I - EXECUTIVE SUMMARY OF CIESM WORKSHOP 35

"Climate warming and related changes in Mediterranean marine biota"

by

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This synthesis was drafted by all workshop participants, under the coordination of Ferdinando Boero and with the support of Paula Moschella. Frédéric Briand reviewed and edited the entire volume whose physical production was carried out by Valérie Gollino.

1. INTRODUCTION

The Workshop took place from 27 to 31 May 2008 at the historical Biologische Anstalt (BAH) on the Island of Helgoland, Germany. Scientists from nine countries (see list at the end of this volume) attended this exploratory meeting at the invitation of CIESM. After welcoming the participants, Prof. Frédéric Briand, Director General of CIESM, emphasized the great importance attached by the Commission to the unprecedented changes now taking place in Mediterranean marine biodiversity, as evidenced by the well-known CIESM Atlas Series on Exotic Species and by the launch of the new CIESM Tropicalization Programme. Clearly one of the challenges posed by this meeting would be to try distinguishing between global climatic change and other anthropic vectors as main determinants. Another would be to better assess the risk of extinction posed to cold-water Mediterranean species by warmer climes and by the advance of species of warm-water affinity. He then thanked Dr Gunnar Gerdts, BAH coordinator, for hosting this seminar and invited him to present a brief survey of the past and current activities of the Station. Then Dr Briand warmly introduced Prof. Christian Dullo, National Representative of Germany on CIESM Board, recalling the long, close cooperation of the Commission – since its origin – with Germany where we were delighted to hold a workshop for the first time. In his presentation, Dr Dullo drew an historical panorama of the multi-faceted marine explorations of German marine scientists in the Mediterranean, with particular emphasis on the role played by regular campaigns of oceanographic research vessels – today exemplified by the *Meteor* and *Poseidon* R/Vs. The final introductory talk was given by Prof. Ferdinando Boero, Chair of CIESM Committee on Marine Resources, who had first suggested the workshop topic, out of concern for the risk of losing cold species trapped in geographical 'dead ends' such as the northern Adriatic, and who signalled the need to dispose of early warning biological signals of upcoming ecosystem shifts.

Global climate change is no longer a controversial issue, and the main feature of the current period is the increased variability in the observed phenomena. The warmest summer in the last centuries occurred in 2003 and was followed by a summer with intense rains leading to massive floods. Both summers were "off the scale", even though, in terms of averages, one might have balanced out the other. In spite of great variance, it is however clear that the identified trends in climatic alteration show a warming trend (see Plate A, page 108).

These changes have a faster effect on the comparatively small and semi-enclosed Mediterranean Sea than on the world ocean. The recorded changes in temperature and rainfalls, among others, are associated to dramatic changes in Mediterranean biota. In the last 50 years, enhanced by both the opening of the Suez Canal, aquaculture and ship transport, hundreds of Non Indigenous Species (NIS) reached and established themselves in the Basin (see collection of CIESM Atlases on Exotic Species). The majority of them are of warm-water affinity. Physical forcing is thus followed by a consistent response of the biota: increased temperatures are associated to increased success of both tropical NIS and of warm-water affinity Indigenous Species (IS). In parallel, it might be expected that higher temperatures represent a "climate deterioration" for the indigenous species of cold-water affinity.

2. PHYSICAL FORCING

The circulation of the Mediterranean Sea is forced by water exchanges through various straits and channels (e.g., Gibraltar, Sicily, and Otranto), wind stress, and buoyancy at the surface due to freshwater and heat fluxes (Figure 1).

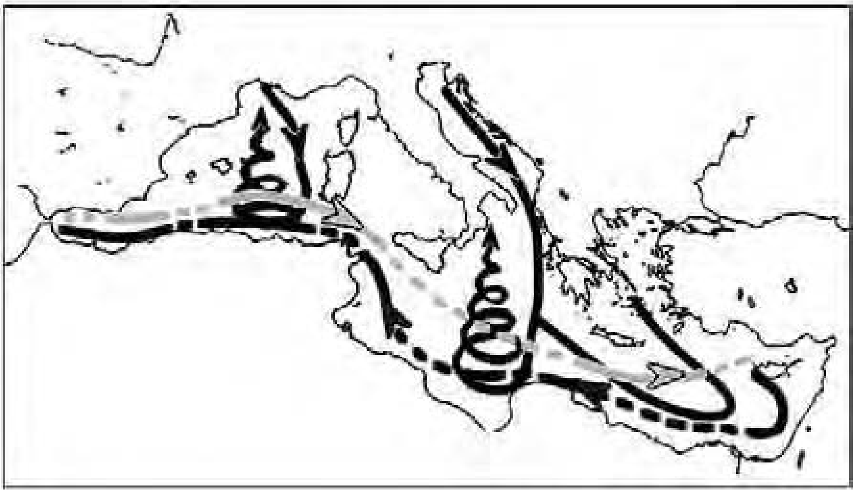

Fig. 1. Scheme of the Mediterranean Sea thermohaline circulation. Grey lines represent the surface/intermediate water mass circulation forced by Gibraltar-Atlantic inflow and Levantine Intermediate Water (LIW) formation processes occurring in the northern Levantine basin. Black lines indicate the meridional vertical circulation in western and eastern Mediterranean forced by the deep water formation processes occurring in the Gulf of Lions and in the Southern Adriatic (after Bianchi *et al.*, 2006; redrawn after Pinardi *et al.*, 2005).

Air-sea heat exchanges occur throughout the entire ocean surface, being particularly vigorous at few places, namely water formation sites, that constitute the engine for the basin-wide thermohaline circulation. In the Mediterranean Sea, water formation processes occur at places such as the Gulf of Lions, the Adriatic Sea, and the Aegean Sea, where winter vertical convection processes destroy density barriers throughout the water column. These processes allow an efficient mixing and exchange of properties between the upper and intermediate and deep layers leading to oxygenation of the abyssal waters (Leaman and Schott, 1991; Leaman, 1994; Mertens and Schott, 1998; Cardin and Gačić, 2003). These newly-formed deep waters spread over the basin, at horizons determined by their density, constituting a thermohaline cell of sinking dense water, counterbalanced by a displacement of the resident warmer and less dense deep water that spreads horizontally and eventually upwells.

In recent times, the interactions among thermohaline circulation, dense water formation, and anthropogenic forcing in the Mediterranean (Bethoux *et al.*, 1999) broke up a precarious equilibrium, resulting in abrupt changes in the circulation and physical properties. During the Eastern Mediterranean Transient (EMT) period, the Eastern Mediterranean thermohaline circulation underwent unexpected changes (CIESM, 2000a).

The Adriatic dense water contribution to the Eastern Mediterranean Deep Water (EMDW) ceased, the thermohaline circulation being sustained by intense dense water production in the Aegean Sea (Figure 2). The EMT has been attributed to important meteorological anomalies in the area, as well as to changes in circulation patterns (Roether *et al.*, 1996; Lascaratos *et al.*, 1999; Klein *et al.*, 1999; Malanotte-Rizzoli *et al.*, 1999; Theocharis *et al.*, 1999). Several mechanisms have been proposed to explain the EMT: reduced input of freshwater by rivers into the Mediterranean, strong anomalies in regional weather patterns as reduced precipitation and very low winter air-temperatures and changes in the large-scale atmospheric circulation (Boscolo and Bryden, 2001; Josey, 2003). None of these mechanisms, considered separately, would however justify the origin of the EMT (Jacobeit and Dünkeloh, 2005; CIESM, 2000a). Other long-term processes, such as the damming of main rivers resulting in salinity increase, may further influence the thermohaline circulation and the properties of sea water. Furthermore, salinity is increasing in the intermediate/deep layer of the Mediterranean Sea, whereas temperature is increasing in the surface layer (Roether *et al.*, 2007; Rubino and Hainbucher, 2007).

