.

Sabates A, Martín P, Lloret J, Raya V (2006)
Sea warming and fish distribution: the case of the small pelagic fish, Sardinella aurita, in the western Mediterranean. Glob Change Biol 12:2209–2219.

Sara G, Bianchi CN, Morri C (2005)
Mating behaviour of the newly-established ornate wrasse Thalassoma pavo (Osteichthyes: Labridae) in the Ligurian Sea (north-western

Mediterranean). J Mar Biol Assoc UK 85:191–196.

Sheridan JA, Bickford D (2011)
Shrinking body size as an ecological response to climate change. Nat Clim Change 1:401–406.

Sims DW, Wearmouth VJ, Genner MJ, Southward AJ, Hawkins SJ (2004)
Low-temperature-driven early spawning migration of a temperate marine fish. J Anim Ecol 73:333–341.

Stenseth NC, Mysterud A, Ottersen G, Hurrell JW, Chan K-S, Lima M (2002)
Ecological effects of climate fluctuations. Science 297:1292–1296.

Streftaris N, Zenetos A (2006)
Alien marine species in the Mediterranean-the 100 "Worst Invasives" and their impact. Mediterr Mar Sci 7:87–118.

Sumaila UR, Cheung WW, Lam VW, Pauly D, Herrick S (2011)
Climate change impacts on the biophysics and economics of world fisheries. Nat Clim Change 1:449–456.

Vergés A, Tomas F, Cebrian E, Ballesteros E, Kizilkaya Z, Dendrinos P, Karamanlidis AA, Spiegel D, Sala E (2014)
Tropical rabbitfish and the deforestation of a warming temperate sea. J Ecol 102:1518–1527.

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJ, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002)
Ecological responses to recent climate change. Nature 416:389–395.

Waycott M, Duarte CM, Carruthers TJ, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL, Hughes AR, others (2009)
Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci 106:12377–12381.

Zenetos A, Ballesteros E, Verlaque M (2012)
Alien species in the Mediterranean Sea by 2012. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part 2. Introduction trends and pathways.

Climate change and fisheries

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There is considerable evidence that Mediterranean marine species have been shifting their ranges, migration patterns, seasonal activities and periodicities, abundances, growth and mortality rates, and consequently their trophic interactions in response to climate change and variability. These responses may ultimately have significant consequences for ecosystem productivity, biodiversity and functioning and hence for the overall goods and ecosystem services they provide, especially the production of living resources (Kirby & Beaugrand 2009, Doney et al. 2012).

Climate change is an additional pressure on marine ecosystems that are already subject to many anthropogenic disturbances such as fishing activities. This is especially true in the Mediterranean Sea, where a series of human impacts co-occur and interact (Coll et al. 2010, Micheli, Halpern, et al. 2013). The consequences of climate change for marine resources need to be evaluated in this context and research and management need to take interactions between fishing, other human impacts, and climate into account (Brander 2010, Perry et al. 2010). This chapter thus has three aims: (i) to investigate the synergy between climate and fishing (a major human impact on Mediterranean marine ecosystems) and, using some examples from the Mediterranean Sea, to highlight how these two factors interact, from the individual to the ecosystem scale, (ii) to assess and quantify the consequences of climate change for the composition of fishery catches in the Mediterranean Sea, and (iii) to address the consequences of climate change for the management tools and strategies implemented in the region.

Fishing and climate act in synergy

Studies that specifically assess the synergistic effects of both climate change and fishing on fish resources and ecosystem functioning in the Mediterranean Sea are rare. However, studies conducted in other regions or at global scale describe a range of changes that can be expected in the Mediterranean. Under climate change, fishing is likely the most significant anthropogenic impact on marine fishes. Fishing has been going on in the Mediterranean Sea for a thousand years and has resulted in overexploitation of the main commercial species, with no less than 90% of stocks assessed in 2015 categorized as overfished (STECF 2016). Fishing does not only reduce the abundance and production of fish populations but also results in changes in their population structure (e.g. by truncating the demographic structure with fewer older fish and by altering life history traits such as mean body size and age at maturity) and in species composition (e.g. by removing populations of large sized fish) (Colloca et al. 2013). In an ecosystem context, where inter- and intra-specific interactions are the main drivers of community structure, fishing exerts direct pressure on the main target species but also indirectly affects their competitors, prey and predators, thereby potentially affecting the whole food web (Scheffer et al. 2005, Daskalov et al. 2007, Coll et al. 2008). In addition to reducing the size of target populations, one direct impact of fishing is simplifying the demographic structure of marine populations, making them more sensitive to climate variability at interannual to interdecadal scales (Perry et al. 2010). Fishing of finfishes and invertebrates can reduce the number of age groups in populations, lead to spatial contraction, sometimes to a loss of population sub-units, and alter life-history traits such as age at maturity and longevity (Perry et al. 2010, Planque et al. 2010). All these effects may make populations more susceptible to climate variability at different temporal scales. For instance in the Mediterranean Sea, Hidalgo et al. (2011) showed that the long-term exploitation pattern has likely eroded the age structure of hake (*Merluccius merluccius*), one of the main commercially exploited species. Hake subsequently became more recruitment-dependent, and thereby more sensitive to climate variability (Figure 1). This phenomenon is called the "age truncation effect" (Hsieh et al. 2006).

