I - Executive Summary of CIESM Workshop 35

"Climate warming and related changes in Mediterranean marine biota"

by

Boero F., Féral J.P., Azzurro E., Cardin V., Riedel B., Despalatović M., Munda I., Moschella P., Zaouali J., Fonda Umani S., Theocharis A., Wiltshire K. and F. Briand

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).

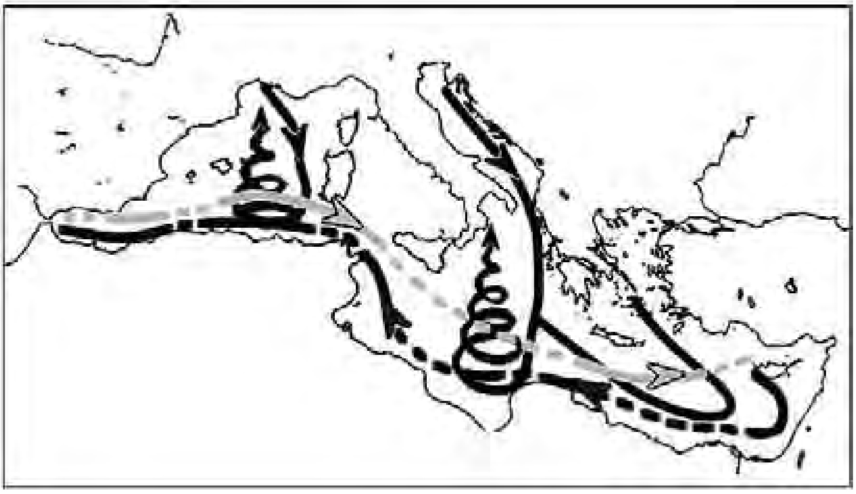

Fig. 1. Scheme of the Mediterranean Sea thermohaline circulation. Grey lines represent the surface/intermediate water mass circulation forced by Gibraltar-Atlantic inflow and Levantine Intermediate Water (LIW) formation processes occurring in the northern Levantine basin. Black lines indicate the meridional 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).

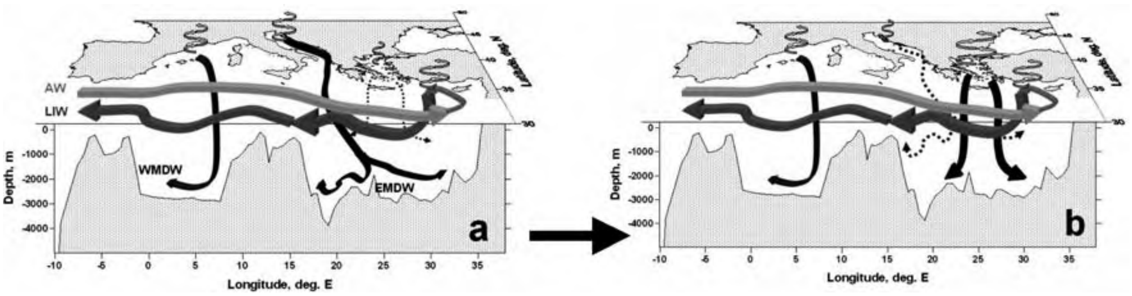

Fig. 2. Schematic representation of Mediterranean water circulation before (a) and during (b) the Eastern Mediterranean Transient (more detail in Theocharis, this volume).

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).

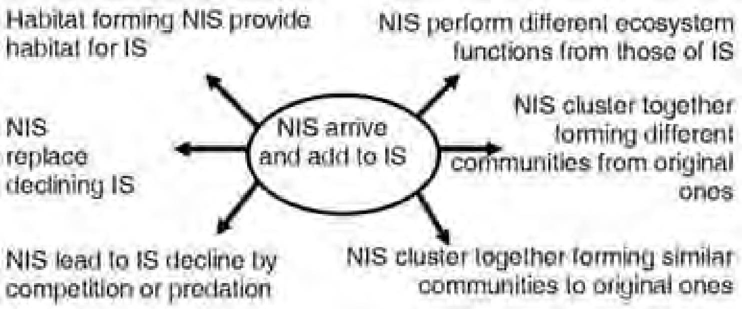

Fig. 3. Possible scenarios deriving from the arrival and establishment of Non Indigenous Species (NIS) and their relationships with Indigenous Species (IS). If a NIS is a habitat former (e.g., a canopy-forming alga) it can provide habitat space for NIS. A NIS might replace a IS whose populations are 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 km² 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 km² to up to 4,000 km² (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, 1979; 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 1973 to 1999), 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 1940 to 1970, however, the negative NAO was associated with a period of cooling, whereas from 1970, 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*

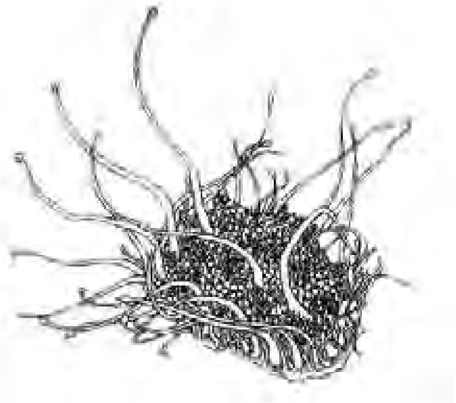

Fig. 6. *Paracoryne huvei*

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.

I - Executive Summary of CIESM Workshop 35

"Climate warming and related changes in Mediterranean marine biota"

by

**Boero F., Féral J.P., Azzurro E., Cardin V., Riedel B., Despalatović M.,
Munda I., Moschella P., Zaouali J., Fonda Umani S., Theocharis A.,
Wiltshire K. and F. Briand**

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).

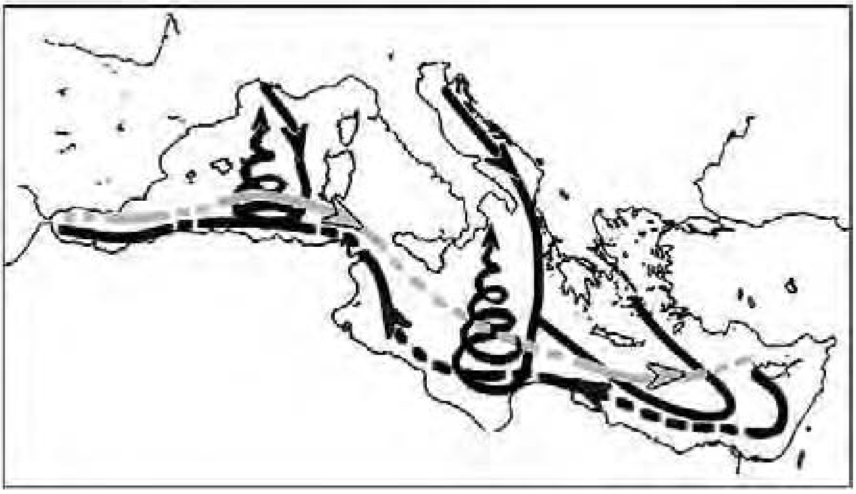

Fig. 1. Scheme of the Mediterranean Sea thermohaline circulation. Grey lines represent the surface/intermediate water mass circulation forced by Gibraltar-Atlantic inflow and Levantine Intermediate Water (LIW) formation processes occurring in the northern Levantine basin. Black lines indicate the meridional 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).

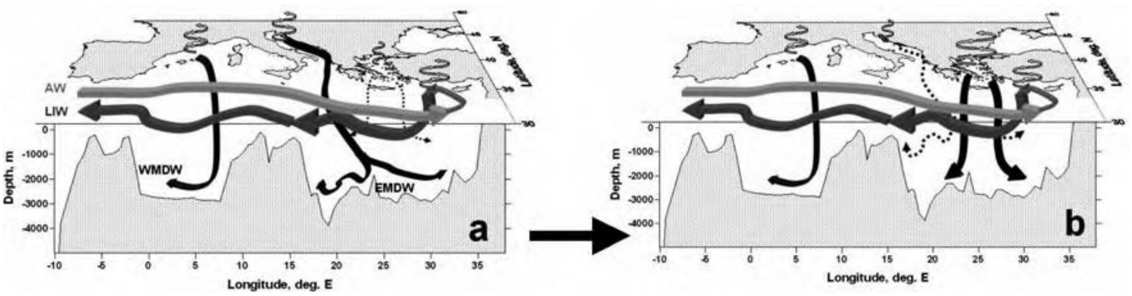

Fig. 2. Schematic representation of Mediterranean water circulation before (a) and during (b) the Eastern Mediterranean Transient (more detail in Theocharis, this volume).

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).

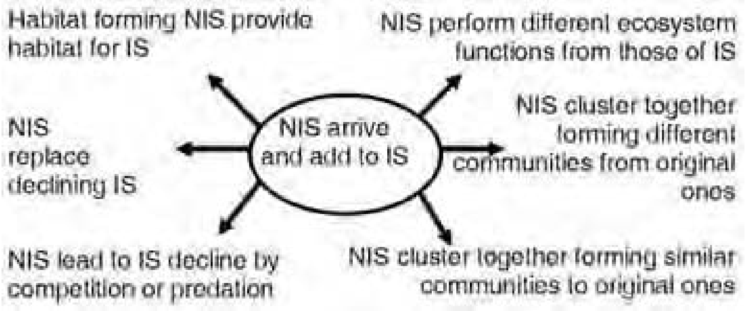

Fig. 3. Possible scenarios deriving from the arrival and establishment of Non Indigenous Species (NIS) and their relationships with Indigenous Species (IS). If a NIS is a habitat former (e.g., a canopy-forming alga) it can provide habitat space for NIS. A NIS might replace a IS whose populations are 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 km² 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 km² to up to 4,000 km² (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*

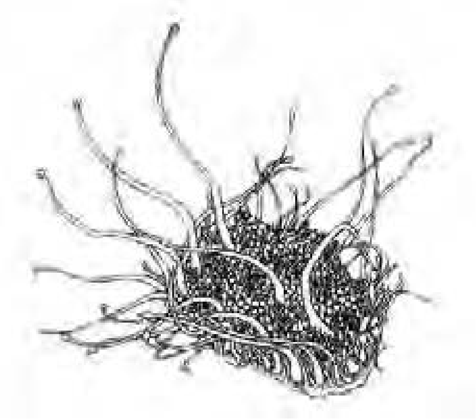

Fig. 6. *Paracoryne huvei*

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.

Do we expect significant changes in the Thermohaline Circulation in the Mediterranean in relation to the observed surface layers warming?

Alexander Theocharis

HCMR, Greece

INTRODUCTION

The Mediterranean Sea, an elongated, semi-enclosed almost isolated midlatitude basin that communicates with the Atlantic Ocean through the narrow (15 km) and shallow (~250 m) Strait of Gibraltar, is composed of two major interacting sub-basins, the western and eastern Mediterranean, connected by the Straits of Sicily with sill depth ~1,000 m. In each sub-basin there exist a number of smaller basins and seas. To the northeast the Mediterranean communicates with the Black Sea through the Strait of Dardanelles (61 km long, 1,2-6,0 km wide and 82 m max depth) that joins the Aegean and Marmara Seas. The Mediterranean region is a climate transition area, tightly related to the global climate variability with intense scale-interaction processes. It is not only under the influence of tropical phenomena, such as ENSO and tropical monsoons, but also under strong control of mid and high latitude meteorological systems (e.g. NAO). Current research has not yet reached conclusive results on these teleconnection mechanisms.

The Mediterranean Sea acts as a miniature ocean, where thermohaline circulation and dense water formation are concerned (Bethoux *et al.*, 1999). The analyses of the existing data sets indicate that the Mediterranean Sea is not in a steady state and is potentially very sensitive to changes in atmospheric forcing. It was believed, especially in the first half of the last century and until the early results of the multinational POEM project (Physical Oceanography of the eastern Mediterranean) in the ’80 s (Özsoy *et al.*, 1989; POEM group, 1992; Robinson *et al.*, 1991; Theocharis *et al.*, 1993; Malanotte-Rizzoli *et al.*, 1999), that the Mediterranean Sea was more-or-less in steady state. Small deviations from that steady state were revealed when the first trends in deep-water T and S were found (Lacombe *et al.*, 1985; Charnock, 1989; Bethoux *et al.*, 1990). Furthermore, abrupt changes since the ’90 s revealed that the Mediterranean is at present in a transitional state. Both long-term and abrupt temperature and salinity changes along with other crucial factors’ variability affected the thermohaline circulation of the entire basin.

THE MEDITERRANEAN THERMOHALINE CIRCULATION AND ITS VARIABILITY. RECENT CHANGES.

In the largest scales of interest, i.e. interannual and basin-wide scales, the circulation of the Mediterranean is determined by its exchanges of water and heat with the atmosphere through the sea surface and the water and salt with the adjacent seas through the Straits. The thermohaline circulation of the Mediterranean, which reflects the largest scale motion, is forced by the buoyancy exchanges and is driven by its negative heat and freshwater budgets. The Mediterranean is classified as a “concentration” basin, where evaporation exceeds precipitation and river runoff, with high-density water production in both sub-basins. It receives light, less saline waters from the Atlantic Ocean and to a lesser extent from the Black Sea at the surface layers and exports dense and more saline waters by underwater currents. The intermediate and deep layers of the Mediterranean Sea are renewed through water mass formation processes that take place at selected regions under favorable meteorological (low temperatures, strong and dry northerlies, increased evaporation**)** and oceanic (intense cyclonic circulation raising the isopycnals) conditions. At these areas surface and/or subsurface sea water that is in contact with the atmosphere, becomes denser than underlying waters, thus unstable, through intense air-sea interaction processes and sinks to deeper layers either balancing at intermediate depths or reaching deeper layers or the bottom of the ocean. The depth of the vertical mixing, namely convection, strongly depends on the pre-conditioning of the water column during previous fall and early winter period. In this process air temperature plays a very important role. This process is also effective in exchanging properties (i.e. heat, salt, oxygen, etc.) between the atmosphere and sea-surface and the euphotic zone and the abyssal depths (e.g. oxygenation of the deep and bottom waters, enrichment of the upper layers with nutrients). Intermediate, deep and bottom water formation occurs in the Mediterranean by both open-ocean and shelf processes during winter storm events. On the contrary, the neighboring Black Sea is an example of “dilution” basin, where precipitation and river runoff exceed evaporation and establish the “estuarine” type of circulation that is a less saline water outflow at surface and more saline water inflow at depth. In this case, the deep and bottom layers of the Basin remain isolated from the atmosphere and consequently have very low oxygen content. Such natural anoxic conditions are found below the surface low salinity water layer in the Black Sea.