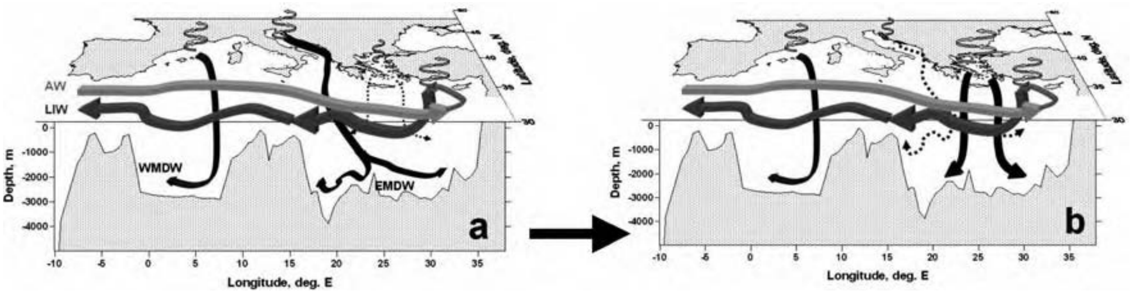

Fig. 2. Schematic representation of Mediterranean water circulation before (a) and during (b) the Eastern Mediterranean Transient (more detail in Theocharis, this volume).

Nevertheless, the spatio-temporal scale of the effects of processes like the EMT on the thermohaline characteristics of the Mediterranean Sea is still unknown. Recent observations in the year 2003 in the western Mediterranean indicate the propagation of the signal from east to west (Theocharis, this volume; Schroeder *et al.*, 2008): newly formed high-temperature and high salinity water seems to fill the deep layer, replacing the resident waters.

The concomitance of changes in the thermohaline characteristics of the deep water masses with anomalous winters (dry, markedly cold and very windy) as in 2005, contributes to an increase of very intense and persistent shelf water cascading in the Gulf of Lions (Font *et al.*, 2007), allowing the mixing of the former water masses with the very dense, fresher and colder water.

Changes in the water column thermohaline characteristics were also evidenced in the Eastern Mediterranean basin in 2003. A noticeable salt input in the intermediate layer (200 - 700 m), probably of Aegean origin, entered the Adriatic Sea. The formed dense water that subsequently outflowed through the Strait of Otranto (Rubino and Hainbucher, 2007; Roether *et al.*, 2007; Cardin and Gačić, this volume) suggests that the Adriatic Sea is resuming the role of source of EMDW. However, this water differs from the “classical” fresh and cold water mass observed before the EMT.

Obviously, Mediterranean circulation regimes result from multiple causes and no simple model can account for them (CIESM, 2005).

3. BIOLOGICAL RESPONSES

The main question stemming from the observed modifications in the physical forcing of the Mediterranean Sea concerns their possible impact on both biodiversity and ecosystem functioning

(BEF). Many signals of a response of the biotic component to large- scale physical changes are being identified.

3.1 Biogeographic responses of thermophilic species

The successful geographical spread of species of warm water affinity is the most evident phenomenon correlated with global warming. The increasing importance of thermophilic biota in the Mediterranean Sea can be described by two major processes of change, involving both indigenous ("meridionalization") and non indigenous ("tropicalization") species.

3.1.1 Northward extension and enhancement of native thermophilic species

In the last two decades, the advance of thermophilic species represented the first and most cited evidence of the linkage between climate change and distribution patterns of Mediterranean Sea biodiversity (Riera *et al.*, 1995; Francour *et al.*, 1994).

Climate warming is predicted to drive species ranges northwards in the Northern Hemisphere and southwards in the Southern Hemisphere (Parmesan *et al.*, 1999; Walther *et al.*, 2002) and this tendency is broadly confirmed in the Mediterranean realm (Bianchi, 2007). This phenomenon has been named "meridionalization" (Bianchi and Morri, 1993; 1994; Riera *et al.*, 1995), since "meridional" species, typical of the southern and usually warmer sectors of the Mediterranean Basin, are spreading northwards. More than 30 Mediterranean warm-water indigenous fish species have now been recorded north of their original geographical distribution. For some of these fishes, similar pole-ward extensions have been also recorded in extra-Mediterranean areas, thus reinforcing the consistency of this pattern (Azzurro, this volume). Similar range extensions have been recorded for sedentary organisms and benthic macro-algae (Bianchi, 2007; Munda, this volume; Despalatović *et al.*, this volume). Generally, an increase in richness ensues from climate warming (Hiddink and Hofstede, 2008). Moreover, our capacity to detect these changes is often unbalanced: it is reasonably easier to find a new species in a new area than to demonstrate its disappearance. As a result, these shifts usually result in the perception of increasing diversity at the local and regional level.

3.1.2 Increasing introductions and range extension of thermophilic NIS

Due to the increasing importance of Non Indigenous Species (NIS) in the Mediterranean Basin, much attention is being devoted to this theme (see CIESM, 2002a; CIESM Atlas). The arrival and establishment of NIS in the Mediterranean Sea is a continuous process which seems to have accelerated in the last decades (Galil, 2007a; Golani *et al.*, 2007; Zaouali, this volume). Today, more than 500 NIS are listed from the Mediterranean Sea (Galil, 2007a), mostly of tropical and subtropical origin. The increasing number, abundance, and success of thermophilic NIS reinforces the signal of climate trends towards warming and it has often been termed "tropicalization" (Andaloro and Rinaldi, 1998; Bianchi and Morri, 2004; Bianchi, 2007)[1]. Clearly, climatic forcing is enhanced by non-climatic reasons, such as the increase of marine traffic and the opening of the Suez Canal, resulting into an unprecedented form of basin-wide change, leading to a general biotic "homogenization" (Ricciardi, 2007) of the Mediterranean.

Rapid and significant range extensions have been recorded for exotic fishes (Ben Rais Lasram and Mouillot, 2008; Golani *et al.*, 2007) and other remarkable cases can be listed among tropical macroalgae (e.g. *Caulerpa racemosa* var *cylindracea*) (Verlaque *et al.*, 2000), crabs *Percnon gibbesi* (Galil, 2007a) and other invertebrates (Despalatović *et al.*, this volume). Particularly significant with regard to climate warming are the northward extensions of thermophilic NIS. These distributional changes are clearly evident for highly mobile species (see Azzurro, this volume, for a focus on fish) but also for some benthic invertebrates (see Çinar and Ergen, 2003 and references therein).

Even though some cases of replacement of IS by NIS have been recorded (see paragraphe 3.2), no final extinctions of Mediterranean IS can be registered. This led to adding NIS to IS, rapidly

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[1] The term "tropicalization" has been also used to define the effects of fishing on body size and age/length at maturity of fish stocks (Stergiou, 2002).

enriching Mediterranean species lists (Boudouresque, 2004; Boero and Bonsdorff, 2007). A biodiversity increase might be perceived as a positive consequence of NIS arrival and establishment, especially in the species-poor eastern basin where some thermophilic NIS have now attained commercial relevance (Galil, 2007a). On the other hand, the extension of these species may lead to biotic homogenization, increasing risk of local extinction of native species, reduction of genetic diversity, loss of ecosystem functions, and alteration of both habitat structure and ecosystem processes.