In the same way, Ottersen et al. (2006) demonstrated that heavily fished stocks were subject to more pronounced variability in recruitment linked to environmental fluctuations, due to changes in the spawning stock age and size composition. Hsieh et al. (2006) showed that exploited species exhibit higher temporal variability in abundance than unexploited species. Indeed, truncation of the age structure caused by fishing may reduce the capacity of exploited populations to buffer environmental events, especially anomaly events. Fishing can thus cause higher fluctuations in the abundance of commercially targeted species thereby increasing the risk of collapse of a heavily fished population from stochastic environmental events (Scheffer et al. 2001, Hsieh et al. 2006). Fluctuations in fish stocks may have consequences for both ecosystem functioning and fishing sustainability. In addition, fishing communities that depend on just a few local species have become more vulnerable to fluctuations in stocks, whether due to overfishing or climate variability (Brander 2010).

Under fishing pressure, the mean turnover rate of fish communities is expected to increase due to a relative increase in the proportion of smaller individuals with higher metabolic rates and to the depletion of the major predatory demersal fish resources that have a lower turnover rate (Myers & Worm 2003). In this

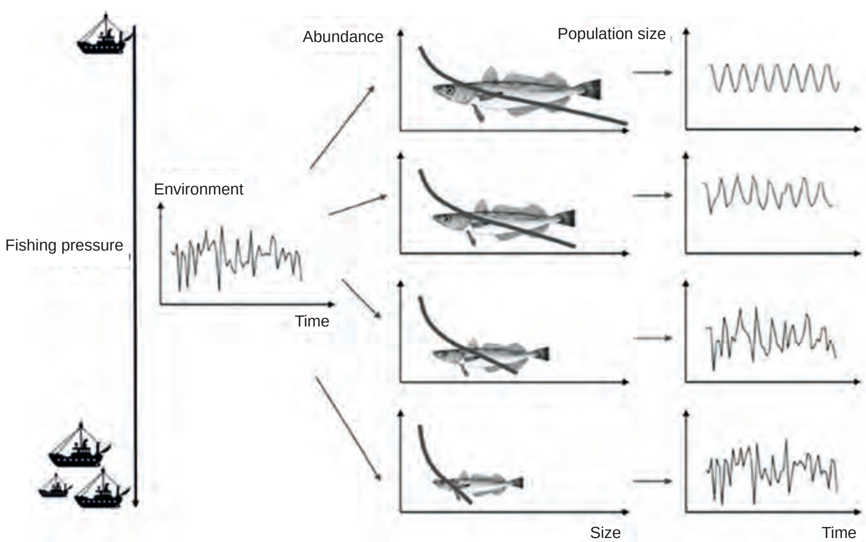


Figure 1
According to Hidalgo et al. (2011), fishing "by altering the demographic structure, populations switch from an internally-generated to an externally-forced fluctuation mode, tracking the environmental variability more closely".
Adapted from Hidalgo et al. (2011).

context, Perry et al. (2010) pointed out that "*these changes are expected to alter how the community responds to climate forcing since exploited fish communities with faster mean turnover times are expected to track more closely the short-term variability in production that results from variability in climate*". In addition, by removing top predators and favoring the dominance of short-lived prey populations with rapid turnover rates, fishing modifies the trophic controls that drive ecosystem dynamics, i.e. generally weakening top-down control and strengthening bottom-up control, which can lead to much greater vulnerability of the marine system to climate forcing (Perry et al. 2010).

In view of the current state of fish stocks in the Mediterranean basin, climate change in the region will strongly affect marine resources with several ramifications in food webs dynamics and ecosystem functioning. The Mediterranean Sea, which for decades has been - and continues to be - subject to intense exploitation of marine resources, is likely to experience stronger bottom-up control. This will lead to greater vulnerability and variability of the system to climate forcing, with implications for fisheries sustainability and biodiversity conservation.

Climate-induced changes in commercial catches

Worldwide, fisheries will be impacted by changes in the distribution and in the catches of exploited marine species (Cheung et al. 2008, 2016, Barange et al. 2014), which will affect the economics of fisheries worldwide (Sumaila et al. 2011). In the Mediterranean Sea, the change in fisheries catch potential is partly due to northward and eastward shifts in fish distribution (see sub-chapter 2.1.3) that result in the invasion of warmer-water species into higher latitudes (e.g. Adriatic Sea) and local extinction in the southern Mediterranean region. Thus, in the near future, species that are commercially important in some areas may no longer be available. This may be already the case of the once abundant sardine (*Sardina pilchardus*), which has decreased drastically in the northern Mediterranean Sea in the last decade (Palomera et al. 2007).

By 2050, under a high emission scenario (Representative Concentration pathway 8.5), Cheung et al. (2016) predicted an up to 5% reduction in the potential catches at the Mediterranean scale (Figure 2). Furthermore, when considering changes in biogeochemistry such as ocean acidification and reduction in oxygen concentration, these authors also predicted a decrease in fish growth performance, which, along with a higher rate of distributional shift, may reduce estimated catch potential (Cheung et al. 2011). Changes in phytoplankton community structure may even reduce the projected catch potential by a further 10% (Cheung et al. 2011).