Therefore, two kinds of thermohaline cells result in the Mediterranean. The first, the upper open conveyor belt, consists of (i) the non-return flow of low salinity Atlantic Water (AW), entering from the Gibraltar Strait, to the easternmost end of the Levantine Basin in the upper 150-200 m and (ii) the formation and westward spreading of the warm and saline (S~39.00-39.1 at the source area) Levantine Intermediate Water (LIW), at depths 200-400 m, to the Gibraltar Strait, where it enters the Atlantic Ocean. Secondly, there exist internal thermohaline cells in each of the Mediterranean sub-basins driven by deep water formation processes (Theocharis *et al.*, 1998). On average, the deep water annual production rate reaches 0.3 Sv at each sub-basin, compared to 1-1.5 Sv for the intermediate water mass (Lascaratos, 1993). The renewal of the deep waters is of the order of 80-100 years.

Western Mediterranean

The major source of dense waters for the Western Mediterranean is considered to be the Gulf of Lions (Stommel, 1972; Hopkins, 1978). Open-ocean convection is the mechanism responsible for the formation of the Western Mediterranean Deep Water (WMDW) (MEDOC group, 1970; Schott and Leaman, 1991; Jones and Marshall, 1993; Send *et al.*, 1996), where heat-dominated local buoyancy flux appears to determine the depth of the deep water convection (Mertens and Schott, 1998). In addition to the open sea formation, dense water formation may also take place on the shelf (Durrieu de Madron *et al.*, 2005). Send *et al.* (1999) suggested that variable deep water formation driven by varying local atmospheric forcing which is subject to NAO-related variability is responsible for the changes in the deep water characteristics that include interannual, decadal and longer term variability. In Tsimplis *et al.* (2006) review it is suggested that positive temperature and salinity trends are observed since the 1950s. However, extensive analysis of the new complete hydrographic data sets carried out by several authors has revealed significant changes and trends in the properties of the entire water column in both Mediterranean sub-basins. Various causes were proposed for the above trends, including anthropogenic influence, local atmospheric conditions and hydrological conditions during dense water formation events, and the first signature of global warming. More specifically, recent observations have shown an acceleration of the trends, which is attributed to the effect of the propagation of the signal of the Eastern Mediterranean Transient (EMT, see the following paragraph), from east to west (Schroeder *et al.*, in press). The authors give insights into the origin and the propagation of the new deep water towards the basin interior and show the evolution of the deep characteristics. In less than two years almost the whole deep western basin has been filled with highly saline and warm new deep water, which substantially renewed the resident deep water. Moreover, time series measurements at a mooring site on the deep slope of the NW Mediterranean (October 2003-July 2005) revealed a sequence of effects on the deep water properties due to the anomalously dry, very cold, and very windy winter of 2005. At the end of January, a dense water mass that was warmer and saltier than usual reached the deep slope. Almost simultaneously, cascading episodes were observed in the Gulf of Lions' submarine canyons. Thirty days later, colder, fresher and even denser waters reached the mooring site, with a 5-day delay from an intensification of the Gulf of Lions' cascading. The signature of these waters was detected for 35 days, and by late spring 2005 a new stable water mass situation was reached, with higher temperature and salinity values than those characterized the deep layer from October 2003 to January 2005 (Font *et al.*, 2007).

Eastern Mediterranean

As part of the steady-state concept, the major source of the deep waters of the Eastern Mediterranean since the beginning of observations (1908) has been considered to be the Adriatic Sea (Pollack, 1951). The Aegean Sea has also been reported as a sporadic secondary source of dense waters (Nielsen, 1912; Miller, 1963; Schlitzer *et al.*, 1991). However, the amounts produced have never been enough to drastically influence the thermohaline structure of the eastern Mediterranean. Abruptly, during the late '80 s the thermohaline circulation and the deep-water hydrological properties of the eastern Mediterranean Sea underwent a strong and rapid change, known as the "Eastern Mediterranean Transient (EMT)" consisting of a shift of the source of the eastern Mediterranean deep waters from the Adriatic to the Aegean (Figure 1) (Roether *et al.*, 1995; CIESM, 2000a). The Aegean Sea became the new more effective source than the Adriatic Sea, since it produced not only denser water, namely the Cretan Deep Water (CDW), but also higher volumes (1 Sv for seven years period [1987-1995] instead of 0.3 Sv). From 1988 to 1995, massive outflow of CDW occurred through the Straits of the Cretan Arc towards the Ionian and

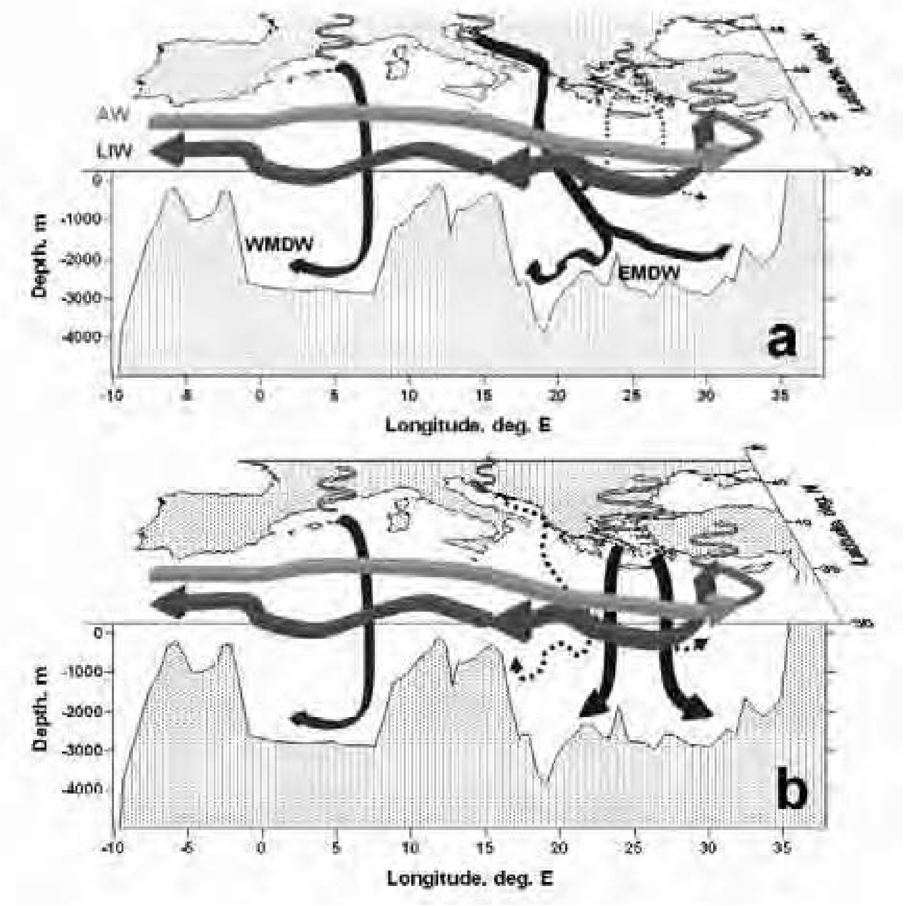

Fig. 1. The thermohaline cells of the Mediterranean Sea before the EMT (a) and after the EMT (b) (from Tsimplis *et al.*, 2006).

Levantine basins. The CDW being of particularly high density (29.3 kg/m^3) sank into the near-bottom layers, uplifting the older deep waters of Adriatic origin, thus strongly affecting the deep water column structure and influencing the exchange between the Aegean and the adjacent basins with the intrusion of Mediterranean Water, the origin of which is the deep-water lying between the Levantine Intermediate Water (LIW) and Eastern Mediterranean Deep Water of Adriatic origin (EMDW). This water, namely Transitional Mediterranean Water (TMW) has formed a distinct layer in the Cretan Sea (200-600 m) during the first stages of EMT, strongly affecting the stratification of the water column and the environmental parameters (Theocharis *et al.*, 1999). Since 1995 the EMT event started to decay, but the rate of the Eastern Mediterranean system relaxation as well as its final state (old or modified) remains still unclear. After the mid-nineties, the Cretan Sea has returned to the pre-EMT condition of exporting small amounts of dense water that does not reach the bottom of the Ionian and Levantine basins, but ventilates the depths of 1500 - 2000 m (Theocharis *et al.*, 2002). Now, it appears that the main contribution of dense water for the Eastern Mediterranean has already passed back again to the Adriatic (Klein *et al.*, 2000). The above "new" findings showed that significant changes in the functioning of the thermohaline circulation could occur rapidly. A recent detailed account of the changing hydrography and the large-scale circulation of the deep waters of the Eastern Mediterranean that resulted from the unique, high-volume influx of dense waters from the Aegean Sea during the 1990s, and of the changes within the Aegean that initiated this event, the so-called 'Eastern Mediterranean Transient (EMT) is given by Roether *et al.* (2007).

Tsimplis *et al.* (2006) reviewed several scenarios, based both on observations and modeling experiments, that have been offered in order to provide insight to the EMT; among others, the internal redistribution of salt through deep water formation processes in the Aegean, based on a sequence of oceanographic observations (Roether *et al.*, 1998 and Klein *et al.*, 1999). However, anomalous atmospheric conditions, such as persistent reduction of precipitation and very low winter temperatures (mean air-temperature 2^{o}C lower than average winter values) triggered the second main phase of the EMT (Theocharis *et al.*, 1999). On the other hand, long term processes, as damming of main rivers resulting in salinity increase, offered as well the suitable background for changes in the thermohaline circulation and the properties of the sea water.

Additionally, during the EMT period, a new intermediate water mass was generated in the Cretan Sea, in the South Aegean Sea, namely Cretan Intermediate Water (CIW), with similar to LIW characteristics, that replaced the LIW within the western region of the Eastern Mediterranean (Ionian Sea), the latter being blocked and recirculating within the Levantine Basin (Malanotte-Rizzoli *et al.*, 1999). This water mass rich in salt fed the Adriatic during the following years, thus strongly supporting the reactivation of the previous long-term dominance of the Adriatic (Theocharis *et al.*, 2006; Manca *et al.*, 2006).

NEW OBSERVATIONS AND CONCLUSIVE REMARKS

From the above it is obvious that temperature is a key parameter in the water mass formation process in the Mediterranean and the revealed variability of the characteristics of the produced intermediate and deep waters, thus affecting the thermohaline circulations of the entire basin. An interesting example of sea surface warming is shown by Raitsos *et al.* (in press) in the Aegean Sea (eastern Mediterranean Sea). The authors used a 20-year series of satellite SST values. Sea Surface Temperature (SST), monthly means derived from AVHRR (1985-2005), were plotted for the Aegean Sea (Figure 2). This 21-year time-series showed that there was a pronounced change during the last decade with evidence for a stepwise increase in 1994. As can be clearly seen, thereafter the annual SST mean remained above the overall mean, whereas the opposite occurred before 1994. During the first decade the annual SST mean was 18.5ºC compared to 19.3ºC in the second decade. However, regionally within the Aegean Sea, the differences of the mean SST are much larger, and can reach 2.5ºC. The most prominent alterations occurred during the summer months and particularly in August (1.2ºC difference between the two decades), along with smaller changes during the winter months. These changes are also evident in the surrounding areas such as Levantine and Ionian Seas. Such trends will affect the water mass formation processes. The decay of the deep water production and the continuing intermediate water production after 1995 reveal a dependency the formation processes and the characteristics of the water produced on the

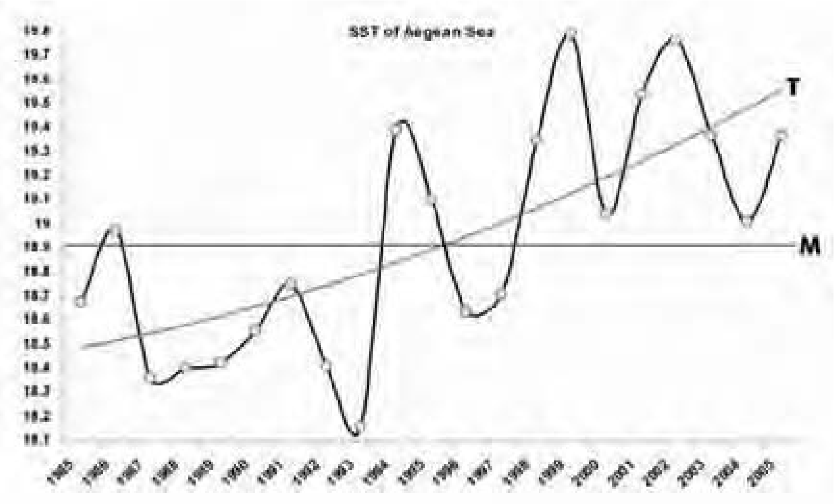

Fig. 2. Trend (T) and mean SST (M) in the Aegean Sea for 20-year period (adapted from Raitsos *et al.*, in press).

variability of temperature (Theocharis *et al.*, 2002). Such studies in combination with monitoring of the water properties and of heat and water air-sea fluxes will offer better insight in the thermohaline circulation changes in the Aegean and the Mediterranean. The continuous effort for monitoring of the deep water characteristics will reduce the higher frequency variability and relatively enhance the climatic signals. Besides, in combination with other bio-geo-chemical parameters, these studies will provide information on the CO_2 absorption rates.

Are decadal variations of Adriatic thermohaline properties related to the Eastern Mediterranean Transient (EMT)?

Vanessa Cardin and Miroslav Gačić

OGS, Trieste, Italy

1. INTRODUCTION

The Adriatic Sea, due to its location (the northernmost part of the Mediterranean Sea), to mountain orography and to a relatively large amount of freshwater river run-off, represents on one hand, a dilution basin, and on the other, together with the Gulf of Lyon, a convection site where deep water is formed. In fact, the southern Adriatic Sea is considered a major site of deep water formation and the origin of the semi-closed thermohaline cell in the Eastern Mediterranean. The dynamics of the area is dominated by the presence of a quasi-permanent cyclonic gyre that in the winter season creates the conditions for the open-ocean convection and the production of dense and oxygenated waters. Studies show that indeed two types of dense water formation processes occur during winter within the Adriatic Sea: the major portion of the Adriatic Deep Water (ADW) is formed through open ocean convection inside the Southern Adriatic Pit (SAP) within the cyclonic gyre, while the remaining dense water is formed on the continental shelf of the Northern and Middle Adriatic that moves southward and ultimately sinks to the bottom of the SAP (Ovchinnikov *et al.*, 1985; Bignami *et al.*, 1990; Malanotte-Rizzoli, 1991). The ADW exits through the bottom layer of the Otranto Strait into the Ionian, joining the Eastern Mediterranean Deep Water (EMDW), which occupies the bottom layer of the entire Eastern Mediterranean (Civitarese *et al.*, 1998). This water has distinct characteristics with respect to other Mediterranean water masses, being less saline and colder (salinity S ~ 38.6; temperature T ~ 13°C).