3.1.3 Flowering events of Posidonia oceanica

The seagrass *Posidonia oceanica* is one of the most important species of the whole Mediterranean Basin. For decades, the blooming of *Posidonia* was considered as extremely rare and unpredictable event (Giraud, 1977; Boudouresque, 1982), the species being thought as reproducing only asexually. Several flowering events of *Posidonia* meadows have been recorded since the early eighties, but fruits were usually not produced (Caye and Meinesz, 1984; Pergent *et al.*, 1989; but see Mazzella *et al.*, 1983). In later years, fruits have been recorded, but they were described as almost sterile, not giving rise to seedlings (Buia and Mazzella, 1991). In recent years, seedlings have been recorded as well (Buia and Piraino, 1989; Boyer *et al.*, 1996; Gambi *et al.*, 1996; Gambi and Guidetti, 1998). An extensive review by Diaz-Almela *et al.* (2007) of *Posidonia* flowering records of the past 30 years showed a positive relationship between the prevalence (flowering records per total records) and intensity of flowering intensity and the annual maximum of sea surface temperature across all the Mediterranean Sea. Furthermore, the high sea temperature anomaly that occurred in the summer 2003 coincided with an extensive flowering event in both western and eastern basins. The onset of successful sexual reproduction of *Posidonia oceanica* might be correlated with the trend in global warming without any causal relationship with it. It is tempting, however, to hypothesize that the reproductive performances of *Posidonia* are being favoured by global warming. Thus, flowering of *Posidonia* meadows could be used as a potential macrodescriptor of climate warming.

3.2 Species replacement

Climate warming can affect competitive interactions between native species of different thermal affinity. For example the increase of *Sardinella aurita* in the western Mediterranean might have contributed to the decrease of the anchovy *Engraulis encrasicolus* and the sardine *Sardina pilchardus* (Sabates *et al.*, 2006).

Climate change can induce species replacement, even in a subtle way, as in shallow-water marine caves. Monitoring endemic species of cavernicole mysids showed that *Hemimysis speluncula* declined while *H. margalefi*, considered as a rare species in the area (Marseille, France), was increasing. This phenomenon began while two major thermal anomalies were reported in 1997 and 1999. Different tolerances to temperature were demonstrated by both the species distribution range and laboratory experiments. Possible physiological properties may explain that populations of cold stenothermal species of endemic cavernicole mysids were replaced by congeners of warmer affinities, with a high risk of extinction (Chevaldonné and Lejeusne, 2003).

In the eastern Mediterranean, especially along the coasts of Israel, many NIS replaced, albeit not completely, IS performing similar ecological roles (Galil, 2007a). The lack of historical datasets prevents a proper evaluation of community changes, but evident replacements likely happened, as Goren and Galil (2005) showed for many species. These replacements are obvious for commercial fish: *Siganus rivulatus*, for instance, might have substituted the native herbivores *Sarpa salpa* and *Boops boops*; the Erythrean *Upeneus moluccensis* replaced the red mullet *Mullus barbatus* in commercial fisheries; *Saurida undosquamis* replaced *Merluccius merluccius*. As for invertebrates, the Erythrean mussel *Brachidontes pharaonis* displaced the indigenous *Mytilaster minimus*; the limpet *Cellana rota* replaced the native *Patella coerulea*; the non indigenous Penaeid prawn *Marsupenaeus japonicus* displaced the native *Melicertus kerathurus*; the starfish *Asterina burtoni* replaced *A. gibbosa*; the tropical oyster *Spondylus spinosus* outcompeted *S. gaederopus*; and *Chama pacifica* replaced *C. gryphoides*.

In the Adriatic, due to intensive fisheries, and maybe also to climate deterioration, the indigenous bivalve *Ruditapes decussatus* (the famous "vongola") became locally extinct at many harvesting

sites, and the remaining populations do not provide sufficient fisheries yields anymore. To replace this species, the NIS *Ruditapes philippinarum* was artificially introduced and it now dominates both the environment and the market that were once dominated by the true "vongola" (Occhipinti Ambrogi, 2002).
The case of *Ruditapes* in the Adriatic suggests an alternative scenario to that of envisaging a NIS as impairing IS by either competing or predating upon them. In this case, the decline of the IS was due to reasons that had nothing to do with the introduction of NIS. On the contrary, the NI Philippine "vongola" was deliberately introduced to replace the declining indigenous one.

The replacement of a IS by a NIS can occur due to multiple causes, sometimes even not mutually exclusive. The arrival of NIS, indeed, might lead to a complex network of interactions with IS (Figure 3).

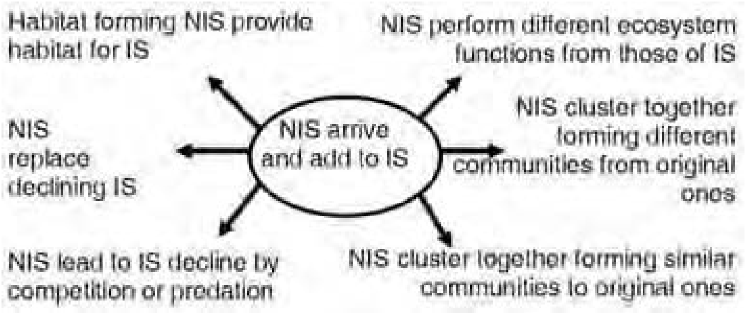

Fig. 3. Possible scenarios deriving from the arrival and establishment of Non Indigenous Species (NIS) and their relationships with Indigenous Species (IS). If a NIS is a habitat former (e.g., a canopy-forming alga) it can provide habitat space for NIS. A NIS might replace a IS whose populations are declining for other reasons than the arrival of the replacing species. A NIS can cause the decline of a IS by using local resources more efficiently (decline by competition), or by directly feeding on it (decline by predation). A NIS might increase ecosystem efficiency by adding novel functions due to features that are not shared by any IS. A group of NIS might cluster together and form either NIS assemblages that replicate those of the area of origin of NIS or, also, new NIS assemblages deriving from the clustering of NIS coming from different original areas.

In littoral environments, the establishment of alien organisms is not only occurring at species level but also at the assemblage level. A remarkable example is the so called "*Tetraclita* community": found in the south west coast of the eastern basin, it represents an exact replica of the "*Tetraclita* tropical community" found in the Red Sea (Ben Souissi *et al.*, 2007; Zaouali, this volume). Interactions among NIS possibly facilitate their establishment. For example, in the Red Sea the herbivorous fish *Siganus luridus* feeds on the alga *Caulerpa racemosa*, which has become its feeding resource also in the Mediterranean Basin where both are NIS (Azzurro *et al.*, 2007a).

3.3 Extreme events leading to mass mortalities

Temperature anomalies and higher sea surface temperatures (SST) have severely impacted entire shallow coastal ecosystems, causing the elimination of sensitive species as well as mass mortalities. The large-scale loss of biodiversity at the ecosystem level can turn diverse and structurally complex benthic and pelagic communities into simpler microbial ones (Sala and Knowlton, 2006).