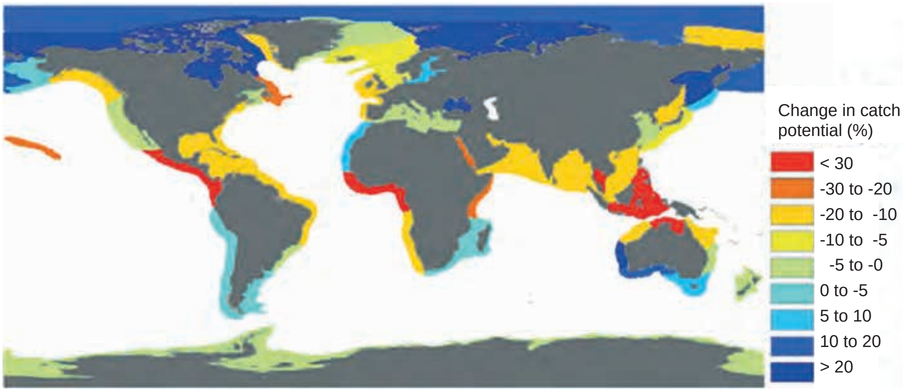


Figure 2
Mean percentage changes in potential catch by 2050 relative to present day, under the RCP 8.5 scenario. From Cheung et al. (2016).

This decrease in catch potential will be accompanied by tropicalization of the catch (i.e. an increase in warm-water species in catch composition). Indeed, Cheung et al. (2013) showed that in the Mediterranean Sea, the Mean Temperature of the Catch (MTC, i.e. the average inferred temperature preference of the exploited species weighted by their annual catch) has significantly increased since 1970, evidence for an increase in the catch of warmer water species and a decrease in the catch of colder water species. This index, which reflects changes in the composition of marine fisheries catch is closely linked to warming of the Mediterranean Sea. For the period 1970-2010, the MTC for the western, central and eastern Mediterranean has increased by 0.56 °C, 1.05 °C and 0.29 °C per decade, respectively (Tsikliras & Stergiou 2014) (figure 3). Moreover, if Lessespsian species are included, the MTC rate would be higher in all areas (Tsikliras & Stergiou 2014).

With the proliferation of non-indigenous invasive species (see sub-chapters 2.1.3), there is a need to explore market options for non-target species currently of low or no economic value. In general, changes in the composition of commercial fisheries catches have detrimental socioeconomic implications for fisheries, markets and consumers (Weatherdon et al. 2016). This is the case of the decline in small pelagic fish species (Van Beveren et al. 2016). However, climate change and the associated increase in sea surface temperature may offer opportunities to some Mediterranean fishermen to increase landings of tropical and subtropical species, some of which are of great commercial interest (e.g. the dolphinfish *Coryphaena hippurus*) (Weatherdon et al. 2016).

From qualitative and quantitative analyses of catch composition of a small tuna trap along the Ligurian coast, Cattaneo-Vietti et al. (2015) showed that in the last few decades there have been notable changes in species composition, with a decrease in the abundance of certain scombroids such as mackerel (e.g. *Scomber scombrus*) and bullet tuna (i.e. boreal species) and an increase in the abundance of carangids such as horse mackerel (*Trachurus* spp.) and amberjacks (e.g. *Seriola dumerili*) and other typical southern-water fish species (e.g. the dolphinfish *Coryphaena hippurus* and the east Atlantic barracuda *Sphyraena viridensis*). Using 'local ecological knowledge' (LEK), a recent study showed an increase in Carangidae and Sphyraenidae (thermophilic species) over time, but a simultaneous decrease in Scombridae and Clupeidae (Azzurro et al. 2011). In the western Mediterranean Sea, LEK information made it possible to record the proliferation of some species, including cephalopods, jellyfish and small-sized fish (Coll et al. 2014). These proliferations may be partly due to the impacts of fishing on the ecosystem and to climate change. Tzanatos et al. (2014) also demonstrated that fisheries landings showed significant year-to-year correlations with temperature for approximately 60% of 59 species. Based on these species, these authors showed that approximately 70% of landings were negatively correlated with temperature (e.g. hake, common sole, sardine and Norway lobster) and had decreased by an average of 44%. However, increasing trends were also found in the landings mainly for species with short life spans (e.g. anchovy, greater amberjack). Finally, Tzanatos et al. (2014) detected a shift in the landings of the 59 most important species/taxa indicating that most of them had undergone a significant abrupt change in the mid-late 1990s paralleling an increasing SST regime shift during the same period. For instance, a negative shift for hake and sardine has been reported along with a positive shift for anchovy (*Engraulis encrasicolus*) or white seabream (*Diplodus sargus*). In addition to northward migration, invasive and endemic populations respond to climate warming by bathymetric displacement. This is particularly true in the case of red mullet (*Mullus barbatus*), hake and spottail mantis shrimp (*Squilla mantis*), three species (local, native and indigenous, respectively) that have been reported to move into cooler and deeper waters to avoid warm-water competitors (Galil & Zenetos 2002). This shift in the distribution of stocks of exploited species is expected to affect their availability to fisheries and possibly to reduce commercial catches. Here, we mainly addressed the effects of warmer temperatures on fish resources and their fisheries, but a rise in CO2 levels also triggers ocean acidification and can affect Mediterranean fisheries. For example, sponge fisheries are seriously threatened by acidification of the sea because of the low capacity of most sponges for acid-base regulation (Linares et al. 2005, Goodwin et al. 2014). Ocean acidification is looked on as a major threat to the marine environment in the coming years and may have dramatic effects on calcifying organisms such as the precious Mediterranean red coral (*Corallium rubrum*), which is a long lived, slow growing gorgonian endemic species in the Mediterranean Sea. Sold at US$ 230-300 per kg, it is one of the most valuable corals thanks to its bright red durable skeleton used in the jewelry industry (Tsounis et al. 2010, Bramanti et al. 2013).