2. DECADAL VARIATIONS WITHIN THE SAP

Despite the canonical description, thermohaline properties in the Adriatic Sea have varied prominently in the last two decades. In the early 1990 s a critical change in the Eastern Mediterranean circulation took place with the Aegean, which became the most important source of the Eastern Mediterranean Dense Water (EMDW) in place of the Adriatic. Maximum Aegean water outflow took place in 1993 (Roether *et al.*, 2007). The event was named Eastern Mediterranean Transient (EMT) and has been attributed to important meteorological anomalies in the area, as well as to changes in the circulation patterns in the Levantine basin (Roether *et al.*, 1996; Lascaratos *et al.*, 1999; Klein *et al.*, 1999; Malanotte-Rizzoli *et al.*, 1999; CIESM, 2000a). Following the EMT, the deep layer of the Eastern Mediterranean, filled earlier by Adriatic waters, was occupied by waters of Aegean origin having higher temperature and salinity (Schlitzer *et al.*, 1991).

In this study, CTD data coming from cruises carried out between 1990 and 2007 in the area of 1°lat x 1°lon in the SAP have been considered. Stations deeper than 1,000 m for each cruise have been averaged to get a single mean profile per campaign (Figure 1). Average temperature and salinity over the water column below the permanent thermocline in the centre of the South Adriatic cyclonic gyre showed a decadal variability and attained their minimum values in the mid 1990 s. Hereafter, the time series will be divided into three parts based on the observed water mass characteristics: the first one from 1990 to 1995 corresponds to the maximum Aegean outflow and to the EMT; the second from 1996 to 2003 is characterized by the presence of low density water in the area; finally, the third from 2004-2007 is when saltier and warmer waters were entering the Adriatic.

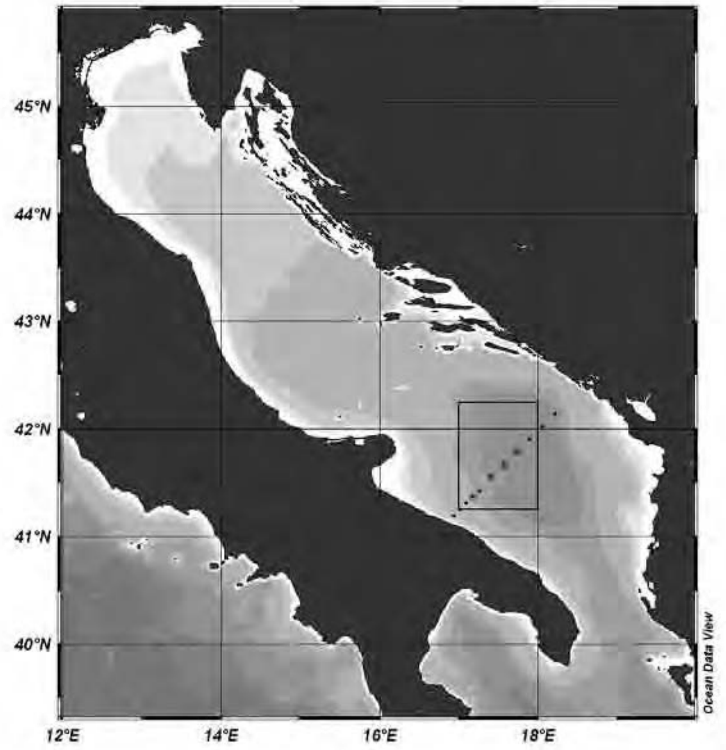

Fig. 1. Study area (parallelogram shows the area for which average thermohaline profiles were calculated).

The decrease in salinity between 1990 and 1995 in the intermediate layer (200-800 m) (Figure 2a) is consistent with the inflow in the Adriatic of a “transitional water,” which is less saline, colder and denser than the LIW (Theocharis and Lascaratos, 2004). This event is thought to be a consequence of the EMT. The maximum dilution of this intermediate water took place in 1995 (- 0.092 psu in salinity) with an average layer value of 38.66. As will be shown later, this salinity decrease in the intermediate layer had a negative impact in the convective process and mixed layer depth, since the high salt content in this layer (essential ingredient for the deep water formation process) was not so prominent. The minimum in salinity coincided with the maximum effect of the EMT in the Adriatic (Klein *et al.*, 2000). At the same time there were two or three rather mild winters that, combined with high stability of the water column, resulted in a weak vertical convection. The year 1994 was, for example, characterized by a net heat gain, a fact without precedent in the entire study period. Since then an inflow of much saltier, and warmer intermediate water was observed in the Adriatic, which went on until 2005 where a maximum difference of 0.15 psu and a mean layer average value of 38.82 was measured. As far as the temperature is concerned, a decrease was observed until 1994 (-0.418°C from the beginning of the ‘90s) followed by an increase reaching the highest value (14.5°C) at the end of 2002. Thus, during the ’90s and until 2003, the period of salinity increase/decrease goes together with an increase/decrease in temperature. Nevertheless, this pattern was broken at the beginning of 2003, which seems to be a transitional year. After that, an inflow of a new saltier but colder water mass was observed. It is very important to notice that the layer-averaged density in the third period never reached the value observed in 1992 when one of the strongest sets of winter conditions and deep convection took place (Cardin and Gačić, 2003; Gačić *et al.*, 2002a,b) (Figure 2b). It should be remembered that these values represent the vertically averaged density.

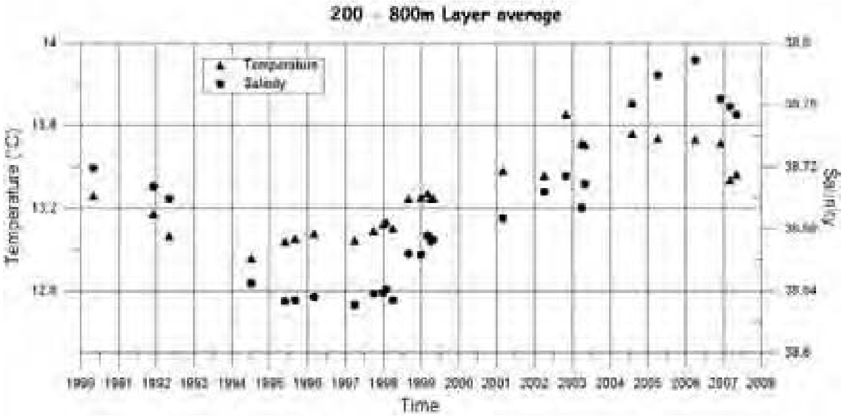

Fig. 2a. Time-series of average potential temperature and salinity data for the 200-800 m layer.

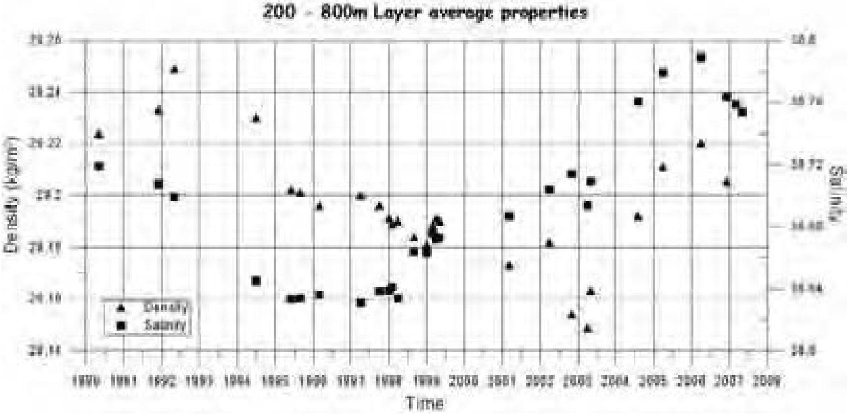

Fig. 2b. Time-series of average density and salinity data for the 200-800 m layer.

The T-S diagram (see Plate C a, page 109) for the 200-600m layer gives a clear picture of the evolution of the thermohaline properties in the area between 1990 and 2007. In concordance with what was seen in the time series (Figure 2a,b), a clear division into three periods can be constructed using the T-S diagram of water masses: 1) the period influenced by the transient (1990-1995) exhibiting temperatures between ~ 13.0°C and ~13.5°C and salinity not higher than ~38.75 psu; 2) a post-transient period between 1996 and 2003 characterized initially by slight variations in temperature and salinity followed by a sharp increase either in temperature or in salinity; and, finally, 3) the period (2004-2007) with saltier and warmer water occupying the intermediate layer. The last period is denser and better mixed showing higher temperature and considerably higher salinity than the period representing the transient, which is characterized by relatively low temperature.

The weakening of dense water production of Adriatic origin as mentioned earlier can be attributed to a concomitance of factors, including the amount of salt entering through the Strait of Otranto and the buoyancy forcing. The water formed, which eventually flowed out from the Adriatic (Manca *et al.*, 2002), was not dense enough to mix with the EMDW and flowed above the bottom layer occupied by EMDW. Nevertheless, from 2004 onwards the noticeable salt input, probably of Aegean origin, to the Adriatic intermediate layer, which was mentioned by Rubino and Hainbucher

(2007) and Roether *et al.* (2007) among others and corroborated by our analysis, suggests the possible strengthening of the role of the Adriatic waters as a source of the EMDW. However, this water differs from the "classical" fresh and cold water mass observed before the EMT.

Looking at the bottom layer of the Adriatic basin for the same observation period, the characteristics of the water differed profoundly in the '90s from those that were observed after 2003 (Figure 3a). As in the intermediate layer, the data show a decrease in the thermohaline properties (Δθ ~ 0.2°C and Δsal ~ 0.008 psu) during the EMT until 1995 followed by a gentle increase until 2003 when a noticeable salt input and higher temperature (Δθ ~0.3°C and Δsal ~ 0.009 psu) is indicated. In fact, the more recently formed ADW is saltier, warmer and denser than the one observed during and shortly after the EMT. The latter is characterized by temperatures below 13°C and salinities lower than 38.68 psu. On the other hand, this recently formed ADW shows temperatures and salinities higher than 13.25°C and 38.75, respectively.

These results are consistent with the major salt intrusion from the Ionian mentioned above, which implies an increase of salt available for convective events in the Adriatic basin. The average density time series for the bottom layer below 800 m (Figure 3b) shows higher values at the beginning of the '90s than for the period 2004-2007. Severe winters took place at the beginning of the '90s (Cardin and Gačić, 2003; Gačić *et al.*, 2002a,b; Manca *et al.*, 2002) with convection reaching the bottom allowing for mixing of the entire water column. This was possible principally due to the buoyancy loss that took place during winter periods. Contrary to this, although there was a high salt content in the intermediate layer, no deep convection took place after 2004, presumably due to a decrease in the buoyancy fluxes.

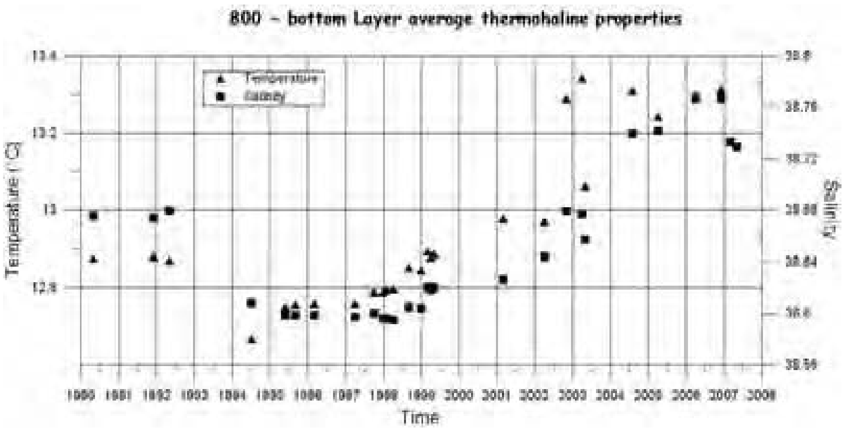

Fig. 3a. Time-series of average potential temperature and salinity data for the 800 m - bottom layer.

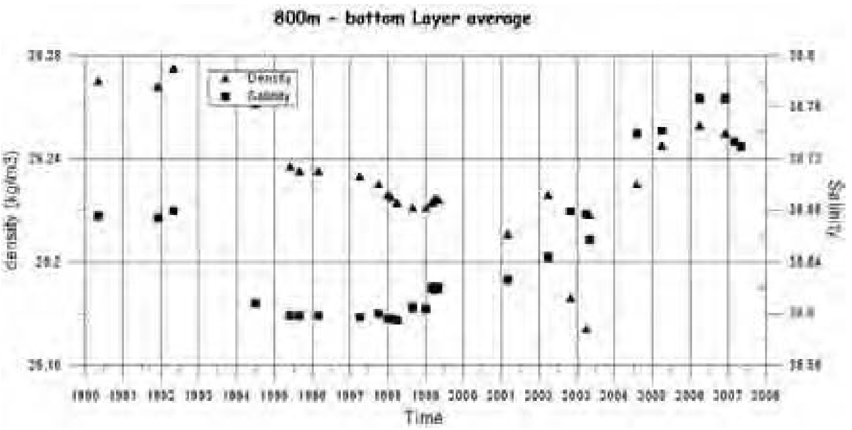

Fig. 3b. Time-series of average density and salinity data for the 800 – bottom layer.

T-S diagrams further reveal clear distinctions between the three periods. Cruises after 2004 show near-bottom water in the SAP with the highest density recorded reaching values greater than 29.3 kg/m (see Plate C b, page 109). This dense water probably remained in the deep layer without exiting the Adriatic Sea. Yet, this water could be mixed and uplifted due to deep convection in concomitance with high buoyancy fluxes or laterally advected water. In contrast with the later period, the intermediate period (1996-2003) is characterized by the lowest bottom water density barely reaching 29.22 kg/m^3. From the T-S diagrams it is also evident that the bottom water density variations are mainly due to salinity changes.

3. SECTIONS ACROSS THE SAP

The hydrographic data collected can also be used to show the variations across the SAP during the three distinct periods identified in the records. The vertical temperature, salinity and density distributions for three different cruises representing the three periods are shown in Figure 4a,b,c. The individual cruises were respectively carried out in April 1992 (Figure 4a) representing the low salinity and temperature period within the influence of the EMT, in March 1999 (Figure 4b) well after the maximum dilution period and finally in March 2005 (Figure 4c) during the high salinity period.

The three chosen situations (winter 1992, 1999 and 2005) show, decadal variability as well as other some common features. The thermocline/halocline is present in all three cases at the Otranto Sill horizon (800 m), but the bottom water in 1999 had extremely low salinity values, suggesting strong intrusion of fresh water of north Adriatic origin. The 1992 transect shows relatively low salinity and temperature with a maximum for both variables in the intermediate layer. More or less the same spatial pattern of temperature and salinity can be observed in the 1999 transects. In 2005 the intermediate salinity and temperature maximum is absent and the spatial pattern is characterized by maximum values at the surface and a prominent vertical gradient. Also, in that year both state variables are the highest of all three analyzed situations.