Increasing frequency, severity and expansion of mass mortalities related to seasonal stratification (hypoxia/anoxia) or to temperature anomalies were observed in different parts of the Mediterranean. No other single environmental variable has changed more drastically in shallow coastal marine ecosystems worldwide than dissolved oxygen (Diaz, 2001). "Dead zones", caused by hypoxia and anoxia in bottom-water layers, are foremost in emerging environmental challenges (UNEP, 2004): hypoxia affects thousands of km^2 of marine waters all over the world and causes responses from the molecular to the ecosystem level (Wu, 2002). Since the 1980s, severe oxygen deficiencies have been reported also from the Northern Adriatic (NA) on a regular basis. The impacted areas range from several km^2 to up to 4,000 km^2 (see Riedel *et al.*, this volume).

In the NW Mediterranean Basin, large mass-mortality events were observed in 1997, 1999, 2003 and 2006. They have been ascribed to extreme warming events. In 1999, for instance, a positive thermal anomaly during summer, combined with an increase in the warm mixed layer down to a depth of 40 m, resulted in an extensive mortality of several dozens of invertebrate species (see Féral, this volume). The zone impacted by this climate anomaly concerned more than 500 km of coast, extending from the Italian to the French shore, and Corsica. Before these dramatic events, alarm signals already occurred: sponge illness in all the Mediterranean Sea during the 1980s (Vacelet, 1994), gorgonian necroses (Bavestrello and Boero, 1987; Harmelin and Marinopoulos, 1994), bleaching of *Oculina patagonica* from Eastern Mediterranean (Kushmaro *et al.*, 1996). Recent predictions on stressing agents (e.g. increasing SST, eutrophication) indicate that the problem is likely to become worse in the coming years (IPCC report, 2007; Selman *et al.*, 2008).

3.4 On the vulnerability of cold-water species

The biological diversity of the northern parts of the Mediterranean Basin, especially the Gulf of Lions and the Adriatic, has been thoroughly studied since at least two centuries. Several nominal species of cold-water affinity, restricted to the northern part of the basin, were described from those localities, especially at the sites of dense water formation. Some of these species have also been recorded from the Atlantic or the North Sea. However, it is probable that, upon molecular investigation, the Mediterranean nominal species of cold-water affinity will come out as separate from their Extra-Mediterranean counterparts.

Until now, more examples exist of species extending than retracting their distributions. However, climate-driven extinctions and range retractions seem to be a widespread consequence of global warming (Thomas *et al.*, 2006). According to the expected climatic trends, native species with cold-water affinity, confined to the northern sectors of the Mediterranean, will probably decline and eventually be lost.

Fucus virsoides is an Adriatic endemic and is considered a glacial relict. Due to its size and easy identification, and to its restricted distribution mainly to the Central and Northern Adriatic (Figure 4), *F. virsoides* is the flagship species of cold-water affinity IS in the whole Mediterranean Basin.

Fig. 4. Map of the distribution of *Fucus virsoides* in the Adriatic Sea based on records from Linardić (1949). According to Linardić (1949) the southernmost occurrence of *Fucus virsoides* was in Boka Kotorska Bay (cca. 42°27'N) on Montenegrin coast, where is still present (Mačić, 2006). Besides these records, which were considered as the southern limit of its range, this species was recorded in non-continuous zones on the Albanian coast, where its abundance decreases from the north to south (Kashta, 1995/96).

It is most common and abundant in the northern Adriatic and its quantity decreases southwards along the eastern Adriatic coast. *F. virsoides* disappeared at some areas of the Dalmatian coast and at offshore islands (Antolić, pers. comm.). Even in the northern Adriatic, the settlements of this fucoid are notably reduced, with a discontinuous distribution (e.g. in the Gulf of Trieste). Transitional reinstallments of *F. virsoides* belts, followed by disappearances, indicate a highly dynamic situation in the upper water layers. *Fucus virsoides* could be regarded as a threatened species, since its populations are going through an obvious trend of reduction along the whole Adriatic coast. According to the limited distributional pattern of this fucoid, the study of its physiology under controlled conditions is urgently needed to elucidate its behavior in the wild (e.g., Munda, 1977; Kremer and Munda, 1982; Lipizer *et al.*, 1995; Munda and Weber, 1996). Temperature responses of the Adriatic *Fucus virsoides* differ from those of Atlantic fucoids, as a result of long-term adaptations to Mediterranean conditions.

Fucus virsoides penetrates into low salinity areas and tolerates a certain degree of eutrophication, whereas the Mediterranean stenoecious *Cystoseira* species are more sensitive to environmental stress; they are habitat-formers, with relatively high biomass and floristic richness, giving rise to conspicuous multi-layered associations with a perennial crustose undergrowth and numerous ephemeral species within the layers of companion species and epiphytes (cf. Munda, l979; Fraschetti *et al*., 2002; 2006). Most *Cystoseira* species are Mediterranean endemics, with the exception of the boreo-Atlantic *Cystoseira compressa*, which is very resistant to environmental changes and persisted even in areas where all other *Cystoseira* species disappeared, as e.g. on the Côte des Alberes (Thibaut *et al.*, 2005) and the eastern Mediterranean. In the Strait of Sicily (Linosa Island) a total desappearance of *Cystoseira* species was observed by Serio *et al.* (2006). Due to the absence of other disturbing factors (eutrophication, sea-urchin grazing, fishing activities) in this area, the authors explained the disappearance of *Cystoseira* by surface temperature increases connected with global climate changes, as well as with changes in the deep circulation of the eastern Mediterranean basin. Alongi *et al.* (2004) described a similar scenario on the Pantelleria Island (from l973 to l999), with an increased proportion of tropical and Indo-Pacific floristic elements and a simultaneous decrease of species of cold-water affinity. Similar changes were observed also at the Tremiti Islands (Cormaci and Furnari, 1999; Cormaci *et al.*, 2000), and the eastern coast of Sicily (Marino *et al.*, 1999). *Cystoseira* populations underwent a considerable reduction also in the northern Adriatic where, similarly to the eulittoral *Fucus virsoides*, their distribution is patchy. As in other Mediterranean areas, they are replaced by Sphacelariales and Dictyotales (e.g., *Dictyota dichotoma*, *Stypocaulon scoparium*) (Alongi *et al.*, 2004). These replacements simplify the vegetation by loss of stratification, with a reduction of benthic algal and invertebrate diversity and biomass. In the 1970s, the deterioration of the Fucacean vegetation (*F. virsoides*, *Cystoseira*- and *Sargassum* species, along with most red algae) along the Istrian area was explained by drastic increases of pollution and eutrophication. From l940 to l970, however, the negative NAO was associated with a period of cooling, whereas from l970, when NAO became positive, a period of warming started. These might be mere coincidences, without causal links to the severe vegetational deterioration which occurred just at the start of the warming period.

The Laminarian species *Laminaria rodriguezii* was found from 80 to 200 m depth in the southern Adriatic (Sika od Trešijavca south of Dubrovnik and outside the Islands of Biševo, Lastovo and Mljet). This typically Mediterranean species was recorded from 20 to 60 m depth close to the Gibraltar Strait. There are no data about its altered distribution which could be connected with changes in deep water circulation. Other representatives of the *Laminariales* were introduced by shipping (e.g. *Laminaria japonica*, *Laminaria ochroleuca*, *Phylariopsis* spp and *Undaria pinnatifida*). *Chorda filum*, a cold boreal species reaching the subarctic regions, however, deserves special attention, since it occurs in the Etang de Thau, where it obviously finds suitable cold-water conditions (Riouall, 1985).