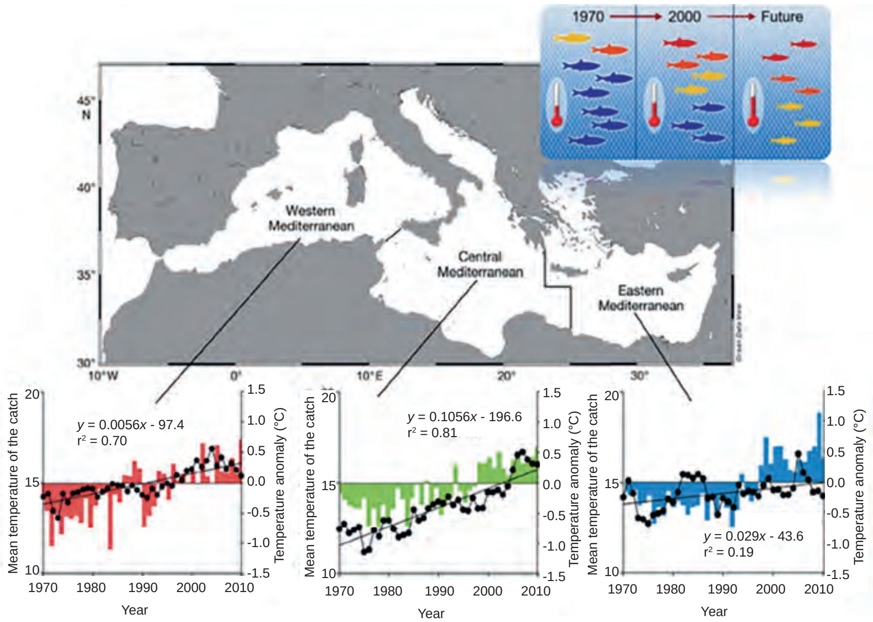


Figure 3
Evolution of the mean temperature of the catch between 1970 and 2010
in the western, central and eastern Mediterranean Sea.
From Tsikliras & Stergiou (2014). The picture at the top right is from Cheung et al. (2013).

Adapting the whole management system

Effectiveness of Marine Protected Areas

Marine protected areas (MPAs) are the flagship management tool for conserving biodiversity and ensuring sustainable ecosystem services (Garcia et al. 2013). The objective of creating MPAs is conserving sensitive habitats and associated species and biodiversity, while taking economic and social considerations into account. Beyond preventing habitat destruction resulting from anthropogenic activities by protecting species from exploitation within a defined area, MPAs are also expected to have beneficial effects outside the protected perimeter through the spill-over effect (i.e. net emigration of adult and juvenile fish) and export of pelagic eggs and larvae from restored spawning stocks within the MPA (Harmelin-Vivien et al. 2008; Stobart et al. 2009; Garcia et al. 2013). More than 100 MPAs have been established in the Mediterranean Sea since the 1960s (Abdulla et al. 2009). However, the most recent investigations suggest that Mediterranean MPAs do not perform as expected in several important respects. First, they do not meet international conservation goals (e.g. Aichi Target 11 of the Nagoya CBD Strategic Plan for Biodiversity, aiming at protecting at least 10% of coastal and marine areas by 2020) with less than 4.6% of the surface area of the Mediterranean continental shelf covered, i.e. 114 600 km^2 (1.1% if we exclude the Pelagos Sanctuary, which is dedicated to the protection of marine mammals) (http://www.medpan.org). Second, MPAs were established based on national or local initiatives and lack cross-regional consistency (Guidetti et al. 2008, Claudet & Guidetti 2010)). Finally, there is evidence for a mismatch between MPAs and the current state of Mediterranean marine biodiversity, with 70% of fish species failing to benefit from improved protection in the current MPA system than could be expected if MPAs were located at random across the continental shelf (Guilhaumon et al. 2015) and Mediterranean MPAs do not protect a substantial proportion of species at risk (Coll et al. 2015) and consensus areas for conservation (Micheli et al. 2013).

Since climate change affects marine species in a number of ways scaling from individual (e.g. vital rates, mortality, timing of migration) to populations (shifts in abundance-size structure or in spatio-temporal distribution), the potential beneficial effects of MPAs on marine populations facing climate change will depend on their ability to enhance the resistance of the populations to these different impacts and to adapt to changing spatial distributions of marine species.

Regarding individual fitness and population resilience, MPAs can act as enhancers and disrupt the detrimental synergistic effects between climate change and fisheries. By maintaining larger individual sizes and higher larval production and recruitment compared to fished populations outside reserves, MPAs enhance the resilience of exploited populations (Micheli et al. 2012).

