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).

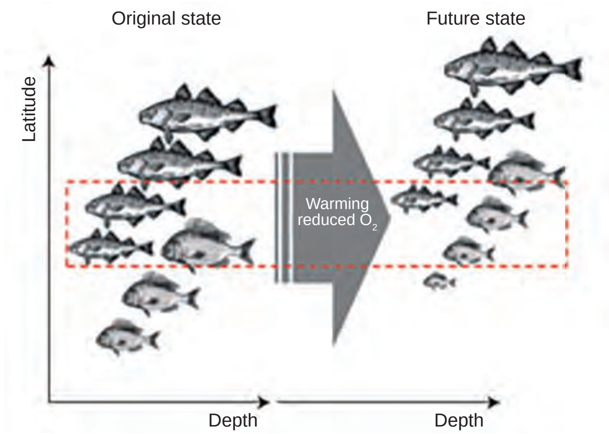

Figure 1
Expected changes in body size at individual and assemblage levels. According to Cheung et al. (2013), due to the invasion/increased abundance of smaller-bodied species and local extinction/decreased abundance of larger-bodied species, the mean maximum body weight is expected to decrease at the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

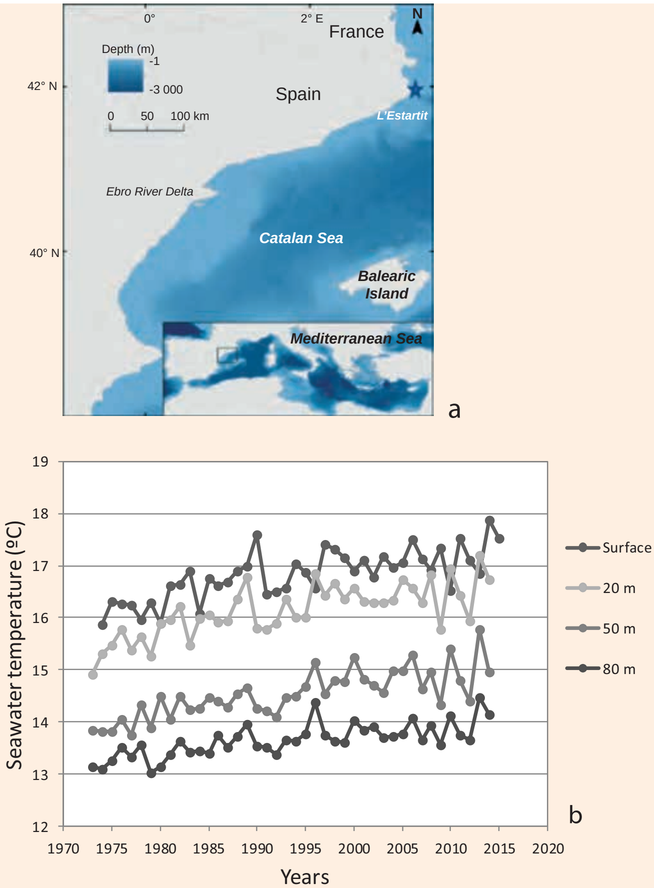

Figure B1
a) The Catalan Sea region in the western Mediterranean Sea. Star: Estartit oceanographic station.
b) Evolution of the mean annual sea temperature at Estartit station from 1974 to 2015.
The curves present data at the surface, 20, 50 and 80 m depth, respectively.
Data source: Josep Pasqual in 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).

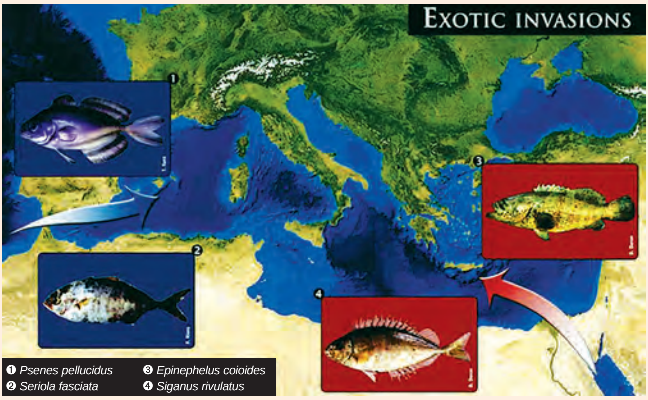

Figure B2
The Mediterranean Sea under southern invasions.

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.