In spite of being much less conspicuous than algae, benthic invertebrates are very informative on biodiversity changes. The hydroids *Tricyclusa singularis* (Figure 5) (known only from the Gulf of Trieste), and *Paracoryne huvei* (Figure 6) (originally described from Toulon and recorded throughout the northern coast of the Western Mediterranean), for instance, are the only representatives of their genus and family. Their loss would be of great impact on biodiversity, not only of species, but also of genera and families. *Tricyclusa singularis* is unrecorded since 1865 (Boero and Bonsdorff, 2007) whereas the state of *Paracoryne huvei* is not well known.

Fig. 5. *Tricyclusa singularis*

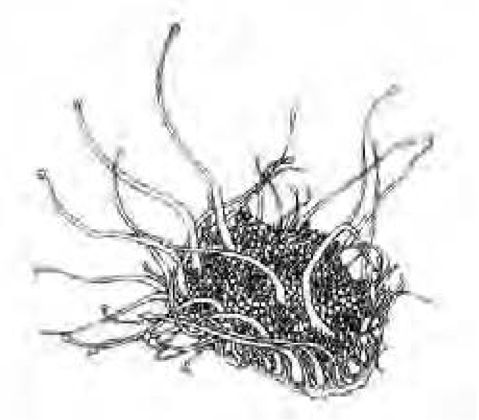

Fig. 6. *Paracoryne huvei*

Even planktonic species, such as *Pseudocalanus elongatus*, can have much restricted distributions, linked to their limits of tolerance. In the Northern Adriatic zooplankton relic cold-water species such as *Pseudocalanus elongatus* are decreasing because of the restricting winter appearance due to fall temperature increase (see Fonda Umani and Conversi, this volume).

Along the Tunisian coast, the distribution area of the mussel *Mytilus galloprovincialis* is increasingly restricted toward colder areas, less influenced by sea warming. Cap Bon is the south-eastern limit of the species on the coast of the Mediterranean. In the Gulf of Trieste, during the 2003 heat wave, mussels detached from the substrate as their byssuses lost adhesiveness.

The information on the dynamics of cold water fish species is scant. Climate change has been invoked as the primary cause for the decline of the anchovy, *Engraulis encrasicolus*, in the Adriatic sea as well as in the whole Mediterranean (Bombace, 2001). Anchovy stocks showed a drastic reduction following years of maximal climatic anomaly in the 1980s, without any apparent evident link with overfishing. Similarly, the sprat, *Sprattus sprattus*, declined in the 1990s. The sprat is a "cold species", typical of the northern Adriatic and the Gulf of Lyon, and presently scarce (Bombace, 2001; Grbec *et al.*, 2002). Temperature changes affected many other cold water species of the North Atlantic, including the families of gadidae, clupeidae and scombridae (Rose, 2005). These rapid changes are perceived as a consequence of direct or indirect effects of climate alterations, such as hydrological changes and mismatched timings in recruitment processes (Roessig *et al.*, 2003).

A thorough analysis of the old taxonomic literature, aimed at reconstructing the distribution of each species through its records, will generate a much needed exhaustive list of species typical of the northern part of the Mediterranean. The charting of records will lead to species distribution maps. Furthermore, the date of the last record will indicate the time elapsed since a given species was last seen. It will be useful to couple information on species to information on habitats, as suggested by Boero and Bonsdorff (2007) with their Historical Biodiversity Index.

Once identified, these species (and maybe habitats) can become "case studies". Being of cold-water affinity, in fact, they might suffer due to warming. Each species on these lists, hence, should be searched for, and its populations studied to ascertain their viability at all levels of biological integration (e.g., in terms of both genetic diversity and of vigour of individuals). The species that will not be found can be proposed as threatened by global warming, and if intensive search would not lead to further records, they might be considered as putative extinct, especially if their last published record is very old.

3.5 Are all Mediterranean cold water species the counterpart of Atlantic ones?

The distribution ranges of many species are thought to encompass the Mediterranean and, at least, the north eastern Atlantic. However even along the Atlantic coast at the level of biogeographical boundaries, for instance between the Atlantic and the English Channel, sharp genetic breaks are detected in certain species (Jolly *et al.*, 2005). Marine cryptic species are not rare (Knowlton, 1993;

2000), but genetic data are not available for most of them. Even well morphologically studied species that seem geographically undifferentiated may form distinct taxa, no longer exchanging genes across the Gibraltar strait or the Almeria/Oran front (Borsa *et al.*, 1997; Patarnello *et al.*, 2007).

This is the case, for instance, for the spatangoid sea urchin *Echinocardium cordatum*, first described in 1777 from the English Channel, considered as widespread from the Arctic Norwegian coast to the whole Mediterranean Sea (at least its northern shore). Despite the use of most up-to-date morphometrical methods and the availability of paleontological data, no morphological diagnostic character congruent with geographical distribution was reported. However, genetic data (nuclear and mitochondrial genome sequences) unambiguously revealed that *E. cordatum* is a species complex, comprising some Atlanto-Mediterranean allopatric pairs that probably diverged much before the Messinian (Féral *et al.*, 1995; Chenuil and Féral, 2003). Other spatangoid species (e.g. *Echinocardium mediterraneum, Spatangus purpureus, Brissopsis lyrifera*), however, did not reveal cryptic species or sharp genetic breaks on both sides of the Gibraltar Strait. Such phenomena stress the importance of genetic markers to properly assess biodiversity.

4. EXAMPLES OF CHANGES IN ECOSYSTEM FUNCTIONING

In addition to the global factors that will affect sea levels, caused mostly by warming water temperatures, extreme inland meteorological events, which seem characteristic of the climatic changes, will also affect the marine ecosystem functioning. The sea and the functioning of certain marine food webs are not independent of what occurs on the continent. It is in particular the case for the quantity and the quality of the organic matter of terrestrial origin (TOM) which arrives at sea *via* the rivers and runoff. This TOM depends especially on river flooding, on their intensity and duration, and of the quality of the soils which they covered and leached out, and also of the drainage capacity (flood-driven TOM transport) (see CIESM, 2006).

4.1 River inputs

Low river fluxes are leading the Northern Adriatic towards oligotrophy, affecting primary production. The western shore is under the influence of river runoffs (particularly from the Po River) that inject nutrients into the system, largely controlling primary production (PP) rates. The year 2003 was characterized, for example, by an extremely long drought, when PP dropped down to significantly low values (2003 average of 21.7 µg C m^{-2} h^{-1} vs. multiyear average of 44 µg C m^{-2} h^{-1}) as well as phytoplankton biomass. The tendency to oligotrophication was discussed by Fonda Umani *et al.* (2004) and can be underpinned by long-term chl *a* trends.

Climate models predict increasing variance in rainfall regimes, with increased frequency of droughts paralleled by unusual amounts of rainfall and floods (IPCC, 2007). Recent unusually high rainfalls, in combination with a saturation of soil due to preceding rainfall (and, to a lesser extent, human interference in the catchment basin), in fact, caused floods in northwest Europe. As a consequence of these changes, the Mediterranean region is subject to extensive river damming, which can have far-reaching impact on coastal foodwebs (see CIESM, 2006).

For instance, the isotopic signatures of the five most abundant flat fish species of the Gulf of Lions (*Arnoglossus laterna, Buglossidium luteum, Citharus linguatula, Solea lascaris* and *S. solea*) and those of their preys, illustrate their trophic dependance on river inputs.
Two trophic networks occur off the river Rhone, one based on the consumption of carbon of marine origin, the other on carbon of terrestrial origin. The transfers of the latter are most significant between 30 and 50 m depth, where river particulate organic matter (POM) sedimentation and its uptake by the benthos are the highest (Darnaude *et al.*, 2004). Interspecific differences in fish diet and habitat-use fully explain the intensity of terrestrial POM uptake during benthic life. The common sole (*Solea solea*) largely profits from the contributions in terrestrial POM, *via* deposit-feeding polychaetes (the main prey exploiting terrestrial POM for growth). The increase in abundance of these polychaetes stabilizes the whole life cycle of the species (Darnaude, 2005), and consequently the associated fisheries.