Beyond the poor performance of the Mediterranean MPA system with regard to current biodiversity patterns, the efficiency of Mediterranean MPAs in the future is called into question by the impacts of climate change on marine populations. Indeed, conservation actions, such as the protection of land or sea, have traditionally been implemented under the assumption that species geographical distributions change relatively slowly, unless they are directly affected by human activities (Araújo 2009). However, climate change is predicted to have profound impacts on the geographical distribution of Mediterranean organisms over the 21st century. For example, modeling studies predict that 25% of the Mediterranean continental shelf will have undergone a complete modification of the endemic fish assemblages by the end of the 21st century (Ben Rais Lasram et al. 2010) (see sub-2.1.3). In a context in which marine species are shifting their geographical ranges, MPAs can lose the very same species that justified their implementation, therefore calling their future relevance for biodiversity conservation into question (Alagador et al. 2016). In the Mediterranean Sea, we observed a strong bias in the geographical distribution of MPAs, with a higher density of MPAs on the northern coast of the Mediterranean Sea than on the southern coast with only eight MPAs located on the North African continental shelf out of the 99 included in the study (Figure 4) (Guilhaumon et al. 2015).

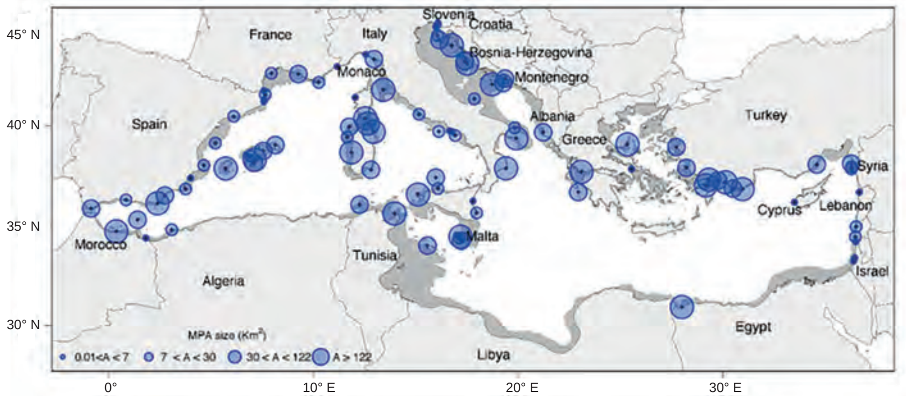


Figure 4
Map of the Mediterranean Sea showing the continental shelf in grey and the location of the 99 MPAs mentioned in the study by Guilhaumon et al. (2015) (blue circles whose size is proportional to the size of the MPA).

Although this geographical bias may be responsible for the current poor performance of the Mediterranean MPA system (Guilhaumon et al. 2015), it can also be seen as an opportunity for the future conservation of fish species. Since endemic and native fish are expected to move northward in the Mediterranean due to sea warming (Ben Rais Lasram et al. 2010; Albouy et al. 2012, Cheung et al. 2015), a potential increase is possible in the congruence between native and endemic biodiversity patterns and MPAs. However, the small size of MPAs on the northern Mediterranean coast and the lack of MPAs in the south are not only obstacles to rebuilding overexploited populations but may also prove problematic for the conservation of newly exploited tropical and subtropical species.

Future climate change may also have notable impacts on connectivity patterns between MPAs and other natural refuges of marine species (such as deep sea canyons and rocky areas). But although connectivity between MPAs is a critical criterion in the design of MPAs, it has not yet been taken into account when establishing MPAs in the Mediterranean Sea. In a recent publication based on the SRES IPCC A2 scenario, Andrello et al. (2015) explored the effects of adult reproductive timing and larval dispersal on the connectivity among MPAs and their ability to seed fished areas with larvae in the Mediterranean. These authors show that, over the 1970-2099 period, larval dispersal distances would decrease by 10%, the continental shelf area seeded with larvae will decrease by 3% and larval retention inside MPAs would increase by 5% (i.e. a higher concentration of larvae in smaller areas of the continental shelf). In fact, these results suggest that climate change will produce higher benefits for fished areas surrounding the MPAs but lower benefits for fished areas that are located too far from the MPAs (Andrello et al. 2015).

Climate change could influence the connectivity and the effectiveness of MPA networks via changes in hydrodynamics, adult reproductive timing, larval growth rates and shifts in population range. The fact that Mediterranean protected areas are geographically fixed, and increasingly isolated by habitat destruction, could be cost-ineffective, as major investments are being made today in areas that will potentially have limited positive impacts in the next several decades (McLeod et al. 2008). Thus, for scientists, managers and planners, designing adaptive and effective MPA networks in the face of climate change is a challenge.

Current stock assessments in the context of climate change

The global climate change context questions the relevance of current models for managing ecological resources and fisheries stocks (Hoegh-Guldberg & Bruno 2010). Lack of understanding of the sources of temporal variability in fish abundance affects the robustness of biological reference points, decision making, and risk assessment in precautionary fisheries management (Hsieh et al. 2006). For instance, Brander (2010) wrote that: "*Reductions in stock productivity mean that levels of fishing to which a stock was previously resilient, become unsustainable. The decline will be exacerbated if underlying changes in growth are not recognised*". As mentioned above, climate change acts on several population processes including mortality, maturity, growth, distribution and recruitment that influence the levels of biomass produced. However, these processes are involved in the definition of biological reference points used as thresholds and targets in fisheries management strategies and decision making. Since the production of biomass is uncertain in the context of climate change and is subject to greater variability, these targets and biological reference points should be adapted to take these risks into account (Grafton 2010). Ignoring the effects of climate change in stock assessment could compromise the validity of stock forecasts and rebuilding plans (Brander 2010; Link et al. 2011). For example, ignoring the fact that fish may shift their range, and not including spatial dynamics could significantly affect the management advice based on stock assessment and associated projections (Link et al. 2011). It is crucial that the effects of changes in ocean properties (i.e. temperature, oxygen, carbonate system, etc.) are incorporated into stock assessment, and that their combined effects with fishing are quantified, in order to build ecosystem-based fisheries management.