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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

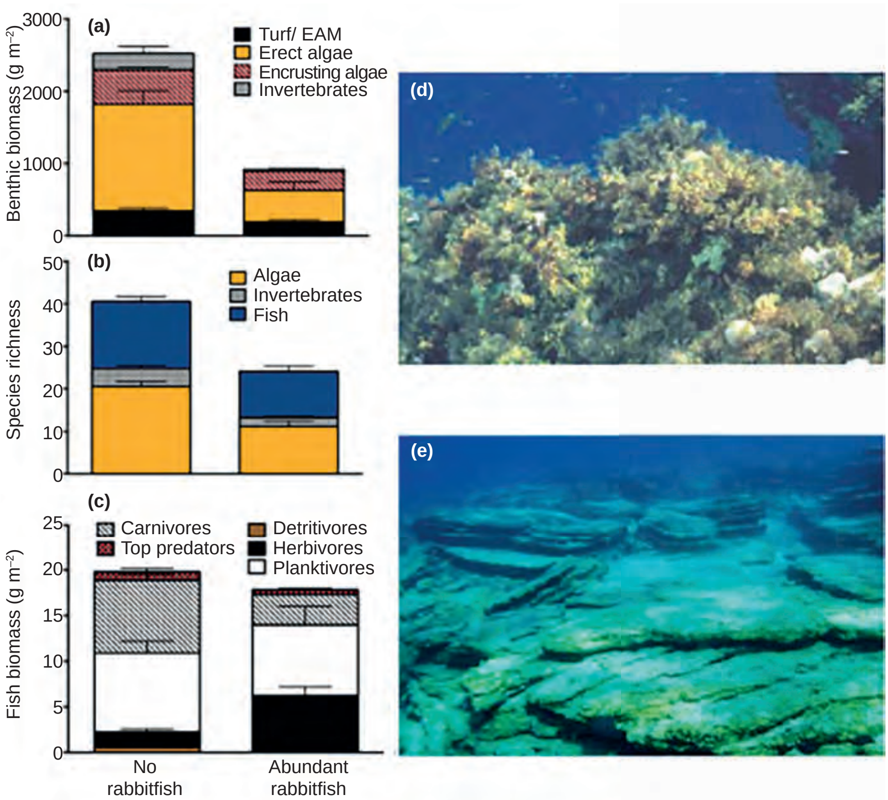

Figure 2

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.

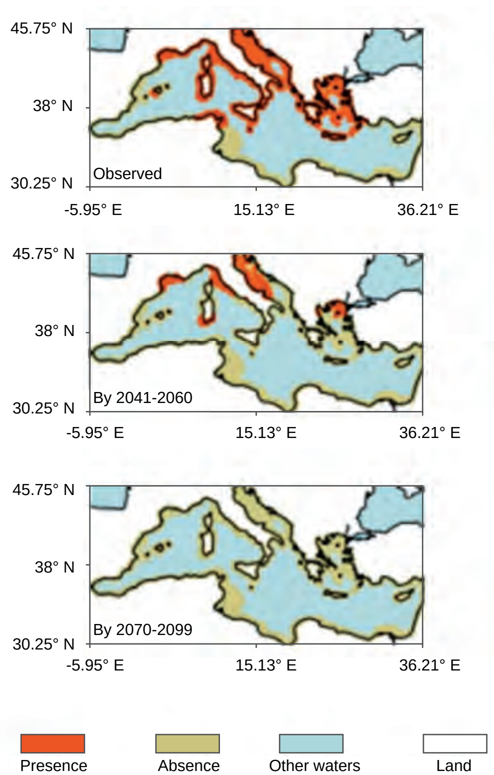

Figure 3
Observed distribution areas of the endemic Mediterranean fish Gobius geniporus *(1980s, top) and projected potential future thermal habitats (by 2040-2060 middle; 2070-2099, bottom). The "cul-de-sac" effect is clearly visible for this species. From Ben Rais Lasram et al. (2010).*

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).