4.2 Shift from fish to jellyfish

An increase in jellyfish populations is being noted throughout the world, and the Mediterranean is no exception (CIESM, 2001; Boero *et al.*, 2008). The establishment of robust populations of *Rhopilema nomadica* in the Eastern Basin is causing severe impacts to human activities (Galil *et al.*, 1990), such as tourism, fisheries and industry management (impairment of cooling systems). The cubozoan *Carybdea marsupialis*, first recorded from the Adriatic in the mid-Eighties (Boero and Minelli, 1986) is now an obnoxious stinger. Also *Pelagia noctiluca* is increasing again, as happened in the early 1980s. Brodeur *et al.* (1999, p. 304) tried to find a causal link between oceanic forcing and increase in jellyfish abundance, concluding with the following statement: “Although we cannot rule out anthropogenic causes for the ecosystem perturbations we observed, our results provide an example of how climate change might influence an Arctic ecosystem, though we are not able to identify the underlying processes that transferred the physical changes through the ecosystem resulting in the observed increase of medusae biomass”. The possible impact of global change on jellyfish species should have favoured warm-water species, and this might be the case for the success of the sole representative of the tropical genus *Rhopilema* in the Mediterranean. Besides climate change, the global trend towards high abundances of jellyfish might also be correlated with overfishing, another worldwide phenomenon. Jellyfish and fish interact both as predators and competitors of each other. The removal of large fish, due to overfishing, is opening ecological space to jellyfish that probably are taking advantage of increased opportunities for growth (Boero *et al.*, 2008).

5. GUIDELINES FOR MONITORING

Ecology is an historical discipline: what happens now is the result of what happened in the past. History, furthermore, can tell us about the occurrence of apparently unexpected events, as happened for Adriatic mucilages, that have been traced back into history, when the invoked causes (e.g., enormous human pressures) did not act (Fonda Umani *et al.*, 2007). Ecological history can be reconstructed *a posteriori* by assembling past records by meta-analyses, but the availability of long time series, designed *a priori* to make crucial information available, is of paramount importance (see CIESM, 2003). The identification of a significant set of variables, both physical and biological (including genetics), is strongly required. Even simple measurements such as the summer temperatures along the nearshore water column to identify the shallowest seasonal thermocline, might prove extremely informative. The sudden thermocline lowering of 1999, for instance, led to mass mortalities of benthic organisms (Cerrano *et al.*, 2000; Féral, this volume).

5.1 Select appropriate macrodescriptors

Chemico-physical variables are measured at wide scales by satellites and, sometimes, by automated buoys. Biological variables (besides chlorophyll) cannot be measured in an automated way and are usually estimated by taking samples and by studying them in the laboratory. This is time-consuming and provides little scientific reward to the scientists involved. For this reason, long time series are quite rare.

The investment in extracting the information must be minimal. To have a reliable network of observations, it is important to use simple variables, easily identifiable at a glance (e.g., particular species used as ecological indicators, as is happening for the record of the expansion of NIS) or by simple measurements, requiring simple instruments (e.g., temperature measurements along the water column near the shore).

Given the variety and intensity of human impacts, there is an increasing need for predictive tools (e.g. response variables, bioindicators) describing the responses of marine biota to environmental factors, as well as the need to assess the environmental status of marine waters (e.g. models, specific biotic indices) according to the EU Water Framework Directive (WFD) (Diaz *et al.*, 2004; Occhipinti Ambrogi and Forni, 2004; Dauvin *et al.*, 2007). Macrobenthic organisms are often used as bioindicators to detect and monitor environmental changes, due to their rapid responses to natural and/or anthropogenic caused stress (e.g. Pearson and Rosenberg, 1978; Grall and Glemarec, 1997; Dauer *et al.*, 2000; Perus *et al.*, 2004). Benthic species/communities are good indicators because they include 1) species with different tolerances to stress, and 2) relatively long-living sessile organisms, unable to avoid unfavourable conditions. By integrating sediment/water quality conditions over time, benthic organisms can be regarded as “long-term memory of disturbance events” (Stachowitsch, 1992), and their presence/absence indicates temporal and spatial disturbances (Reiss and Kröncke, 2005; Zettler *et al.*, 2007).

5.2 Multiscale approaches

Monitoring can identify key events (e.g., 1987 EMT) not found elsewhere in the global ocean. What might be considered of local importance if recorded at a single place, becomes a far sharper signal if recorded over a regional or a basin scale. When assembled into a wider-scale picture, events seemingly irrelevant might turn into a global trend, as is the case for instance with the massive presence of jellyfish.

Marine Protected Areas (MPAs) might prove useful in this respect: organized as a monitoring network, and compared with non-protected sites, they could be used as references to compare the effects of putative climatic impacts in presence or in relative absence of human pressures.

Despite the increasing visibility of rapid physical and biotic alterations in the Mediterranean Sea, our understanding of climate-related impacts remains sparse and mainly based on anecdotical, fragmented, and generally local observations. Moreover, the existence of other important stressors such as fishing, pollution and habitat modification, is a clear obstacle to our understanding of this phenomenon and to our ability to predict changes. Long term studies at regional geographical scale are hence priority requirements for future studies.

5.3 Monitor biogeographic boundaries for key species

The Mediterranean basin is divided into several sub-basins, connected by straits and channels. Obvious changes in species distribution can be found at their geographic distribution limits and at certain focal spots, especially in correspondence of transitional areas and biogeographic boundaries (Bianchi, 2007).

Within the Mediterranean, a major transitional sector can be identified in correspondence of the Sicily Channel, separating the western from the eastern basin. Other sectors of strategic importance are the coldest sectors of the Mediterranean (i.e. the Gulf of Lyon, the North Adriatic and the North Aegean sea) clearly requiring to be monitored with special care.

The medusa *Rhopilema nomadica*, for instance, is confined to the eastern Mediterranean and its distributional limits should be properly monitored to record any extension towards the west. It is obvious, however, that different species have different boundaries, so this concept is to be used in a very careful way.

The southern coast of the Mediterranean might be considered as an “acclimatisation site” for tropical newcomers that, once adapted to the new conditions, might then spread throughout the basin.

5.4 Monitor genetic biodiversity

Biodiversity originates from genetic modifications that are sorted at the phenotypic level when gene expression faces environmental problems. There is a need to establish long-term monitoring of intra-specific (genetic) biodiversity (and gene expression levels) to study impacts of global change and human activity on selected species. Genetic markers characterized within populations at different geographical locations provide crucial information. If population genetic surveys are repeated in time, they provide reliable inferences and allow estimating the effective size of populations and species. Directly related to the potential of adaptation (available amount of genetic variability), the effective size of populations is obviously relevant to conservation biology. In addition, genetic monitoring allows inference on contemporary temporal variations in effective sizes and genetic variability. These parameters, associated with ecological studies, are of primary importance to detect when a population is endangered, and to predict the influence of environmental change on individual species (see Féral, 2002; and Chenuil, 2006 about genetic markers and biodiversity management).