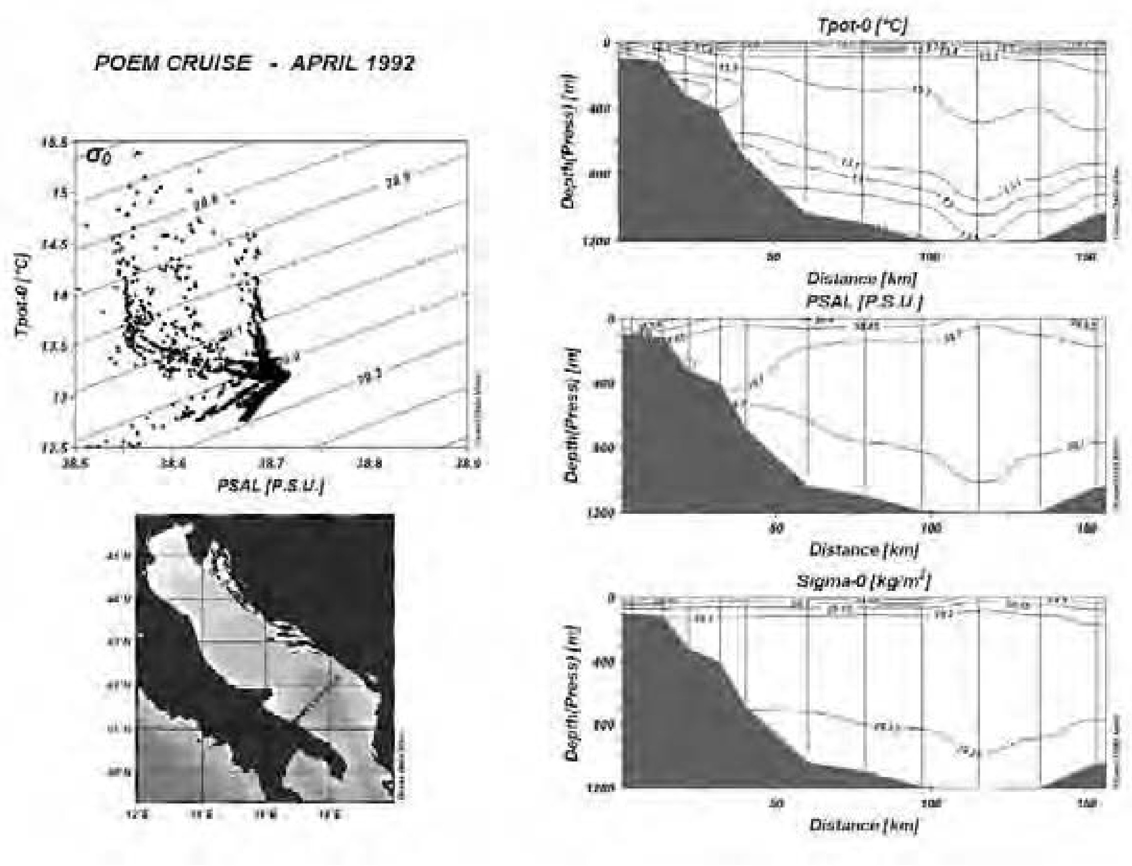

Fig. 4a. Vertical transects of potential temperature, salinity and density for April 1992.

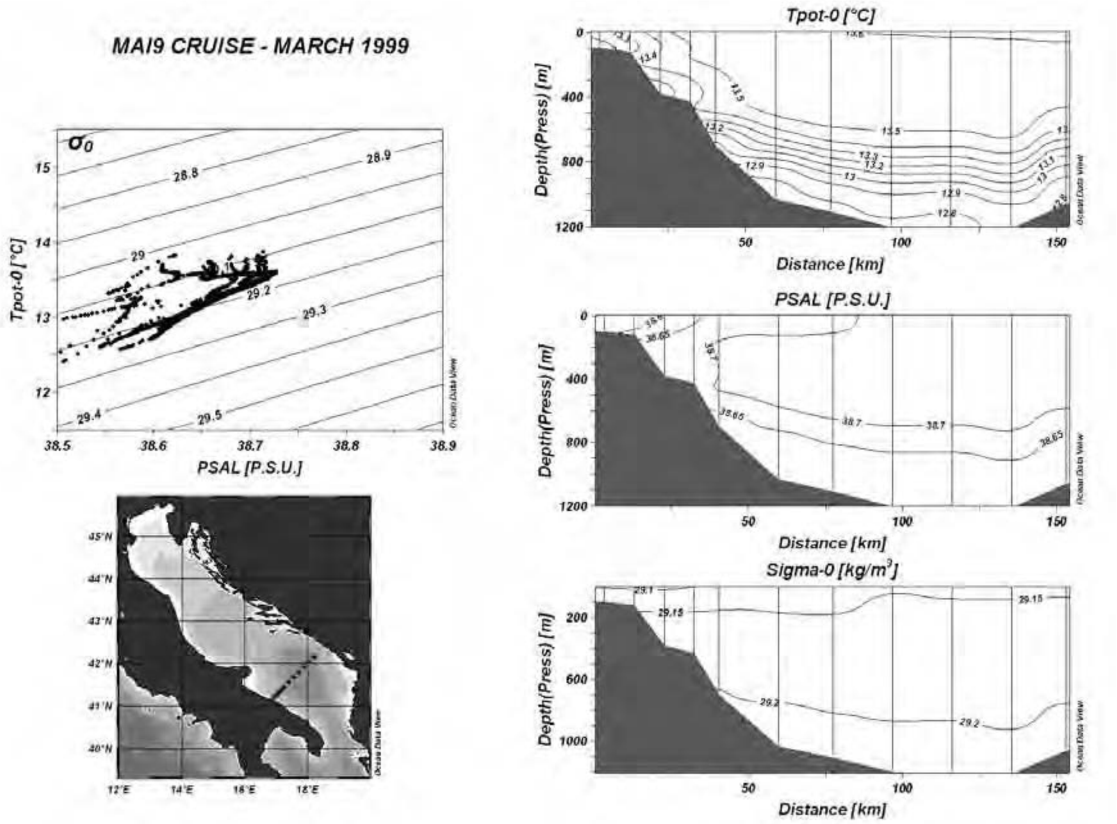

Fig. 4b. Vertical transects of potential temperature, salinity and density for March 1999.

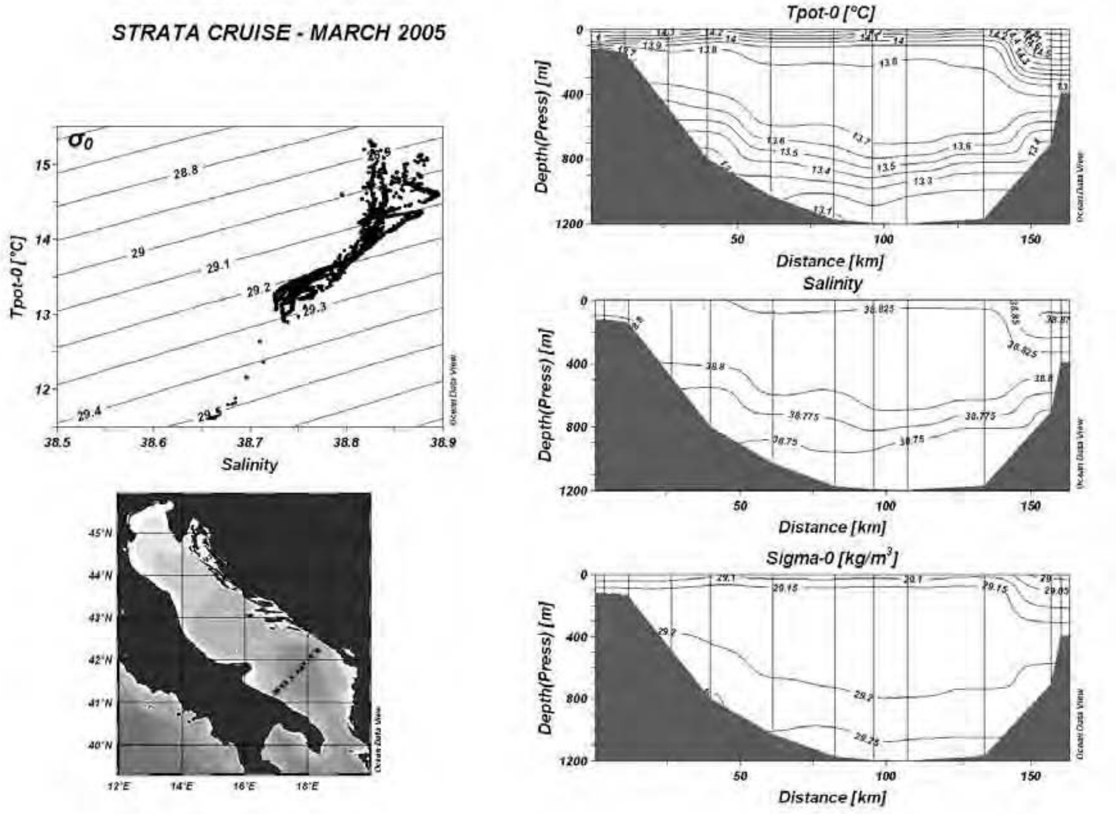

Fig. 4c. Vertical transects of potential temperature, salinity and density for March 2005.

4. CONCLUSIONS

Important decadal variability of oceanographic conditions in the deep convection site in the South Adriatic Pit has been seen using direct observations of the hydrographic conditions. Over the period studied the minimum temperature and salinity in the intermediate layer occurred in mid 1990's coinciding with the maximum EMT impact. Nevertheless, in concomitance with the inflow of more saline and warmer water in early 2000 the bottom water formed in the Adriatic did not have density as high as in early '1990s. This indicates that the recently formed AdDBW has changed its thermohaline properties that will reflect on the EMDW characteristics.

Prominent influences of the Eastern Mediterranean Transient are manifested in changes in the vertical temperature and salinity patterns. The pre-EMT pattern shows the presence of the sub-surface salinity maximum associated with the LIW inflow. During the strong Aegean impact on the EMDW (mid and late 1990 s) the inflowing water in the Adriatic was characterized by higher heat content over the entire water column. In that period, even with high surface heat losses, the density of the AdDW was not high enough to spread over the bottom layer over the Eastern Mediterranean. Only after the year 2000 an increased salt content associated with the Aegean water influence, this time at higher horizons, was able to create the necessary conditions for the deep convection in the South Adriatic Pit and for the formation of water dense enough to spread below the bottom water of Aegean origin. The present analysis also illustrates the important contribution of the water of North Adriatic origin especially in the second half of the 1990 s.

The advance of thermophilic fishes in the Mediterranean Sea: overview and methodological questions

Ernesto Azzurro

ICRAM, Milazzo, Italy

ABSTRACT

This paper focuses on the advance of thermophilic fishes in the Mediterranean Sea, a phenomenon that has received increasing attention in recent times. By reviewing published records of the last 15 years, a list of 51 species occurring northwards with respect to their known distribution ranges, is compiled. With only two exceptions, all of them have a sub-tropical and tropical character and many of them can be considered as good indicators of climate warming. Methodological possibilities, suitable to perceive this complex process of change, are raised and discussed.

INTRODUCTION

Climate is one of the most important determinants for living organisms, shaping the distribution of plants and animals all over the planet trough the combination of direct and indirect effects. In poikilothermic organisms such as fishes[1], the temperature may shape population and community structures, through its direct influence on the survival, reproduction and patterns of resource use of single individuals. Effects of temperature on marine organisms can be also mediated by indirect effects such as by the modification in water circulation, with clear consequences on larval dispersal and recruitment (Bianchi and Morri, 2004). Fishes have long been used as indicators of environmental changes (Mearns, 1988; Stephens *et al.*, 1988; Roessig *et al.*, 2004). Their high dispersal potential, ecological differentiation, general non-resilience, sensitivity to temperature, large size and ease of identification, make them excellent candidates for the study of the effects of climate variability (Wood *et al.*, 1997). In addition, the Mediterranean Sea, located in the temperate zone of the northern hemisphere, includes species with different origin and thermal tolerance, providing an excellent field of investigation.

THE ADVANCE OF THERMOPHILIC FISHES

Up to now, not many ecological efforts have been directed to understand the role that climate warming plays in controlling Mediterranean fish dynamics but biotic consequences have already emerged. Climate warming is driving species ranges toward the poles (Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Perry *et al.*, 2005) and this ‘harbinger’ is now perceptible in the Mediterranean realm, where a variety of thermophilic organisms belonging to macroalgae, plankton, invertebrates (Bianchi, 2007) and - as we will see - fishes, are extending their distribution towards northern areas.

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[1] Exceptions of partial endothermy are known for some sharks, tunas and billfish.

Thermophilic fishes have evolved in tropical or subtropical marine environments and hence are adapted to warm waters. In the Mediterranean, these species can be broadly categorized into two major groups, which are distinguished by different histories:

1) NATIVE fishes, with tropical or subtropical affinity and origin, entered in the Mediterranean during previous interglacial phases of the Quaternary. These species occur typically in the southern Mediterranean, where water temperature is higher than average. The northern spread of the native warm water biota has been named “meridionalization” by some (Bianchi and Morri, 1993; 1994; Riera *et al.*, 1995).

2) EXOTIC fishes, have recently entered the Mediterranean, mainly from the Red Sea or from the Atlantic Ocean. These species have taken advantage of suitable pathways for dispersal, i.e. the Strait of Gibraltar and the Suez canal, and are found mainly in proximity of their entry point, in the western and eastern sectors of the Mediterranean, respectively. This phenomenon enhances the tropical character of the Mediterranean and can be indicated as “tropicalization”[2] (Andaloro and Rinaldi, 1998; Bianchi and Morri, 2004; Bianchi, 2007). Another definition that has been used is “demediterraneization” (Quignard and Tomassini, 2000), to put the emphasis on the process of biotic homogenization of the Mediterranean Sea.

In the last two decades, the advance of thermophilic species has represented the first and most cited evidence of the linkage between climate change and distribution patterns of Mediterranean Sea biodiversity. When consequences of climate warming still had a hypothetical character, these ‘unusual occurrences’ have served as sentinels, by providing the first indication of changes that (maybe) were still not clearly evident in the temperature records (Riera *et al.*, 1995; Francour *et al.*, 1994). By reviewing the relevant literature of the last 15 years (Table 1 – see page 44), a total of 51 Mediterranean fishes, were founded to have expanded northwards. Among them, I counted 34 native and 17 exotic species (6 Atlantic and 11 Lessepsian[3]) (Figure 1a). Most of these species have a subtropical or tropical character and live mainly in coastal habitats, whilst only two species live in deep waters (Figure 1b). Serranidae (N=6 species) and Carangidae (N=5 species) were the most represented families, showing a good coherence in their response.