According to the evaluation of the current state of the resources and the projected impacts of climate change, the future of the Mediterranean Sea appears to be jeopardized. The levels of exploitation of most assessed fish stocks are outside safe biological limits and several fish populations are now endangered by the strong impacts of this millennium activity (Tsikliras et al. 2015). In the context of global change, combined with other anthropogenic disturbances such as biological invasions, pollution, habitat losses and in particular, climate change, the biological and physicochemical features of the Mediterranean Sea are changing at an unprecedented rate. The lack of data and the poor knowledge of the status of existing stocks, especially in the southern and eastern parts of the Mediterranean, strong human population pressure along the coasts of the basin, and weak governance at regional scale threaten the conciliations of biodiversity conservation and sustainable fisheries management.

References

Abdulla A, Gomei M, Hyrenbach D, Notarbartolo-di-Sciara G, Agardy T (2009)
Challenges facing a network of representative marine protected areas in the Mediterranean: prioritizing the protection of underrepresented habitats. ICES J Mar Sci J Cons 66:22–28

Alagador D, Cerdeira JO, Araújo MB (2016)
Climate change, species range shifts and dispersal corridors: an evaluation of spatial conservation models. Methods Ecol Evol

Andrello M, Mouillot D, Somot S, Thuiller W, Manel S (2015)
Additive effects of climate change on connectivity between marine protected areas and larval supply to fished areas. Divers Distrib 21:139–150

Araújo MB (2009)
Climate change and spatial conservation planning. Spat Conserv Prioritization Quant Methods Comput Tools:172–184

Azzurro E, Moschella P, Maynou F (2011)
Tracking signals of change in Mediterranean fish diversity based on local ecological knowledge. PLoS One 6:e24885

Barange M, Merino G, Blanchard JL, Scholtens J, Harle J, Allison EH, Allen JI, Holt J, Jennings S, others (2014)
Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat Clim Change 4:211–216

Ben Rais Lasram F, Guilhaumon F, Albouy C, Somot S, Thuiller W, Mouillot D (2010)
The Mediterranean Sea as a “cul-de-sac”for endemic fishes facing climate change. Glob Change Biol 16:3233–3245

Bramanti L, Movilla J, Guron M, Calvo E, Gori A, Dominguez-Carrió C, Grinyó J, Lopez-Sanz A, Martinez-Quintana A, Pelejero C, others (2013)
Detrimental effects of ocean acidification on the economically important Mediterranean red coral (Corallium rubrum). Glob Change Biol 19:1897–1908

Brander K (2010)
Impacts of climate change on fisheries. J Mar Syst 79:389–402

Cattaneo-Vietti R, Cappanera V, Castellano M, Povero P (2015)
Yield and catch changes in a Mediterranean small tuna trap: a warming change effect? Mar Ecol 36:155–166

Cheung WW, Close C, Lam V, Watson R, Pauly D (2008)
Application of macroecological theory to predict effects of climate change on global fisheries potential. Mar Ecol Prog Ser 365:187–197

Cheung WW, Dunne J, Sarmiento JL, Pauly D (2011)
Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J Mar Sci J Cons:fsr012

Cheung WW, Jones MC, Reygondeau G, Stock CA, Lam VW, Frölicher TL (2016)
Structural uncertainty in projecting global fisheries catches under climate change. Ecol Model 325:57–66

Cheung WW, Watson R, Pauly D (2013)
Signature of ocean warming in global fisheries catch. Nature 497:365–368

Claudet J, Guidetti P (2010)
Improving assessments of marine protected areas. Aquat Conserv Mar Freshw Ecosyst 20:239–242

Coll M, Carreras M, Ciércoles C, Cornax M-J, Gorelli G, Morote E, Sáez R (2014)
Assessing fishing and marine biodiversity changes using fishers’ perceptions: the Spanish Mediterranean and Gulf of Cadiz case study. PLoS One 9:e85670

Coll M, Palomera I, Tudela S, Dowd M (2008)
Food-web dynamics in the South Catalan Sea ecosystem (NW Mediterranean) for 1978–2003. Ecol Model 217:95–116

Coll M, Piroddi C, Steenbeek J, Kaschner K, Ben Rias Lasram F, Aguzzi J, Ballesteros E, Bianchi CN, Corbera J, Dailianis T, others (2010)
The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PloS One 5:e11842

Coll M, Steenbeek J, Ben Rais Lasram F, Mouillot D, Cury P (2015)
"Low-hanging fruit"for conservation of marine vertebrate species at risk in the Mediterranean Sea. Glob Ecol Biogeogr 24:226–239

Colloca F, Cardinale M, Maynou F, Giannoulaki M, Scarcella G, Jenko K, Bellido JM, Fiorentino F (2013)
Rebuilding Mediterranean fisheries: a new paradigm for ecological sustainability. Fish Fish 14:89–109

Daskalov GM, Grishin AN, Rodionov S, Mihneva V (2007)
Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. Proc Natl Acad Sci 104:10518–10523

Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, Galindo HM, Grebmeier JM, Hollowed AB, Knowlton N, others (2012)
Climate change impacts on marine ecosystems. Mar Sci 4

Galil BS, Zenetos A (2002)
A sea change—exotics in the Eastern Mediterranean Sea. In: Invasive Aquatic Species of Europe. Distribution, Impacts and Management. Springer, p 325–336

Garcia SM, Boncoeur J, Gascuel D (2013)
Aires marines protégées et la pêche: bioécologie, socioéconomie et gouvernance. Presses universitaires de Perpignan

Goodwin C, Rodolfo-Metalpa R, Picton B, Hall-Spencer JM (2014)
Effects of ocean acidification on sponge communities. Mar Ecol 35:41–49

Grafton RQ (2010)
Adaptation to climate change in marine capture fisheries. Mar Policy 34:606–615

Guidetti P, Milazzo M, Bussotti S, Molinari A, Murenu M, Pais A, Spano N, Balzano R, Agardy T, Boero F, others (2008)
Italian marine reserve effectiveness: Does enforcement matter? Biol Conserv 141:699–709

Guilhaumon F, Albouy C, Claudet J, Velez L, Ben Rais Lasram F, Tomasini J-A, Douzery EJ, Meynard CN, Mouquet N, Troussellier M, others (2015)
Representing taxonomic, phylogenetic and functional diversity: new challenges for Mediterranean marine-protected areas. Divers Distrib 21:175–187

Harmelin-Vivien M, Le Diréach L, Bayle-Sempere J, Charbonnel E, García-Charton JA, Ody D, Pérez-Ruzafa A, Reñones O, Sánchez-Jerez P, Valle C (2008)
Gradients of abundance and biomass across reserve boundaries in six Mediterranean marine protected areas: Evidence of fish spillover? Biol Conserv 141:1829–1839

Hidalgo M, Rouyer T, Molinero JC, Massutí E, Moranta J, Guijarro B, Stenseth NC (2011)
Synergistic effects of fishing-induced demographic changes and climate variation on fish population dynamics. Mar Ecol Prog Ser 426:1–12

Hoegh-Guldberg O, Bruno JF (2010)
The impact of climate change on the world's marine ecosystems. Science 328:1523–1528

Hsieh C, Reiss CS, Hunter JR, Beddington JR, May RM, Sugihara G (2006)
Fishing elevates variability in the abundance of exploited species. Nature 443:859–862

Kirby RR, Beaugrand G (2009)
Trophic amplification of climate warming. Proc R Soc Lond B Biol Sci 276:4095–4103

Linares C, Coma R, Diaz D, Zabala M, Hereu B, Dantart L (2005)
Immediate and delayed effects of a mass mortality event on gorgonian population dynamics and benthic community structure in the NW Mediterranean Sea. Mar Ecol Prog Ser 305:127–137

Link JS, Nye JA, Hare JA (2011)
Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish Fish 12:461–469

McLeod E, Salm R, Green A, Almany J (2008)
Designing marine protected area networks to address the impacts of climate change. Front Ecol Environ 7:362–370

Micheli F, Halpern BS, Walbridge S, Ciriaco S, Ferretti F, Fraschetti S, Lewison R, Nykjaer L, Rosenberg AA (2013)
Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. PLoS One 8:e79889

Micheli F, Levin N, Giakoumi S, Katsanevakis S, Abdulla A, Coll M, Fraschetti S, Kark S, Koutsoubas D, Mackelworth P, others (2013)
Setting priorities for regional conservation planning in the Mediterranean Sea. PLoS One 8:e59038

Micheli F, Saenz-Arroyo A, Greenley A, Vazquez L, Montes JAE, Rossetto M, De Leo GA (2012)
Evidence that marine reserves enhance resilience to climatic impacts. PloS One 7:e40832

Myers RA, Worm B (2003)
Rapid worldwide depletion of predatory fish communities. Nature 423:280–283

Ottersen G, Hjermann DØ, Stenseth NC (2006)
Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (Gadus morhua) stock. Fish Oceanogr 15:230–243

Palomera I, Olivar MP, Salat J, Sabatés A, Coll M, Garcia A, Morales-Nin B (2007)
Small pelagic fish in the NW Mediterranean Sea: an ecological review. Prog Oceanogr 74:377–396

Perry RI, Cury P, Brander K, Jennings S, Möllmann C, Planque B (2010)
Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. J Mar Syst 79:427–435

Planque B, Fromentin J-M, Cury P, Drinkwater KF, Jennings S, Perry RI, Kifani S (2010)
How does fishing alter marine populations and ecosystems sensitivity to climate? J Mar Syst 79:403–417

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001)
Catastrophic shifts in ecosystems. Nature 413:591–596

Scheffer M, Carpenter S, Young B de (2005)
Cascading effects of overfishing marine systems. Trends Ecol Evol 20:579–581

STECF (2016)
Reports of the Scientific, Technical and Economic Committee for Fisheries (STECF)-51st Plenary meeting Report (PLEN-16-01). 2016. Publications office of the European union, Luxembourg, EUR 27458 EN, JRC 101442, 95 pp.