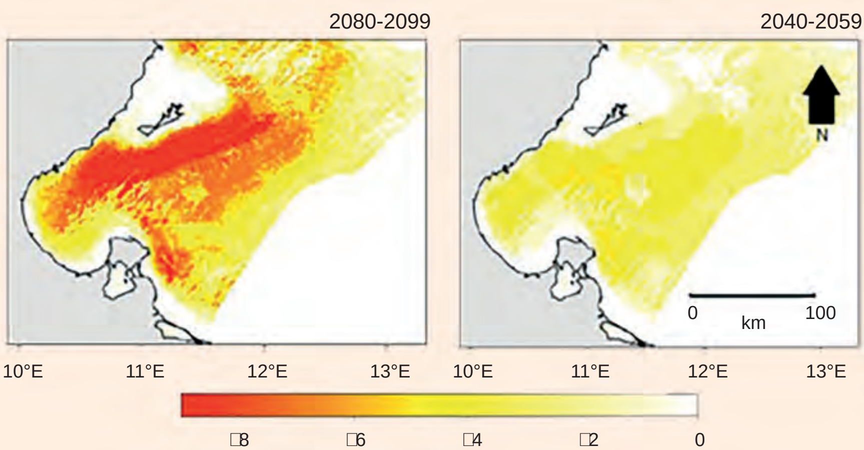

Figure B3 Differences between species richness predicted under current climate conditions (1982-2009, baseline scenario) and values predicted under a mid-century climate scenario (2040-2059, right panel) and an end-century climate scenario (2080-2099, left panel) (Hattab et al. 2014).

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

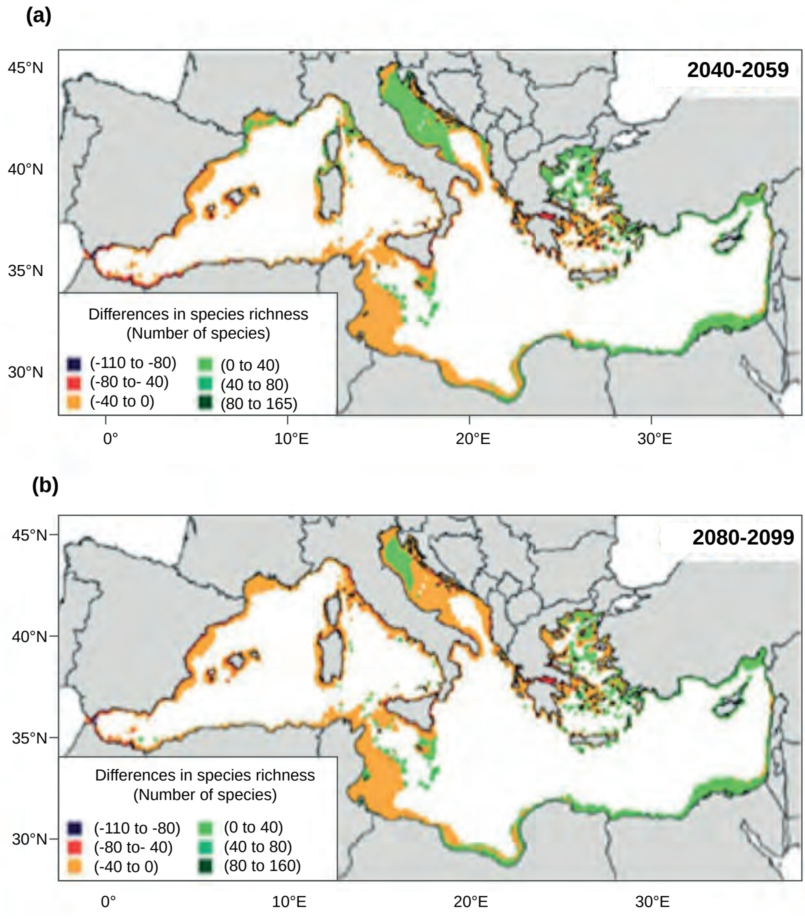

Figure 4
Differences in species richness between a baseline scenario (1961-1980) and two time periods (a: 2040-2059 ; b: 2080-2099) predicted for the continental shelf of the Mediterranean Sea (all fish species of the continental shelf are represented) according to the SRES IPCC A2 scenario. Adapted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

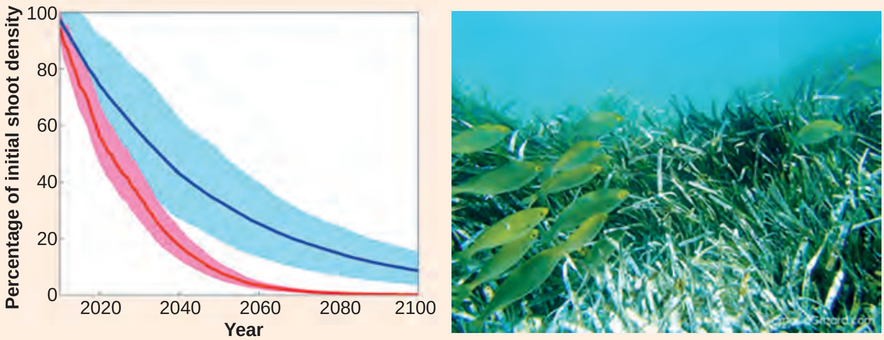

Figure B4
Left: percentage of P. oceanica shoot density in the twenty-first century. The pink line represents the projected percentage of shoot density under warming and local impacts, and the blue line represents the projected trend in the absence of warming. From Jordà et al. (2012). *Right*: photo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