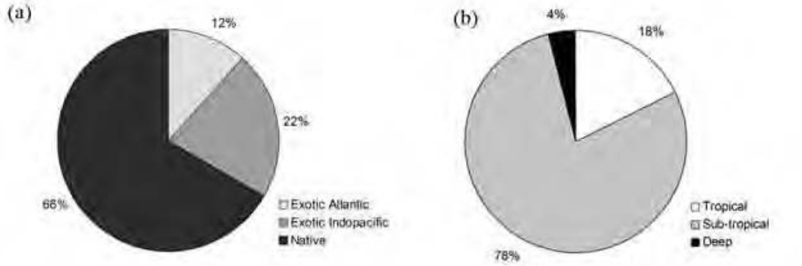

Fig. 1. Percent distribution of Mediterranean northward expanding fish species, based on the relevant literature records of the last 15 years: (a) distribution according to their geographic origin (Native, Atlantic, Indo-Pacific); (b) distribution according to their climate affinity (tropical, sub-tropical, deep). N = 51.

The bulk of these ‘northwards records’ came from the Adriatic Sea (Dulčić *et al.*, 1999; Dulčić and Grbec, 2000; Dulčić *et al.*, 2004 and references therein included), where even juveniles of various thermophilic fishes, e.g. *Trachinotus ovatus* (Dulčić *et al.*, 1997a), *Sparisoma cretense* (Guidetti and Boero, 2001) *Pomatomus saltator*, *Stromateus fiatola* (Dulčić *et al.*, 2000) and *Campogramma glaycos* (Dulčić *et al.*, 2003), have been recently registered. Furthermore, new species are now appearing in the coldest sectors of the Mediterranean, such as the northern Adriatic Sea (Parenti and Bressi, 2001; Bettoso and Dulčić, 1999; Sinovčić *et al.*, 2004; Psomadakis *et al.*, 2006) the northern Aegean Sea (Karachle *et al.*, 2004; Psomadakis *et al.*, 2006; Tsikliras and Antonopoulou, 2006) and the Gulf of Lion (Francour *et al.*, 1994). These areas are considered as the hotspots for

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[2] In a different way, the term ‘tropicalization’ has been referred to fish stocks, to indicate smaller body sizes and age/length at maturity as consequences of fishing (see Stergiou, 2002 and references therein included). Lloris (2007) has used this term to indicate the poleward displacement of tropical species (not just the exotic ones).

[3] Species coming from the Red Sea that have entered the Mediterranean through the Suez Canal (Por, 1978).

endemic species and concern has been expressed for their conservation in view to the advance of thermophilic species (Ben Rais Lasram and Mouillot, 2008).

Meridionalization

Looking at native fishes, we are probably used to have just few examples of ‘meridionalization’ (e.g. the Mediterranean parrotfish *Sparisoma cretense,* the ornate wrasse *Thalassoma pavo,* the dusky grouper *Epinephelus marginatus* and the barracuda *Sphyraena viridensis*). Instead, this phenomenon can be illustrated by a large series of new presence records (Table 1 – see page 44). Moreover, increasing abundances have been recently demonstrated for *Sardinella aurita* (Sabatés *et al.*, 2006) and possibly for other southerly species such as *Caranx crysos, Caranx ronchus* and *Balistes capriscus* (Bradai *et al.*, 2004).

Tropicalization

The other component of thermophilic ichthyofauna is represented by exotic fishes that demonstrate a clear increase in their invasion rate (Ben Rais Lasram and Mouillot, 2008). These species have now attained an extraordinary relevance for the Mediterranean biodiversity. Today, we can count 111 exotic fishes, nearly the 16% of Mediterranean ichthyofauna[4] and almost all of them are of tropical and subtropical origin (Golani *et al.*, 2002; Golani *et al.*, 2007). Evidences of geographical extension (Table 1 – see page 44) are particularly numerous for species coming from the Red Sea. The latest and most remarkable case is undoubtedly the bluespotted cornetfish, *Fistularia commersonii,* which has been observed for the first time in 2000 in Israel (Golani, 2000) and soon afterwards recorded all over the eastern and central Mediterranean coasts (Azzurro *et al.*, 2007b), up to the proximity of the Strait of Gibraltar (Sánchez-Tocino *et al.*, 2007). A few kilometers more and we will have the first case of ‘trans-Mediterranean migration’, from the Indo-Pacific to the Atlantic Ocean! Less pronounced may the expansion of Atlantic subtropical invaders appear, but their introduction rate has been clearly correlated with the temperature (Ben Rais Lasram and Mouillot, 2008) and significant longitudinal spreads have recently observed (Ragonese and Giusto, 2000; Corsini *et al.*, 2006; Ben Rais Lasram and Mouillot, 2008).

In our inventory of north expanding species (NES), several fishes have been included on the basis of one single record. I have also considered *Fistularia petimba,* even if its expansion has been documented only in extra-Mediterranean sightings. Within these limitations, the list attempts to define a groups of species which is responding to the same historical process. Here, the average taxonomic distinctness AvTD (Warwick and Clarke, 1995) has been used to compare NES with other group of Mediterranean fishes. This index is a measure of the taxonomic complexity which takes into account the taxonomic distances between species[5]. According to Figure 2, AvTD of NES

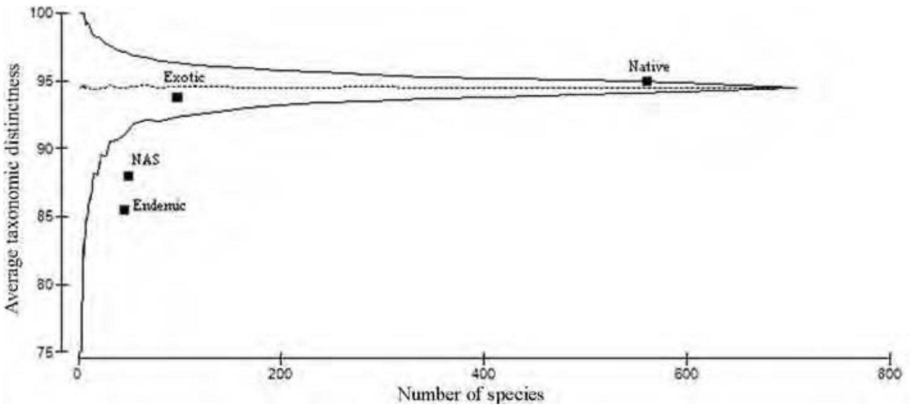

Fig. 2. Funnel plot for simulated average taxonomic distinctness AvTD for Mediterranean fishes based on a 3-level classification (species, families, orders). (N=707 species: master list taken from Froese and Pauli, 2008). The interrupted line denotes the simulated AvTD; continuous lines indicate the limits within which 95% of simulated TD values lie. The TD values calculated for the sub-groups of ‘exotic’, ‘endemic’, ‘native’ and north expanding species ‘NES’ are superimposed.

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[4] If we consider 707 species to be the total number of fish species in the Mediterranean Sea (Froese and Pauly, 2008). Other Authors (Ben Rais Lasram and Mouillot, 2008) counted more than the 19%.

[5] Differently from the commonly used diversity indexes, *AvTD* is independent from the number of species.

seems to be reduced with respect to the mean Mediterranean value and this would reflect the importance of a few higher taxa (families such as Serranidae, Carangidae and orders such as Perciformes and Tetraodontiformes) in the process of northward expansion. We can also observe that AvTD of NES is higher with respect to endemic species and lower if compared with exotic species.

Visibly, the advance of thermophilic fishes is not confined to the Mediterranean Sea (McFarlane *et al.*, 2000; Perry *et al.*, 2005). Similar range extensions have been observed in the Atlantic European waters (e.g. Quéro *et al.*, 1996; 1998; Bañón *et al.*, 2002; Stebbing *et al.*, 2002; Brander *et al.*, 2003; Bañón, 2004), and in other regions of the northern and southern hemisphere (Parker and Dixon, 1998; Irigoyen *et al.*, 2005); were tropical and subtropical species are crossing their northernmost or southernmost limits, respectively. Particularly significant are those examples which involve the same taxa across different marine areas. This is the case of native species such as *E. marginatus*, *C. crysos*, *B. capriscus*, *Pseudocaranx dentex*, *Solea senegalensis*, *Sphyraena* spp. (Table 1 – see page 44) which have extended their distribution margins, in both Mediterranean and extra-mediterranean areas. These synchronous responses[6] strongly confirm the existence of a single overriding force in the ocean environment. The coherence of such poleward spreads across distant and different locations stresses, once again, the valve of these organisms as indicators of warming in the marine environment.

Every single distributional extension generates community changes at the local and regional levels. Since no species losses have been recorded in the Mediterranean, the advance of southerly species is probably augmenting the total number of species in the northern basin. Moreover, this pattern follows general predictions: fish species richness normally decreases with latitude (Macpherson and Duarte, 1994) and in temperate marine areas, a gain in species is expected as a consequence of climate warming (Hiddink and Hofstede, 2008). A decrease in the size of fish species with climate warming, has been also predicted, being fish species typically smaller at lower latitudes (Macpherson and Duarte, 1994).

The effects of climate change on the distribution patterns of Mediterranean faunas are thought to be more noticeable in population located at the geographic distribution limits of the species and in certain focal spots, especially in correspondence of transitional areas and biogeographic boundaries (Bianchi, 2007). In the Mediterranean a major transitional sector is the Sicily Channel, which separates the western from the eastern basin and may be regarded as a privileged observatory for biodiversity changes. In the course of the Mediterranean history, this area acted as a filter to the eastern advance of Atlantic fauna (Quignard and Tomasini, 2000) and, up to recent times, it has been considered the western frontier to Lessepsian migration (Por, 1990; Quignard and Tomasini, 2000, Golani *et al.*, 2002). As a matter of facts, this barrier is now showing an astonishing weakness, being ineffective to stop the spreading of both the Atlantic and Indo-Pacific fish species which ultimately are crossing the Channel from West to East and from East to West, respectively. Taking into account published information and available species lists (e.g. Bradai *et al.*, 2004; Bianchini and Ragonese, 2007), the number of exotic fishes currently recorded in this area is of 10 Lessepsians (*Upeneus moluccensis*, *Fistularia commersonii*, *Stephanolepis diaspros*, *Leiognathus klunzingeri*, *Etrumeus teres*, *Siganus luridus*, *Siganus rivulatus*, *Pempheris vanicolensis*, *Parexocoetus mento*, *Priacanthus hamrur*) and 12 Atlantic invaders (*Beryx splendens*, *Gephyroberyx darwinii*, *Pisodonophis semicinctus*, *Microchirus boscanion*, *Solea senegalensis*, *Chaunax suttkusi*, *Psenes pellucidus*, *Trachyscorpia cristulata chinata*, *Seriola rivoliana*, *Seriola fasciata*, *Seriola carpenteri* and the Tetraodontiform *Sphoeroides pachygaster*, recorded all over the Mediterranean in the last two decades[7]). This observation can be taken as a reinforced signal of change for the Mediterranean biogeography.

METHODOLOGICAL QUESTIONS

Attempts to predict climate-change impacts on biodiversity have often relied on the 'species-climate envelope' (Pearson and Dawson, 2003). In such a context, projections of distributions under future climate change scenarios can be formulated on the basis of climatic variables that

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[6] ...of different populations belonging to the same species.

[7] See Psomadakis *et al.* (2006) and references therein included.

limit the current geographical distribution of any given species. The major drawback of this approach is that many non-climatic forces can influence species distributions (Hampe, 2004) and this is particularly obvious for exotic species. In fact, when a new species enters a new environment, a "pletora" of variables linked to the invasion process may play a major role, influencing species dynamics and adding new layers of complexity[8]. A strong variability characterizes also native fishes with respect to environmental changes. For these reasons, caution must be used when dealing with single species or populations. Obviously, the collection of data at the community level is a more powerful tool to evaluate the consequences of climate warming.

Another difficulty that we encounter in extrapolating the effects of temperature on biotic communities is represented by spatial and temporal variability and, so far, only few studies have taken it into appropriate consideration. One of these (Sabatés *et al.*, 2006) clearly demonstrated a link between temperature and the abundance of *S. aurita*. Results also showed the successful reproduction of *S. aurita* in the North-West Mediterranean, where this clupeid has recently expanded its distribution. As a matter of fact, knowledge of the reproductive condition of individuals that occur in correspondence of their geographical borders or are found outside these limits, is an essential information in the study of thermophilic expanding species (Azzurro *et al.*, 2007c). Among them, several species that previously were thought not to reproduce on the north, like *T. pavo* and the dusky grouper *E. marginatus* (Sara and Ugolini, 2001; Francour *et al.*, 1994), are now naturalized in these areas and seasonal recruitment occurs.

The contemporary relevance of range dispersal events has raised our interest for organisms that are found outside of their geographical limits. Indeed the number of scientific notes or brief articles, commonly called 'presence' or 'biodiversity records', has significantly increased in recent years. The sum of these anecdotal evidences makes us aware about the existence of large scale processes of change in marine biodiversity but how are these 'unusual' fishes usually intercepted? And what are our possibilities of study? The discovery of an exotic fish species in the Mediterranean is usually a fortuitous, unplanned episode and we generally have to wait until these species are found by chance (Azzurro, in press). Certainly, we miss specific procedures to detect of these 'newcomers' and this seems to be is a rather general constrain in invasion biology (Wittenberg and Cock, 2001).

In one recent attempt to ameliorate our capability to monitor fish biodiversity changes, an experimental system of early detection was developed in the Pelagie islands (Azzurro, 2007; MonItaMal, 2008). The system was inspired by community-based actions (Cooper *et al.*, 2007), recently developed with the aim to engage a dispersed network of volunteers to assist in professional research. People who could notice 'unusual fishes' in the course of their activities, i.e. fishermen and divers, were involved on the basis of a simple advertisement campaign and personal interactions. Given the familiarity of fishermen with local species, no training on taxonomy was considered necessary and no blacklist was proposed. Researchers were employed to validate the reports and to evaluate the effectiveness of the experiment. At the end, fishermen were mainly engaged by personal interactions, and only few by simple media promotion. In any case, fishermen were particularly helpful, both for the high frequency of validated records and for providing voucher specimens, suitable for biological analyses.

This small experiment provided very valuable results to our purposes. 'Scientists cannot be everywhere' and volunteer participants gave us the possibility to multiply our eyes on the scene. Hopefully, this practice could extend our capacity of research at larger geographical and temporal scales. Future efforts will be directed to develop a strong cooperation with the fishery and recreational sectors and to expand community-based monitoring experiences at the international level.