Stobart B, Warwick R, González C, Mallol S, Díaz D, Reñones O, Goñi R (2009)
Long-term and spillover effects of a marine protected area on an exploited fish community. Mar Ecol Prog Ser 384:47–60

Sumaila UR, Cheung WW, Lam VW, Pauly D, Herrick S (2011)
Climate change impacts on the biophysics and economics of world fisheries. Nat Clim Change 1:449–456

Tsikliras AC, Dinouli A, Tsiros V-Z, Tsalkou E (2015)
The Mediterranean and Black Sea fisheries at risk from overexploitation. PloS One 10:e0121188

Tsikliras AC, Stergiou KI (2014)
Mean temperature of the catch increases quickly in the Mediterranean Sea. Mar Ecol Prog Ser 515:281–284

Tsounis G, Rossi S, Grigg R, Santangelo G, Bramanti L, Gili J-M, Gibson RN (2010)
The exploitation and conservation of precious corals. Oceanogr Mar Biol 48:161

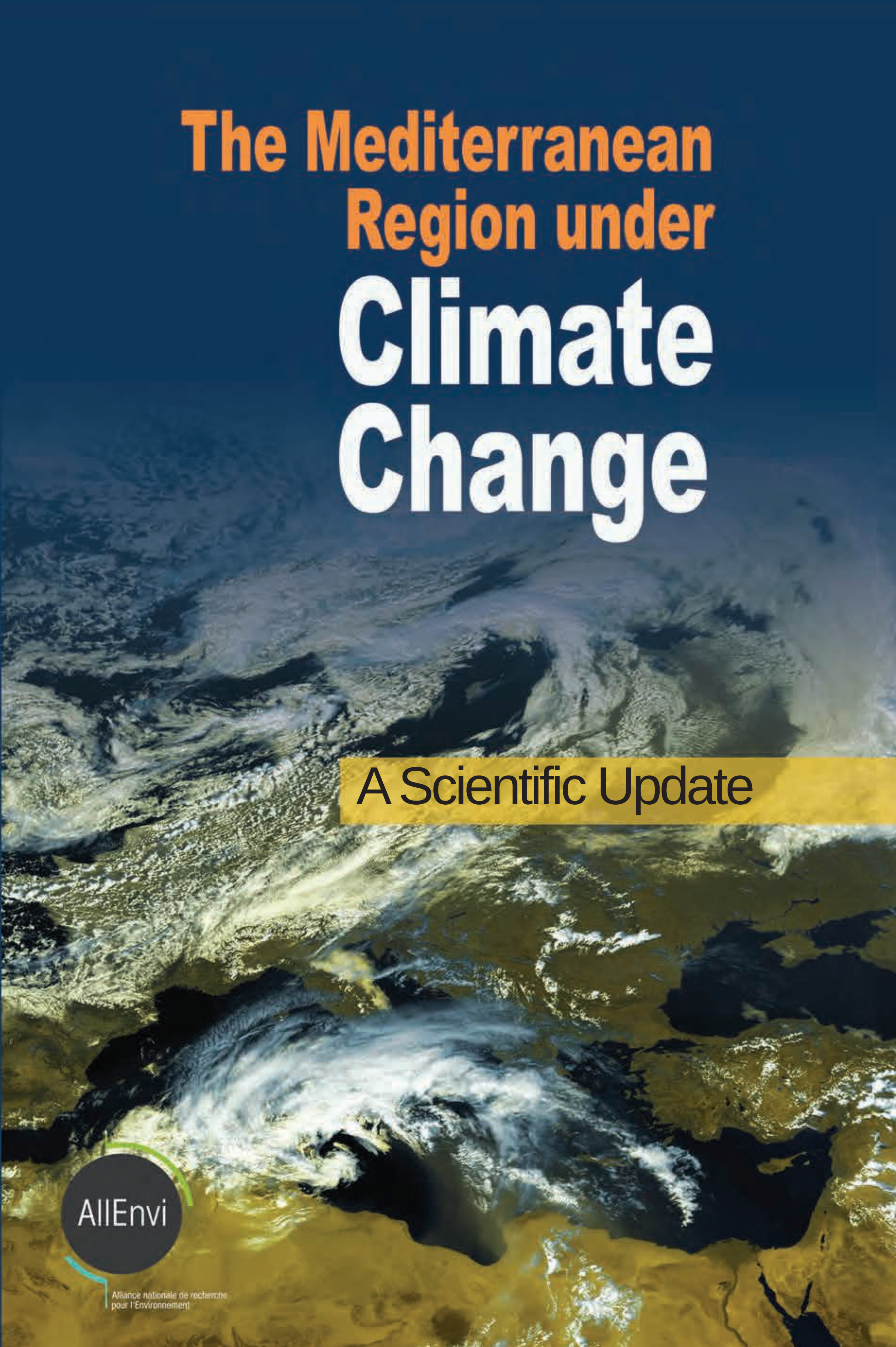
Tzanatos E, Raitsos DE, Triantafyllou G, Somarakis S, Tsonis AA (2014)
Indications of a climate effect on Mediterranean fisheries. Clim Change 122:41–54

Van Beveren E, Fromentin J-M, Rouyer T, Bonhommeau S, Brosset P, Saraux C (2016)
The fisheries history of small pelagics in the Northern Mediterranean. ICES J Mar Sci J Cons:fsw023

Weatherdon LV, Magnan AK, Rogers AD, Sumaila UR, Cheung WW (2016)
Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. Front Mar Sci 3:48

The Mediterranean Region under Climate Change

A Scientific Update



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A Scientific Update

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