Genetic markers are easily characterized by PCR from tiny pieces of tissue which can be dried or conserved in ethanol, though cooling is recommended for long term storage. This can easily be performed together with both faunal and floral sampling, constituting collections of numerous samples. cDNA libraries constitute a perennial collection (reamplifiable) of the set of genes expressed at a given time in an individual (or a set of individuals) living in a given environment. It is also possible to envisage whole genome amplification (WGA) of individual samples (pooling individuals) which can be re-amplified subsequently, and therefore could be used an infinite number of times, using the same set of individuals to validate hypotheses or to build new ones, when new methods will become available. Constituting collections to apply those techniques, now robust and widespread, to environmental monitoring should start as soon as possible.

5.5 Monitor metabolic performances

Biomarkers are often used as a proxy to establish the general conditions of an area (see CIESM Mediterranean Mussel Watch Program) by using the metabolic performances of some key species, that are especially sensitive to the putative change. The identification of the key species depends on the phenomenon under study. In the case of global warming, for instance, the species that might be affected in their metabolic performances might be those adapted to cold climates, such as the gorgonians (that underwent mass mortalities due to sudden warming of the water) or the species of glacial affinity, such as *Fucus virsoides*. Particular interest should be paid to the conditions of individuals at the boundary of the distribution patterns of their species.

The viability of individuals, as seen through the measurement of certain physiological performances, will be a useful indicator. On the one hand, the viability of the populations of cold-water species, for instance, might be used to ascertain their state of conservation under deteriorating conditions. On the other hand, the viability of warm-water species might be used to ascertain their spreading potential under more proper conditions for their survival.

5.6 Improve public awareness and participation

The use of macrodescriptors, easily recordable even by non-specialists, allows the involvement of laypeople, in order to add further data to those provided by the scientific community. Fishermen and divers make observations of macroscopic events such as red tides, mucilages, jellyfish blooms or the arrival of “strange” species that might be of paramount importance in supporting scientific evidence (see Azzurro, this volume, for cases regarding fish), increasing the coverage of larger geographical scales than those by the scientific community alone. This practice is important also within the scientific community. It might happen, for instance, that researchers working at a specific problem witness an event that does not fall within their specific expertise. These events usually pass unnoticed, whereas they might prove important in delineating large-scale phenomena that become apparent only after having reached an acute state, when the formation processes are already over.

Public awareness of the problem of global change and of the biological response to it is also important from a cultural point of view, leading to a better appreciation of the natural environment and to the acceptance of its protection.

6. Future prospects for the Mediterranean biota

The Mediterranean Sea is undergoing fast, dramatic changes. Added to the recent connection with warmer seas – *via* the opening of the Suez Canal some 150 years ago – and to intensive human impacts, global warming is transforming the Mediterranean into a much different sea than it was 20 years ago.

The ongoing climatic anomaly, leading to a warmer climate at a global scale, is following a sharp trend. While several projections have been made in terms of global temperature and sea level rise, the effects of climate change on the complex circulation regimes are still difficult to forecast. We know that climatic anomalies can bring profound, long-lasting modifications in the thermohaline circulation, water masses formation and mixing, as happened in the Mediterranean Sea during the EMT event (CIESM, 2000a). Such changes have also clear impacts on the geographic distribution of species (Astraldi *et al.*, 1995) as well as on deep-sea functioning and biota (Danovaro *et al.*, 2001). It is thus reasonable to suppose that the occurrence of another event of similar or greater magnitude (e.g. impairment of the three Mediterranean sites of dense water formation) could lead to even more dramatic consequences, but current knowledge impedes any further speculation.

Making predictions on what will be the future state of Mediterranean marine ecosystems implies even more uncertainties. Nevertheless, the attributes, the geographical scale and the synchrony of the biological signals observed in the last decades across the whole basin (see Box 1) provide enough evidence to trace some possible scenarios of the response of the Mediterranean biota to climate warming in the future.

BOX 1. Emerging biotic responses to climate warming in the Mediterranean Sea.

1- Northward extension and increase in the abundance of native thermophilic species (meridionalization)

Relevance to climate change: it is probably the first and most detectable early warning signal of climate warming in the Mediterranean Sea.

Geographic scale: northern and central sectors of the Mediterranean Sea. Similar poleward expansions of low latitude species are recorded all over the world.

Time scale: emerging evidence since the 1980s.

Taxa affected: mainly species with high potential dispersal rates (e.g. fish species) but also sedentary organisms and benthic macro-algae.

Positive effects: increasing species richness in the northern and central sectors of the Mediterranean Sea. A few North-expanding species are commercially relevant.

Negative effects: ecosystem changes; increasing risk of retreat of cold-temperate species, increased risk of extinction for endemic species, loss of regional faunistic distinctness.

Monitoring: current range limits of selected sentinels, biogeographic boundaries and cold areas.

2- Increase in the arrival, establishment and range extension of thermophilic NIS (tropicalization)

Relevance to climate change: the acceleration of successful introduction of thermophilic NIS in the Mediterranean Sea is a reinforced signal of climate warming. In fish, the correlation between invasion rate and climate has been recently proven.

Geographic scale: the whole Mediterranean, more evident in the eastern Basin.

Time scale: emerging evidence since the 1980s.

Taxa affected: all taxa, from microscopic algae to fish. Those with high dispersal rates are likely to expand more quickly.

Positive effects: increasing species richness in the Mediterranean, especially in the eastern basin. Several NIS are commercially relevant and their presence is perceived as favorable by the Levantine coastal fishery.

Negative effects: homogeneization of the Mediterranean biota; increasing risk of local extinction of native species (in the eastern basin, the populations of several native species have declined drastically after NIS introduction), especially endemic ones; reduction of genetic diversity; loss of ecosystem functions and alteration of both habitat structure and ecosystem processes. In many cases, changes can be considered irreversible.

Monitoring: incoming of new NIS, current range limits and abundance of established alien species, biogeographic boundaries and cold areas.

3- Northward retreat of cold water species

Relevance to climate change: it is a global harbinger of climate warming. In the semi-enclosed Mediterranean Sea, cold water species have obvious limits in their northern retreat and into finding suitable thermal refuges. In the Adriatic Sea, vertical migration to deeper, cold water is limited.

Geographic scale: Northern Mediterranean Sea, especially: Gulf of Lyon, North Adriatic and North Aegean Sea.

Time scale: first evidence in the 1990s but observations remain scarce.

Taxa affected: all species with affinity to cold waters (boreal and temperate species). Some examples are evident among fishes (e.g. *Sprattus sprattus*), algae and invertebrates. Concern has been expressed for endemic species.

Positive effects: none.

Negative effects: risk of species extinction, accrued by other stressors (e.g. overfishing, habitat destruction); collapse of some important commercial species; change in food chains.

Monitoring: abundance and distribution of cold water species, especially endemic ones, current range limits of selected sentinels, depth ranges and cold areas, especially endemism hotspots (e.g. Adriatic Sea and Gulf of Lion).

4- Increased frequency of mass mortality events

Relevance to climate change: several Mediterranean invertebrates (e.g., gorgonia corals) are particularly sensitive to temperature changes.

Geographic scale: single observations are localized (~10 km) but distributed across the whole Basin.

Time scale: significant mass mortalities on marine invertebrates have been observed in the last 15 years.

Taxa affected: mainly sessile species such as corals (i.e. gorgonians and anthozoans), sponges and associated invertebrates.

Positive effects: none.