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[8] Ecological and biological factors may generate species-specific responses that are typically difficult to foresee and may be often contradictory. For instance, the spread of an invasive species may occur after a long time lag (Sakai *et al.*, 2001) or even immediately after the propagules introduction - see the different cases of *S. luridus* and *F. commersonii* as examples of 'long time lag' and 'immediate dispersion', respectively (Azzurro and Andaloro, 2004; Azzurro *et al.*, 2006; Azzurro *et al.*, 2007b).

Table 1. A list of Mediterranean northward expanding fish species based on the relevant published records of the last 15 years. Species thought to be increasing in their abundances are marked with asterisks. Evidences older than 1993 are indicated with the symbol "◊".
Extra-Mediterranean records testifying northward expansion were also reported, when available.
Information about the species origin (IP Indo-Pacific; A Atlantic; N native), habitat and climatic affinity (Trp = Tropical; Sbt = Sub-tropical; Deep = Deep waters) is reported, according with Golani *et al.* (2002) and Froese and Pauli, 2008 (<www.fishbase.org>).

Family	Species	Origin	Climate	Habitat	Intra-Mediterranean sources	Extra-Mediterranean sources
Balistidae	*Balistes capriscus**	N	Sbt	Reef-associated	Dulčić *et al.*, 1997b; Bradai *et al.*, 2004	Bañón *et al.*, 2002
Belonidae	*Tylosurus acus imperialis*	N	Sbt	Pelagic	Bello, 1996	–
Blenniidae	*Parablennius pilicornis*	N	Sbt	Demersal	Riera *et al.*, 1995; Nieder *et al.*, 2000	–
	Scartella cristata	N	Trp	Reef-associated	Nieder *et al.*, 2000	–
Carangidae	*Campogramma glaycos*	N	Sbt	Benthopelagic	Dulčić *et al.*, 2003	–
	*Caranx crysos**	N	Sbt	Reef-associated	Bradai *et al.*, 2004	Swaby *et al.*, 1996; Bañón and Casas, 1997
	*Caranx ronchus**	N	Sbt	Benthopelagic	Bradai *et al.*, 2004	–
	Pseudocaranx dentex	N	Trp	Reef-associated	Azzurro, unpublished data	Fernández-Cordeiro and Bañón, 1997
	Trachinotus ovatus	N	Sbt	Pelagic	Dulčić *et al.*, 1997a	
Clupeidae	*Etrumeus teres**	IP	Sbt	Pelagic	Falautano *et al.*, 2007	–
	*Sardinella aurita**	N	Sbt	Reef-associated	Dulčić and Grbec, 2000; Sinovčić *et al.*, 2004; Tsikliras *et al.*, 2006; Sabatés *et al.*, 2006	–
Coryphaenidae	*Coryphaena hippurus*	N	Sbt	Pelagic	Dulčić, 1999	–
Dasyatidae	*Taeniura grabata*	N	Sbt	Demersal	Quignard and Tomasini, 2000	–
Exocoetidae	*Parexocoetus mento*	IP	Trp	Pelagic	Dulčić and Grbec, 2000	–
Fistularidae	*Fistularia petimba*	A	Trp	Reef-associated	–	Bañón and Sande, 2008
	Fistularia commersonii	IP	Trp	Reef-associated	Sánchez-Tocino *et al.*, 2007	–
Gempylidae	*Ruvettus pretiosus*	N	Sbt	Bathipelagic	Bettoso and Dulčić, 1999	–
Haemulidae	*Plector. mediterraneus*	N	Sbt	Demersal	Lipej *et al.*, 1996	–
	Pomadasys incisus ◊	N	Sbt	Demersal	Quignard and Tomasini, 2000	
Hemiramphidae	*Hemiramphus far*	IP	Sbt	Pelagic	Dulčić and Grbec, 2000	–
	Hemiramphus picarti ◊	N	Sbt	Benthopelagic	Quignard and Tomasini, 2000	
Istiophoridae	*Tetrapterus albidus*	N	Sbt	Pelagic	Quignard and Tomasini, 2000	–
Kyphosidae	*Kyphosus sectator*	N	Sbt	Reef-associated	–	Bañón, 2004
Labridae	*Thalassoma pavo*	N	Sbt	Reef-associated	Vacchi *et al.*, 1999; Guidetti, 2002; Guidetti *et al.*, 2002; Sara *et al.*, 2001; 2005	–
	Xyrichthys novacula	N	Sbt	Reef-associated	Dulčić and Pallaoro, 2001	–
Leiognathidae	*Leiognathus klunzingeri*	IP	Trp	Demersal	Dulčić and Pallaoro, 2002	–
Lobotidae	*Lobotes surinamensis* ◊	N	Sbt	Benthopelagic	Quignard and Tomasini, 2000	Fishkeeping, 2008; Contreras-Balderas *et al.*, 2003
Monacanthidae	*Stephanolepis diaspros*	IP	Trp	Demersal	Dulcic and Pallaoro, 2003; Bdioui *et al.*, 2004	–
Nomeidae	*Psenes pellucidus*	A	Deep	Bathidemersal	Quignard and Tomasini, 2000	–
Ophichthidae	*Pisodon. semicinctus*	A	Sbt	Demersal	Quignard and Tomasini, 2000; Ragonese and Giusto, 2000; Serena, 2001	Bañón *et al.*, 2002
Pomatomidae	*Pomatomus saltatrix*	N	Sbt	Pelagic	Dulčić *et al.*, 2000	Contreras-Balderas *et al.*, 2003
Scaridae	*Sparisoma cretense*	N	Sbt	Reef-associated	Guidetti and Boero, 2001, Dulčić and Pallaoro, 2001	–
Scorpaenidae	*Pontinus kuhli*	N	Deep	Bathidemersal	Riera *et al.*, 1995	–
Sebastidae	*Trachysc. cristulata ech.* ◊	A	Sbt	Demersal	Massuti *et al.*, 1993	
Serranidae	*Epinephelus aeneus*	N	Sbt	Demersal	Riera *et al.*, 1995; Dulčić *et al.*, 2006	–
	Epinephelus caninus	N	Sbt	Demersal	Quignard and Tomasini, 2000	–
	Epinephelus coioides	IP	Sbt	Reef-associated	Parenti and Bressi, 2001	–
	Epinephelus costae	N	Sbt	Reef-associated	Riera *et al.*, 1995	–
	Epinephelus marginatus	N	Sbt	Reef-associated	Francour *et al.*, 1994; Dulčić and Lipej, 1997; Zabala *et al.*, 1997	Irigoyen *et al.*, 2005
	Mycteroperca rubra	N	Sbt	Demersal	Quignard and Tomasini, 2000; Glamuzina *et al.*, 2002	–
Siganidae	*Siganus luridus*	IP	Sbt	Reef-associated	Azzurro and Andaloro, 2004; Castriota and Andaloro, 2005	–
	Siganus rivulatus	IP	Sbt	Reef-associated	Dulčić and Pallaoro, 2004	–
Soleidae	*Solea senegalensis*	A	Sbt	Demersal	Quignard and Tomasini, 2000	Bañón *et al.*, 2002
Sparidae	*Diplodus cervinus* ◊	N	Sbt	Reef-associated	Quignard and Tomasini, 2000	
	Pagrus auriga	N	Sbt	Benthopelagic	Quignard and Tomasini, 2000	–
Sphyraenidae	*Sphyraena chrysotaenia*	IP	Sbt	Pelagic	Pallaoro and Dulčić, 2001	–
	Sphyraena sphyraena	N	Sbt	Pelagic	–	Bañón and Garazo, 2006
	Sphyraena viridensis	N	Trp	Pelagic	Quignard and Tomasini, 2000, Dulčić and Soldo, 2004	–
Stromateidae	*Stromateus fiatola*	N	Sbt	Benthopelagic	Dulčić *et al.*, 2000	–
Tetraodontidae	*Lagocephalus sceleratus*	IP	Trp	Reef-associated	Kasapidis *et al.*, 2007	–
	Sphoeroides pachygaster	A	Sbt	Demersal	Psomadakis *et al.*, 2006	–

FINAL REMARKS

Large scale forces are reshuffling Mediterranean fish biodiversity and a growing body of evidence testifies to the coherence of these changes with the putative effects of climate warming. Nevertheless, the extent of this phenomenon remains in some way hidden, because of the sporadic nature of monitoring efforts and of difficulties in exploring appropriate spatial and temporal scales. So far, our knowledge of this process has been limited to the sum of causal observations. Hence we need new methodologies, suitable to deepen our capability to perceive this complex process of change. The northward advance of thermophilic fishes is one of the first, and maybe most detectable biotic response to climatic changes. From this perspective, presence/absence data resulting from community-based surveys may be added to the tools for monitoring climatic-induced changes of Mediterranean biota. This information will be helpful to analyze the rates of spread and for species-climate modeling. Nevertheless, transitional sectors of the Mediterranean and cold areas (which represent endemic hotspots), should be considered with special care, as the best places where to detect biodiversity changes and where to concentrate our monitoring activities.

Other effects of climate change will be addressed by examining the response of ‘cold water’ biota and by comparing the phenology (i.e. the timing of biological events) of key species along spatial and temporal scales. The discussion on these possibilities of study goes far beyond the purposes of this paper but deserves further attention.

The new CIESM Tropicalization Programme – effects of climate warming on Mediterranean key taxa

Paula Moschella

Commission Internationale pour l’Exploration Scientifique de la mer Méditerranée (CIESM)

SUMMARY

In the Mediterranean Sea, where some 30 % of species are endemic, changes in biodiversity are occurring at unprecedented rate. In particular, the warming of Mediterranean waters is accelerating the establishment of tropical species and the retreat of temperate species towards colder areas of the Basin. This ongoing process of Mediterranean “tropicalization” remains poorly understood, based on fragmented, occasional, usually local observations. The importance of investigating causes for these changes is a matter of urgency.

The overall aim of the CIESM programme is to use reliable, representative biological macrodescriptors to track at basin-scale the effects of tropicalization of the Mediterranean Sea on marine biodiversity. The programme will implement a systematic, long-term field monitoring of changes in Mediterranean biodiversity, in particular the expansion of “warm-water” species (with affinity to warmer waters) and the retreat of “cold-water” species (with affinity to colder waters).

EFFECTS OF CLIMATE CHANGE ON DISTRIBUTION RANGES OF MEDITERRANEAN SPECIES

Climate change is affecting the whole earth: scientific evidence for significant effects in the oceans and seas has been available in recent years (IPCC, 2001; 2007). Climate change will lead to warming waters, increased frequency of extreme precipitation events, winter floods and summer droughts, and increased storminess. The Mediterranean Sea, with its peculiar location at the cross-road between the Atlantic and Indo-Pacific biogeographic domains, the magnification of climatic signals in its enclosed basin, and the unique biodiversity (28% of species are endemic) represents a remarkable case study to investigate the influence of climate change on biodiversity. The CIESM Hydrochanges Program has detected several signals of change in the Mediterranean Sea (Millot *et al.*, 2006). *In situ* long-term measurements of temperature and salinity recorded at the Strait of Gibraltar show that the deep waters outflow through the Strait of Gibraltar is warmer (~0.3 °C) and saltier (around 0.06 units saltier) than 10 years ago. An increase in temperature and salinity has been recorded also in many other areas of the Basin (e.g. Tyrrhenian Sea; Sicily Channel, see Fuda *et al.*, 2007). In shallower waters, stratification will likely occur earlier and extend deeper in the water column. Results from the CIESM MedGLOSS Program indicate a sea level rise at several locations along Mediterranean coastlines and in the eastern Basin in particular. Sea level rise, along with increasing coastal erosion, will impinge low lying deltas, saltmarshes and lagunal systems.

Two types of responses by biodiversity and ecosystems to global environmental change can be envisaged: direct climate-driven effects and indirect effects due to human mitigational strategies and adaptational actions (i.e. sea defences, de-salination plants, enhancement of irrigation).

Furthermore, there will be interactions between different scales if impacts: global climate driven change will likely interact with regional (overfishing, eutrophication) and local impacts (sea defences, point source pollution).

Changes in sea temperature, apparently small, can have dramatic effects on the biology and diversity of communities. The mass mortality of gorgonians (e.g. *Paramuricea clavata*) and many other invertebrates, that affected several areas of the Ligurian and Provençal coast as a result of a sudden increase in temperature in the water column, is a clear example of the fragility and vulnerability of marine ecosystems (Torrents *et al.*, 2008; Cerrano *et al.*, 2000; Perez *et al.*, 2000). Other changes in the biodiversity are less evident, as they occur gradually over a much longer period of time or indirectly, through loss or modification of habitats necessary for the survival of species. Nevertheless, they can be serious and may result in species loss or permanent alteration of ecosystem functioning.

Susceptibility to global climate change will vary depending on the type, biology and physiology of organisms. The complex geological history of the Mediterranean Sea, its connections with the Atlantic and the Red Sea, and its climatic and hydrologic regimes have led to the coexistence in the Basin of boreal, temperate, sub-tropical and tropical species.

There are cold temperate species which take refuge in particular habitats: examples include *Fucus virsoides* in the north Adriatic; *Laminaria rodriguezii*, restricted to the western Basin at depths where the water temperatures do not exceed 15 °C; the crab *Carcinus* and the polychaete *Nereis diversicolor* in lagoons and estuaries, the hake *Merluccius merluccius*, the whiting *Merlangus merlangus*, the poor cod *Trisopterus minutus* and the Norway lobster *Nephrops norvegicus* in the deep waters. In the Atlantic, northern species can retreat northwards as well as into deeper waters (Perry *et al.*, 2005), whilst the only possible retreat in the Mediterranean is to deeper waters. Furthermore, as changes in water stratification will lead to warmer water extending deeper, cold-temperate, shallow water species will have no possibility of shifting to deeper waters. As some of these cold water species are already at risk from overfishing, a much more precautionary approach is required before relating their changes in abundance and distribution to climate warming.

Mediterranean species also face competition from Erythrean immigrants (see CIESM Atlases of Exotic Species) now expanding into the western basin. Climate change is known to increase the probability of success of invasion of non-native species by facilitating their recruitment (Stachowicz *et al.*, 2002). In the last decades there has been a significant increase in the introduction of tropical, alien species that settled permanently in Mediterranean habitats, sometimes even replacing native species (Galil, 2007b; Occhipinti-Ambrogi, 2007; Streftaris *et al.*, 2005). Climate warming is also favouring native warm water species such as the dusky grouper (*Epinephelus marginatus*), the barracuda (*Sphyraena viridensis*) and the ornate wrasse (*Thalassoma pavo*), which are extending their distribution ranges northwards.