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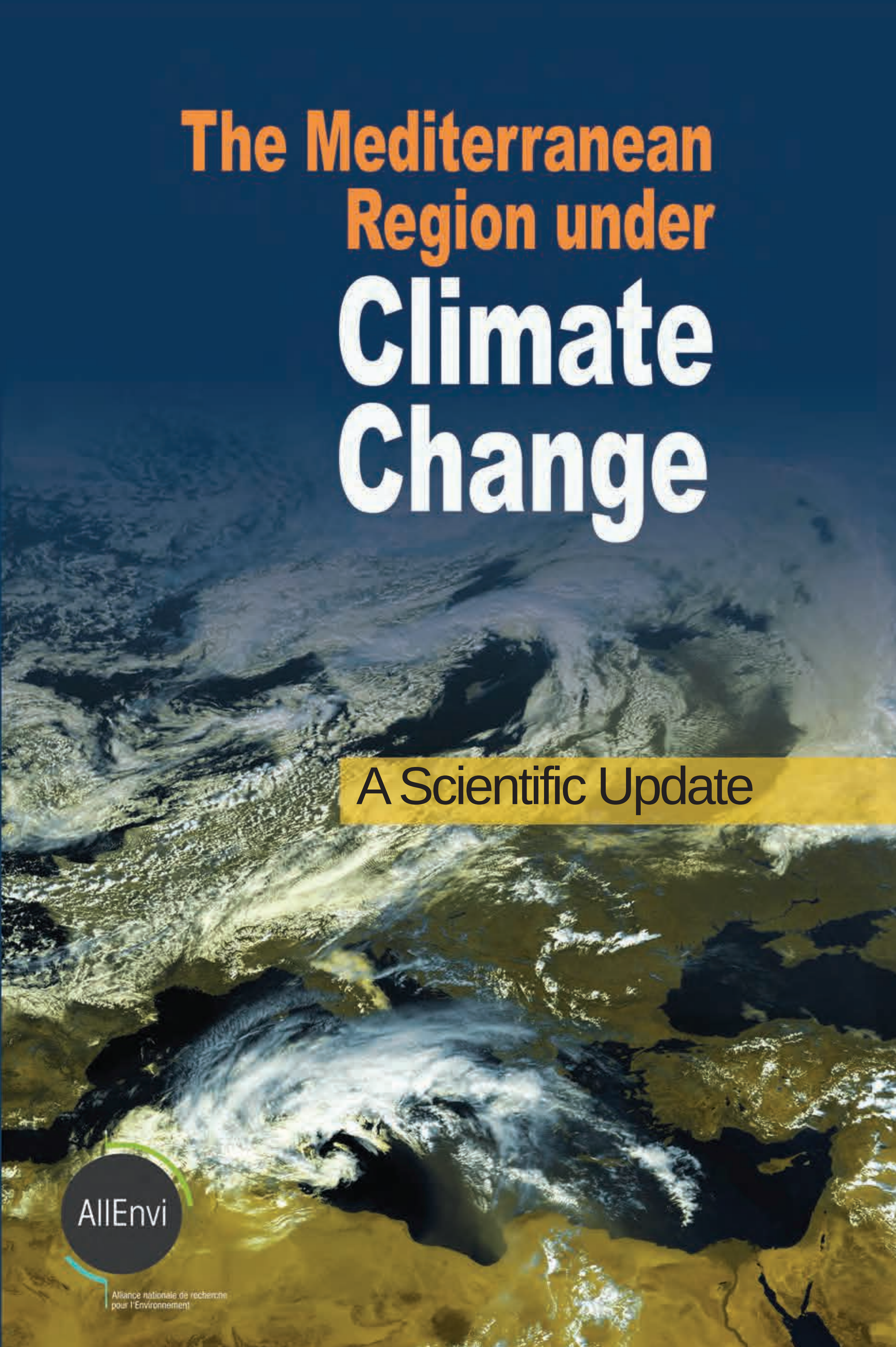
The Mediterranean Region under Climate Change

A Scientific Update



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A Scientific Update

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