Negative effects: increased risk of loss of habitat-forming species, with associated ecological consequences.

Box 1. Continued

Monitoring: physical parameters of the water column, sensitive species in vulnerable areas.

5- Population explosion of species (e.g. jellyfish outbreaks)

Relevance to climate change: population outbreaks are increasing all over the world and the Mediterranean Sea is not an isolated case. These phenomena are often the signal of a disfunction in the marine ecosystem due to the effect of multiple stressors. The relative importance of climate change in determining these phenomena is thus difficult to evaluate.

Geographic scale: the whole Mediterranean.

Time scale: the phenomenon seems to have increased significantly in the last 10 years.

Taxa affected: mainly jellyfish (e.g. *Pelagia noctiluca*) and different phytoplankton species.

Positive effects: none.

Negative effects: these phenomena can have serious ecological and socio-economical (tourism, fishery) impacts. Jellyfish outbreaks affect fish populations through zooplankton predation and changes in ecosystem functioning. Anomalous phytoplanktonic blooms may release toxic substances, cause mass mortalities of marine organisms and have harmful effects on humans through contaminated shellfish and fish populations.

Monitoring: frequency and magnitude of phytoplankton blooms and jellyfish outbreaks over large spatial and temporal scales.

6- Changes in phenology (e.g. timing of life-history events)

Relevance to climate change: phenological changes in natural populations are a direct consequence of climate warming and a global harbinger for this phenomenon. Scarce information is available for the Mediterranean Sea (see Bavestrello *et al.*, 2006, for hydroids).

Geographic scale: theoretically the whole Mediterranean, especially in areas more affected by temperature changes. Changes in phenophases have been observed all over the world, in many terrestrial, freshwater and marine taxa.

Time scale: scarce evidence, undefined time scale.

Taxa affected: theoretically mainly coastal species that undergo seasonal cycles.

Positive effects: these processes represent an acclimation response of species that can withstand climate change by accommodating their cycles of activity to the new conditions.

Negative effects: possible disruption of synchrony of biologically associated species; trophic "mismatch" and other changes at the community and ecosystem levels.

Monitoring: timing of recruitment and reproduction (e.g. gonadal maturity, flowering of *Posidonia*) of selected sentinel species.

7- Increase in formation of anoxia zones

Relevance to climate change: while the link between current hypoxic episodes and global warming has not been proven scientifically, the impact of these phenomena on marine ecosystems should be considered in the forecast of global future scenarios.

Geographic scale: low-oxygen events are known all over the globe. In the Mediterranean they appear as localized phenomena across the whole basin.

Time scale: likely prediction, undefined time scale.

Taxa affected: mainly sessile and slow-moving species.

Positive effects: none.

Negative effects: the formation of "dead zones" is among the worst predictions associated with climate warming. Risk of scale up effects leading to permanent changes in community composition and ecosystems.

Monitoring: mortality events, coastal thermocline, sea temperature and oxygen.

6.1 Towards a tropical Mediterranean Sea

The Mediterranean Sea is characterised by a surface temperature gradient increasing along the W-E axis of the Basin. The warmer Eastern Basin, with the exception of the colder area of the North Aegean Sea, is already dominated by species of warm water affinity and, in the last decades, has been enriched by a large number of exotic, tropical species (see CIESM collection of Atlas on Exotic Species). A further increase in the sea warming will not probably cause spectacular changes in its biota. The colder and less saline Western Basin, however, will become more and more similar to the Eastern Basin, allowing exotic and native warm-water species to spread and thrive in the northern areas. As a result, sub-regional peculiarities in biodiversity might eventually disappear, leading to taxonomic, genetic and functional homogenization (Olden and Rooney, 2006). This would have implications for the conservation of endemic species and biodiversity hotspots. Likely, Mediterranean tropicalization will affect also fisheries, as the stocks of cold-temperate species will decline. Further, as southerly species are generally smaller than northerly ones, a decrease in size of commercial species might be predicted, with consequent decrease of the value of fisheries (Hiddink and Hofstede, 2008).

6.2 Decline and extinction of cold water species

Mediterranean cold water species will not be able to migrate at higher latitudes, contrary to their Atlantic congeners, because the cold areas (Gulf of Lyon, North Adriatic and North Aegean) are already located in the northernmost parts of the Basin. If the temperature will continue to rise, the distribution ranges of these species will gradually shrink and eventually the species will be lost. In the summer, the increase in sea surface temperature will affect water stratification by shifting the thermocline at greater depths. Cold water stenotherm species will be pushed deeper, where temperatures are more stable, since they cannot withstand even short periods of warming (as demonstrated by the mass mortalities of benthic invertebrates due to sudden thermocline deepening in 1999). In the Adriatic, characterised only by shallow depths, species of cold water affinity will be at higher risk of extinction. Extinctions of marine species are rarely recorded (Carlton *et al.*, 1999): if the species of cold water affinity, endemic to the colder parts of the basin, will become extinct, these would be the first recorded marine extinctions due to global warming. At present, this species guild should be regarded as threatened by deteriorating environmental conditions.

6.3 From a fish to a jellyfish ocean

In the last decade there has been a marked increase in the frequency and extent of jellyfish outbreaks in the whole Mediterranean Sea. Although overfishing has been identified as the major factor causing such outbreaks, global warming undoubtedly plays an important role in facilitating the proliferation of tropical (e.g. *Rhopilema nomadica*) and native warm water (e.g. *Olindias phosphorica*) jellyfish species. If the effects of overfishing are amplified by climate warming, the likely, foreseen scenario will be a shift from a fish- to jellyfish-dominated ecosystem, with major consequences on food web diversity and functioning. Further, many stinging native and exotic jellyfish will become a serious health issue for coastal users and authorities with obvious negative consequences on the tourism economy.

7. RESEARCH GAPS AND PRIORITIES

The following main gaps in knowledge and research priorities have been identified on the way to improve detection and monitoring of climate-induced changes and enable future predictions of impacts.

To better assess the effects induced by changes in the Mediterranean thermohaline circulation and its hydrological features, biologists will need to know the answers to the following questions:

1. Is there a possibility of transient for the Western Mediterranean, as happened in the Eastern Basin?
2. What might happen if the three sites of dense water formation will not play their role anymore, or will play it at a lower intensity?
3. Is there a possibility of permanent stratification of the basin?
4. What are the consequences of this possible stratification for the deeper parts of the basin? Anoxic crises?

To date, there is a body of scientific evidence strongly indicating a significant alteration of the Mediterranean biota in response to climate warming. The important ecological (biodiversity and ecosystem functioning) and socio-economic (fisheries, health) impacts induced by climate change should receive much attention not only from scientists but also from policy and decision makers. A major effort should be made in particular to estimate uncertainty in the formulation of scenarios and improve prediction tools.

Research programmes focussing on the impacts of climate change on Mediterranean biota should consolidate and / or give priority to the following integrated actions:

1. Monitor coastal hydrological parameters.
2. Make existing information available (especially historic records) on the distribution of both warm- and cold-water species at the basin scale.
3. Standardize and simplify methodologies. Low-cost methodologies and observing networks could be used to collect large quantities of semiquantitative data.
4. Establish long term studies over wide geographical scales.
5. Identify key species as suitable descriptors of climatic changes.
6. Develop early detection systems, to track geographic expansions and retractions of species.
7. Identify simple biomarkers to monitor metabolic performance (e.g. physiological changes) in climate-sensitive indicator species.
8. Collect new data on the population structure and genetic diversity of selected species.