THE NEED FOR A LONG-TERM, CROSS-BASIN PROGRAM ON MEDITERRANEAN TROPICALISATION

Current investigations on the effects of climate warming on biodiversity and more specifically on the tropicalization process are relatively fragmented, temporally patchy and geographically limited. The need for a long-term, basin-scale programs aiming to monitor the effects of climate change on Mediterranean species is clear. The establishment of a systematic, standardized monitoring program on tropicalization impacts across the Basin will allow a proper interpretation of biodiversity changes, that is, discriminating between local and regional factors and disentangling short term fluctuations (“noise”) from longer term change (“signal”). Furthermore, impacts of climate change on the preservation of Mediterranean biodiversity and its natural environments have become a matter of great concern not only for specialists but also for the wide community in all riparian countries. Such a program will provide deeper understanding of patterns and trends characterizing the status and distribution of Mediterranean species, thus helping stakeholders (environmental managers, coastal planners, policy makers) in formulating of appropriate management and conservation strategies.

The challenge of the new CIESM Tropicalization Program is to monitor at regional level changes in the geographic range of distribution of key selected marine species in relation to climate change. The program will:

- review and integrate existing information on past and current status of selected taxa;
- identify a set of "sentinel species" which can reliably represent indicators of climate change;
- track the geographic expansion of "warm-water" species (with affinity to warmer waters) and the retreat of "cold-water" species (with affinity to colder waters);
- record mass events (invasions, blooms, mass mortalities) in the Basin;
- relate changes in abundance and distribution ranges of Mediterranean species to the variability and trends of the hydro-climatic environment;
- establish a long-term, dedicated "Mediterranean Network" to detect and monitor major changes in key species in response to climate.

SELECTING SPECIES AS RELIABLE MACRO-DESCRIPTORS OF CLIMATE CHANGE

As Mediterranean ecosystems are subject to both natural and anthropogenic pressures, the difficulty is to identify climate-specific impacts on species. We already know that species respond to changes in the climatic environment by shifting geographically (Fields *et al.*, 1993; Southward *et al.*, 1995; Parmesan, 1996; Sagarin *et al.*, 1999). Hence monitoring changes in the species range of distribution can provide a good estimation of the effects of climate change on Mediterranean biodiversity.

There are two categories of species that will likely signal changes in the hydro-climatic conditions. First, the species most vulnerable to warming, characterised by a combination of some of the following ecological traits: affinity to cold waters (e.g. ice-age relict species) coupled with stenothermy/stenohalinity, sedentarity, low recruitment and dispersal rates, limited vertical distribution, species threatened by human driven factors (i.e. overfishing) or already rare in the past. On the other hand, increasing temperatures and salinity will reduce the hydrological gradient between the western and eastern basins, thus facilitating the westward and northward range extension of warm water Mediterranean species and particularly Erythrean species. An increase in sea temperature will also favour the reproductive output and recruitment success of this type of organisms (Walther *et al.*, 2002; Herbert *et al.*, 2003).

The basis of the CIESM Tropicalization Programme: historic archives

The selection of climate macrodescriptor species will be based on an in-depth study of available historic information on Mediterranean macrobiota. In the past, and in contrast to current research "priorities", taxonomy and biogeography of the marine fauna and flora were considered two fundamental subjects of study for early marine biologists. In the Mediterranean, there is a wealth of information and inventories of marine species compiled in the last century by illustrious taxonomists. CIESM archives (Congress papers, special publications, *Fiches Faunistiques*) represent one of the richest source of historic records dating back to the 1920s. Other local and national data (time series from the Marine Stations, Museum collections, grey literature) will complement the CIESM archives.

The *Fiches Faunistiques de la mer Méditerranée*, published by CIESM between 1927 and 1934, provide a detailed account of the morphology, ecology and biogeography of 476 Mediterranean species, belonging to nine taxa. For certain taxa such as the Asteroidea and the Rajidae, there are descriptions for almost all species recorded to date in the Mediterranean Sea, allowing to assess the dynamics of a full taxonomic group in response to change. In the Asteroidea group, some species probably will respond differently to climate warming: for example, *Opidiaster ophidianus* original description indicates that this species was distributed only in the warmer areas of the Mediterranean Sea, while *Anseropoda placenta* and *Luidia sarsi*, a cold-temperate species quite common in the north Atlantic, appeared to be restricted to the deep waters in the Basin. In the Rajidae family, most of the species have a northenly distribution and in the Mediterranean (Western Basin) they generally inhabit the deep, colder waters, especially in the north Adriatic and the North Aegean (*Dipturus oxyrinchus*, *Leucoraja melitensis*, *L. circularis*, *Raja brachiura*). Warming of waters could further endanger these species which are in a vulnerable status due to overfishing.

Past and current information on species geographic distribution will be then compared and analysed to screen those species that have shown fluctuations and geographic shifts in relation to changes in climatic conditions.

PLANNED ACTIVITIES AND EXPECTED OUTCOMES

After the careful selection of key macrodescriptors of change, which will be made as a concerted decision by expert partners, field surveys will be carried out across the basin in strategic areas such as the species distribution limits (including depth ranges), biogeographic transition zones (e.g. Sicily Channel) and cold spots (e.g. North Adriatic). Data will be then analysed and correlated with hydro-climatic trends from field (e.g. Hydrochanges, MedGLOSS) and satellite data.

The expected Programme outcomes will include: the identification of species most threatened by increasing warming of waters and climate-related events and thus in need of special protection; the development of dynamic, web-interfaced, databases with interactive distribution maps providing information on taxonomy, ecological traits and geographic trends of climate-indicator species; the publication of scientific collaborative articles in international journals and expert reports synthesising trends in Mediterranean marine biodiversity.

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Allochthonous warm water species in the benthic communities and ichthyofauna of the eastern part of the Adriatic Sea

M. Despalatović, I. Grubelić, V. Nikolić, B. Dragičević, J. Dulčić, A. Žuljević, I. Cvitković and B. Antolić

Institute of Oceanography and Fisheries, Split, Croatia

1. ABSTRACT

The paper presents data on the extension of allochthonous warm water species in the eastern part of the Adriatic Sea. Particular emphasis is given to the algae *Womersleyella setacea, Asparagopsis taxiformis, Acrothamnion preissii, Caulerpa taxifolia, Caulerpa racemosa,* to the opisthobranchs *Melibe fimbriata, Bursatella leachii, Aplysia dactylomela,* to the pulmonate *Siphonaria pectinata* and to the anthozoan *Astroides calycularis.*

2. INTRODUCTION

Water temperature in the deepest layers of the Adriatic Sea, as in the rest of the Mediterranean Sea, is always above 11 to 12ºC. In the open surface waters during the summer temperature is usually from 22 to 25ºC, decreasing to 11.5ºC (Jabuka pit) and 12.7ºC (South Adriatic pit). Decrease of temperature occurs through the depth gradient, from the surface to the bottom. During the warmer season, especially summer, the thermocline is found at 10 to 30 m depth (Buljan and Zore-Armanda, 1971). During the winter, in periods of lower salinity, temperatures of the open surface waters are 13-15ºC in the South Adriatic, 12-13ºC in the Middle Adriatic and 6-12ºC in the North Adriatic. In the period of higher salinity: 15ºC in the South Adriatic and 6-13ºC in the North Adriatic (Pérès and Gamulin-Brida, 1973). The Adriatic Sea has a relatively high salinity, 38.3‰, that is slightly lower than salinity in the Eastern Mediterranean Sea but higher than in the Western part of the basin (Buljan and Zore-Armanda, 1971). There is a constant exchange between Adriatic and incoming salinity-rich and warm Mediterranean water that enters in intermediate layer and has a great impact on biota in the Adriatic Sea (Buljan and Zore-Armanda, 1971; see also various CIESM Atlases of Exotic Species in the Mediterranean <http://www.ciesm.org/online/atlas/index.htm>).

In this region three major biogeographic sectors are recognized: the northern, central and southern Adriatic Sea (Bianchi, 2007). In the last decades introduction of many allochthonous species has been recorded and many of them are considered as warm water. Increased occurrence of warm water biota is already recorded for the Mediterranean Sea, and it has been said that the Mediterranean is under the process of “tropicalization” (Bianchi, 2007).

In this paper we are reviewing and discussing the occurrence of warm water allochthonous species recorded in last few decades in benthic communities along the eastern Adriatic coast and their impact on native communities.

3. ALGAE

To date, about 650 taxa of benthic macroalgae were recorded in the Adriatic Sea. In the last two decades a number of allochthonous, often highly invasive algae were recorded for the first time and their invasion monitored. There are various reasons for their fast establishment and successful expansion. Some of them, like *Caulerpa* species, lack natural and effective predator to control their populations. Others, like *Womersleyella setacea*, create very dense turfs and propagate very fast by vegetative growth which is favourable after perturbations in marine environments. All invasive species have a strong potential to severely impact the natural habitats and communities in the Adriatic Sea.

• *Womersleyella setacea* (Hollenberg) R.E. Norris (Rhodophyta, Ceramiales, Rhodomelaceae) is a filamentous red alga with a tropical Indo-Pacific-Caribbean distribution. It was first described from specimens collected in the Hawaiian Islands (Hollenberg, 1968). Verlaque (1989) reported the first occurrence of *W. setacea* in the Mediterranean Sea, stating that it was probably introduced. Other authors report a rapid spread of this invasive species in the Mediterranean (Airoldi *et al.*, 1995; Athanasiadis, 1997). The most probable ways of spreading are via ships' fouling, currents and fishing nets.

Womersleyella setacea was first reported for the Adriatic Sea in 1997 (Batelli and Arko-Pijevac, 2003) for the area of Rijeka (45º16.23N, 14º33.36E). Since then it was frequently found throughout the Adriatic Sea with a total number of almost 50 locations (unpublished data). It is found from 8 to 50 meters on the rocky and sandy substrate, covering up to 100 percent of the sea bottom. Experimental growth in culture from specimens collected near Livorno, Italy (Rindi *et al.*, 1999) showed the upper thermal limit of 28ºC, and algae able to tolerate temperatures of 5ºC for a period of 4 weeks without any damage. This is consistent with the fact that the northernmost distribution of *W. setacea* is in the northern Adriatic Sea where winter sea temperature reaches values below 10ºC for a period of few months. These observations suggest that the Mediterranean entity of *W. setacea* might not survive in tropical areas and that there may exist thermal ecotype of this species in temperate seas (Rindi *et al.*, 1999). The existence of such ecotype of *W. setacea* can also be supported by the fact that *W. setacea* has not yet been found in the area of southern Turkey and Levant states where summer sea temperatures reach 28ºC (Rindi *et al.*, 1999).

Womersleyella setacea is a highly invasive alga in the Mediterranean Sea (Boudouresque and Verlaque, 2002; Streftaris and Zenetos, 2005). There are indications that it is becoming dominant or taking the place of keystone species in the infralittoral algal community (Airoldi *et al.*, 1995; Piazzi and Cinelli 2001; Piazzi *et al.*, 2002). In the Adriatic Sea its dense monospecific turfs were observed almost completely covering native algal cover on the rocky bottom up to 50 meters deep and also on *Posidonia oceanica* rhizomes where it displaces natural epiphytes. Only vegetative reproduction is recorded (personal observation). The spread of this invasive alga in the Adriatic Sea is monitored through the state-funded project.

• *Asparagopsis taxiformis* (Delile) Trevisan de Saint-Léon (Rhodophyta, Bonnemaisoniales, Bonnemaisoniaceae) is a red alga with a tropical and subtropical distribution (Bonin and Hawkes 1987; Huisman and Walker 1990). It was first described from Egypt in 1813 which shows that there existed Mediterranean populations before the opening of the Suez Canal. It has become a focus, recently, for molecular taxonomic research. Andreakis *et al.* (2004) believe that two separate introductions to the Mediterranean Sea happened. The first, earlier one, from the Atlantic Ocean which established populations in the southeast and the other, more recent one, from the Indo-Pacific which is now becoming invasive in the northern Mediterranean Sea.

A study by Ní Chualáin *et al.* (2004) divides *A. taxiformis* into two clades, a Pacific-Italian clade and a Caribbean-Canaries clade, which together might represent cryptic sibling species or temperature ecotypes. A Caribbean clade has a minimum of 17ºC for survival and growth and upper survival limit of 31ºC. The Pacific/Italian clade has a much lower survival temperature of 9-13ºC, with a similar upper survival limit of 29-31ºC.

The gametophyte phase of *A. taxiformis* is spreading and considered invasive in the northern Mediterranean Sea (Boudouresque and Verlaque, 2002). It is spreading by currents or ships' fouling. In the Adriatic Sea it was first found in 2000 in the area of Dubrovnik (42º38.23N, 18º06.48E) on the rocky bottom between 1 and 10 meters deep and also in the National Park Mljet (unpublished data). Both populations are not increasing in size. This invasive alga is monitored through a state-funded project.

• *Acrothamnion preissii* (Sonder) Wollaston (Rhodophyta, Ceramiales, Ceramiaceae) is a tropical filamentous red alga with a recorded distribution in Japan, South Africa and Australia. It was recorded for the first time in the Mediterranean Sea in 1969 in Italy (Cinelli and Sartoni, 1969). To date, it colonised the coasts of Italy and France (Cinelli *et al.*, 1984; Bianchi and Morri, 1994; Verlaque, 1994).
In the Adriatic Sea it was found for the first time in 2007 in Dubrovnik (42º38.27N, 18º06.47E). This invasive species deeply affects native communities of benthic algae and epiphytic communities on *Posidonia oceanica* rhizomes (Piazzi *et al.*, 1996; Piazzi *et al.*, 2002). Its dense turfs can outgrow native erect algal species and prevent their settlement. This invasive alga will be monitored in the Adriatic Sea through the state-funded project.

• *Caulerpa taxifolia* (Vahl) C. Agardh (Chlorophyta, Bryopsidales, Caulerpaceae) is a siphonous green alga with a native distribution in tropical and subtropical areas of the world oceans (Phillips and Price, 2002). It was likely introduced to the Mediterranean Sea in recent decades. The origin of this invasive alga is the area of Moreton Bay, Australia (Meusnier *et al.*, 2001; 2002; Phillips and Price, 2002). By the end of 2000 *C. taxifolia* had been recorded in 120 locations in Monaco, France, Italy, Spain, Tunis and Croatia (Meinesz *et al.*, 2001). It is spreading by anchors and fishing nets. In the Croatian part of the Adriatic Sea, *C. taxifolia* had been found in three distant areas: in Stari Grad Bay (Hvar Island) during the summer of 1994, in Malinska (Krk Island) at the end of 1994, and in Barbat Channel (between the Islands of Dolin and Rab) at the end of 1996 (Špan *et al.*, 1998; Žuljević, 2005). *Caulerpa taxifolia* introductions are now a global problem with populations in the Mediterranean and Australian waters. It is one of the most invasive organisms in the Mediterranean Sea (Streftaris and Zenetos, 2006) that can completely change the natural habitat and profoundly impoverish infralittoral algal communities. It is found from the surface up to 40 meters and even 100 meters deep (Belsher and Meinesz, 1995), on all types of the sea bottom and inside the *Posidonia oceanica* meadow. In the Mediterranean, it develops on temperatures higher then 15ºC, but it can experimentally survive a temperature between 10ºC and 15ºC for a period of three months (Komatsu *et al.*, 1997). The northernmost location of *C. taxifolia* in Croatia is Malinska bay. A well established meadow of *C. taxifolia* has been nearly eliminate in the period 2002 - 2004, when sea temperatures reached 9ºC for a period of few months. The only successful eradication of the invasive *C. taxifolia* was done in California, USA (Williams and Schroeder, 2004).

• *Caulerpa racemosa* var. *cylindracea* (Forsskål) J. Agardh (Chlorophyta, Bryopsidales, Caulerpaceae) is a siphonous green alga originating from south-western Australia. It was first recorded in the Mediterranean in 1990 and since then has reached the coastline of 12 countries.
First record of *C. racemosa* in the Adriatic Sea dates from 2000 in the area of Pakleni Islands (Žuljević *et al.*, 2003). In the end of 2007, a total of 60 affected locations were recorded. *Caulerpa racemosa* is highly invasive, changing the habitat structure and native macroalgal populations.
Some differences were noted compared to its native populations in Australia. Mean sea surface temperatures in south-western Australian waters range from 14ºC to 16ºC in summer (Verlaque *et al.*, 2003). In the Mediterranean Sea, *C. racemosa* is exposed to a wider temperature range, down to 8ºC (Žuljević, 2005) and up to an average of 28ºC. Additionally, unlike its natural populations in Australia, in the Mediterranean Sea it is creating monospecific assemblages on all types of substrates from 0 to 60 meters of depth.
Eradication of *C. racemosa* colonies is continuously done in the National Park Mljet near one of the largest recorded banks of the coral *Cladocora caespitosa* in the Mediterranean Sea. The advance of this highly invasive species is monitored through the state-funded project.

4. Benthic invertebrates

Fauna of invertebrates in the Adriatic Sea shows a high diversity, with 5,427 species recorded (Radović, 1999). This number is rising due to new research of some taxonomic groups and sampling of previously not sampled habitats. Further occurrence of allochthonous species due to anthropogenic impact and environmental changes was recorded recently. We discuss below the presence of a few warm water allochthonous species recorded in benthic communities in the eastern Adriatic.

• *Astroides calycularis* (Pallas, 1767) (Cnidaria, Anthozoa) is a typical species of the southern part of the western Mediterranean Sea and Ibero-Moroccan Bay and is believed to be a warm water species with narrow temperature tolerance (Bianchi and Morri, 1994). It inhabits caves and fissures of rocky shore from 1 to 50 m depth (Rossi, 1971). In the Mediterranean Sea, the species is distributed along the northern African coast, from Morocco to Tunisia, southern coast of Spain, area of Sicily and some parts along the western Italian coast (Zibrowius, 1980; 1983; Bianchi and Morri, 1994; Bianchi, 2007). The northernmost record of the species in the Mediterranean is Giglio Island (42º22’N, 10º53’E), Tuscan Archipelago, where a dead colony was found in 1989, having possibly settled in one of the previous years, but not surviving a subsequent winter (Bianchi and Morri, 1994; Zibrowius, 1995).
In the Adriatic Sea the species was recorded for the first time in 1899 in Rijeka Bay in the northern Adriatic. Thereupon, *A. calycularis* was noted in 1904 in Boka Kotorska Bay in the southern Adriatic, and in 1945 in Dalmatia in the middle Adriatic (Pax and Müller, 1962). Since *A. calycularis* is a warm water species, there were doubts about the proper determination of the species in the Adriatic, particularly its northern part (Zibrowius and Grieshaber, 1975/1977; Zibrowius, 1978; Zavodnik and Kovačić, 2000). In spite of numerous investigations of benthic fauna of the littoral part of the Adriatic Sea, the warm-water coral *A. calycularis* was not recorded until 1990s when Grubelić *et al.* (2004) recorded species on three locations in the middle Adriatic Sea: on the coast of Čiovo Island in 1990, area of Makarska in 1991, and in 2001 on the rocky shore of islet Borovnik (43º55’N, 15º17’E), that is recently the northernmost record of this species either inside or outside of the Adriatic Sea. Beside these records, Kružić *et al.* (2002) reported two more findings of *A. calycularis* in 1999 from the southern Adriatic, on the rocky shore of the Glavat Island (42º45.8’N, 17º9.0’E). The colony was checked in the summer 2007 and was still alive (Kružić, pers. comm.).

• *Melibe fimbriata* Alder and Hancock, 1864 (Mollusca, Gastropoda, Opisthobranchia) is an Indo-Pacific species, recorded in the Mediterranean Sea for the first time in 1982 from the Astakos inlet in the Ionian Sea (Thompson and Crampton, 1984), who suggested that it may have entered the Mediterranean via the Red Sea and the Suez Canal. Before the finding in the Adriatic Sea where it is well established, the species has been recorded from various places in the Mediterranean, Greece, Tunisia and Italy (see CIESM Atlas of Exotic Species in the Mediterranean Vol. 3 Zenetos *et al.*, 2003).
In the Adriatic Sea *M. fimbriata* was found in October 2001 in Starigrad Bay (43°11’N, 16°35’E), Island of Hvar, furthest north record in Mediterranean basin (Despalatović *et al.*, 2002). A large number of specimens (1/100 m^2) was observed in *Cymodocea nodosa* and some in *Posidonia oceanica* beds on the sandy and sandy-muddy bottoms at depths of 2 to 15 m. Spawning was also observed (Despalatović *et al.*, 2002). In successive years, the species was not found in that area and there is no any other record along the eastern Adriatic coast.

• *Bursatella leachii* de Blainville, 1817 (Mollusca, Gastropoda, Opisthobranchia) is distributed in warm temperate and tropical waters throughout the world. It is considered as true Lessepsian migrant, recorded first from Israel (O’Donoghue and White, 1940). Before the record in the Adriatic Sea, it was recorded in many locations in the Mediterranean, Turkey, Malta, Gulf of Taranto and Sicily (see CIESM Atlas of Exotic Species in the Mediterranean, Vol. 3 Zenetos *et al.*, 2003). In the Adriatic Sea it was first recorded in its southern part, in the area of Bari (Vaccarella and Pastorelli, 1983) and successively in the northern part, in the lagoon of Venice, the area of Trieste, and near Rovinj (western Istrian coast) (Cesari *et al.*, 1986; Jaklin and Vio, 1989; De Min and Vio, 1998). In the last two decades the species was occasionally observed in the area of the middle Adriatic (around Split and Island of Hvar).

• *Aplysia dactylomela* Rang, 1828 (Mollusca, Gastropoda, Opisthobranchia) is a species of worldwide distribution in tropical to warm temperate waters. The first record of the species in the Mediterranean Sea is from Lampedusa Island (Trainito, 2003). After that, the species was recorded in several Mediterranean places, in Greece, Cyprus, Turkey and Italy (posts on <www.seaslugforum.net>; Yokes, 2006). The first record of the species in the Adriatic Sea is from

Island Sušac in July 2006 (Turk, 2006). Additionally, in the same year in September, one specimen was observed in the area of Island of Mljet (southern Adriatic Sea) at 2 m depth on rocky shore and was spawning (Prkić, pers. comm.).

• *Siphonaria pectinata* (Linnaeus, 1758) (Mollusca, Gastropoda, Pulmonata) inhabits the intertidal on rocky shores at warmer latitudes on both sides of the Atlantic, from Portugal to Cameroon (break at the Gulf of Guinea) and in the area of Florida (Voss, 1959; Ocaña and Emson, 1999). In the Mediterranean Sea, it is originally distributed in the Alboran Sea, Algerian coast, west of Algiers, and the southern coast of Spain. Nicolay (1980) recorded the presence of the species for the Saronikos Gulf in the south Aegean Sea where it was still thriving according to Gofas and Zenetos (2003). Another published record away of the original species distribution area was from two areas along Tunisian coast (Antit *et al.*, 2007).
In the Adriatic Sea the species was recorded for the first time in spring 2003 in the area of Split. Since the observed population was numerous, we supposed that the species inhabited the area in previous years. It is quite certain that the species is introduced in this area by ships, because Split has two harbours for international maritime transport. *S. pectinata* continues to thrive in the wider area around the town of Split. In 2008 the species was observed from Trogir to Omiš, small towns north and south from Split, and in the area of Brač Island. In intertidal rocky shores were the species was firstly recorded the population is now abundant, with mean density per 20 cm x 20 cm squares at 33.4±17.9 in May 2007, and dominating over native *Patella* species. Deposited egg mass ribbons were observed from April to October 2007.

Among exotic molluscs referred by De Min and Vio (1998) for the northernmost part of the eastern Adriatic coast, some species are also from tropical regions: *Strombus persicus* Swainson, 1821, recorded as accidental in area of Trieste, and unlikely to survive because of low winter temperatures; few specimens of *Brachidontes pharaonis* (Fischer P., 1870) were recorded from Punta Salvore (Croatia); *Pinctada radiata* (Leach, 1814) recorded in Trieste on oil platform originating from the Sicily.

5. ICHTHYOFAUNA

Jardas (1996) enumerated 407 fish species in the Adriatic Sea. Later revision raised this number to at least 432 (Dulčić *et al.*, 2004). The general conclusion regarding the occurrences of previously unrecorded fish species over the last 25 years is that, probably due to water warming effects, a great number of thermophilic species has been recorded in the Adriatic (Dulčić and Grbec, 2000). A majority of these species are lessepsian migrants.

As various studies suggest, changes in ichthyofauna may reflect climatic and oceanographic changes (Mearns, 1988; Stephens *et al.*, 1988; Francour *et al.*, 1994).

In the Adriatic, many warm water fish species move toward higher latitudes with incoming warmer and more saline Mediterranean water (Dulčić and Grbec, 2000).

Recently recorded species like *Sphoeroides pachygaster, Plectorhinchus mediterraneus* and *Mycteroperca rubra* probably extended their distribution from the southern areas to the north due to warming, but whether those findings represent an abortive or a successful attempt of colonization of northern areas is yet to be evaluated. The finding of *Epinephelus aeneus* in the middle-eastern Adriatic in 2006 represents the northernmost occurrence of this species in the Mediterranean. This record, along with two previous records of this species in the Adriatic, could suggest that this species is in the process of colonization of northern areas, particularly Adriatic (Glamuzina *et al.*, 2000; Dulčić *et al.*, 2006). A similar pattern is observed with other members of genus *Epinephelus* (sensu Glamuzina *et al.*, 2000).

Recently, ten lessepsian fish species were recorded in the Adriatic (one migrant, *Pampus argenteus*, was recorded in the Adriatic in 1896 hence its exclusion from this list). Temperature is the most important factor in determining the dispersal of lessepsian fish (Ben-Tuvia and Golani, 1995; Pallaoro and Dulčić, 2001) and so presence of lessepsian migrants in the Adriatic could be in correlation with Adriatic ingressions rather than a consequence of species adaptation to new environment. As a key argument for this conclusion stands the fact that, except in the case of *Fistularia commersonii*, there are no subsequent records that could suggest that these fishes have established their population in the Adriatic Sea and it is impossible to perform any ecological analyses based on sporadic and rare records. However, established populations of some lessepsian migrants in the Eastern Mediterranean Sea, especially in the Ionian and Aegean Sea, could provide "recruits" capable of invading and establishing populations in Adriatic waters.

As warming continues, further increase in abundance of some thermophilic species could be expected. There are many indices showing that climate change on a global scale has influenced and changed assemblage of ichthyofauna in the Mediterranean, including Adriatic, in a more or less significant amount in regard to new species present in the area. The hypothesis of northward spreading of thermophilic fish species caused by warming is supported with numerous records of fish species previously characteristic of more southern and warmer areas. The Adriatic Sea is obviously becoming a northward distribution path of lessepsian migrants and other thermophilic species. Therefore, continuous scientific research should evaluate the impact of such invasions on local ichthyofauna and ecosystem in general.

Here below the reader will find a list of allochthonous thermophilic species recorded in the last few decades in the eastern part of the Adriatic Sea.

- *Hemiramphus far* (Forsskål, 1775) is a Lessepsian migrant, recorded in the Adriatic Sea for the first time near the Albanian coast (Collette and Parin, 1986). There is no additional record for this species in the Adriatic.

- *Parexocoetus mento* (Valenciennes, 1847) is a Lessepsian migrant, recorded in the Adriatic Sea for the first time near the Albanian coast (Parin, 1986). There is no additional record for this species in the Adriatic.

- *Saurida undosquamis* (Richardson, 1848) is a Lessepsian migrant, recorded in the Adriatic Sea for the first time near the Albanian coast (Rakaj, 1995). It is possible that the species has established a population near the Albanian coast (pers. comm.).

- *Sphoeroides pachygaster* (Müller and Troschel, 1848) is a thermophilic species with circumglobal distribution in tropical and temperate seas. The first record in the Adriatic Sea is from 1992 (Dulčić and Lipej, 2002). Many new records of this species could indicate the establishment of a self-sustaining population in the Adriatic.

- *Plectorhinchus mediterraneus* (Guichenot, 1850) is a thermophilic species distributed along the West African coast and in the western Mediterranean. First records for the Adriatic coast were reported in 1993 from Trieste Bay and Piran Bay (Lipej *et al.*, 1996). There is no additional record for this species in the Adriatic.

- *Tylosurus acus imperialis* (Rafinesque, 1810) is a thermophilic species distributed in the eastern Atlantic and the Mediterranean Sea. This species was recorded for the first time in the southeastern Adriatic in 1994 (Bello, 1995). There is no additional record for this species in the Adriatic.

- *Epinephelus coioides* (Hamilton, 1822) is a Lessepsian migrant, recorded in the Adriatic Sea for the first time in Trieste Bay in 1998 (Parenti and Bressi, 2001). There is no additional record for this species in the Adriatic.

- *Epinephelus aeneus* (Geoffroy Saint-Hilaire, 1817) is thermophilic species from the eastern Atlantic and southern Mediterranean Sea. In the Adriatic Sea, this species was recorded for the first time in 1999 near Dubrovnik, and additionally near the island of Dugi otok in 2006 (Dulčić *et al.*, 2006). There is evidence of northward spreading of groupers, and this is the northernmost occurrence of this species.

- *Mycteroperca rubra* (Bloch, 1793) is a thermophilic species distributed in the eastern Atlantic and Mediterranean Sea. The first report of the species in the Adriatic Sea is from the area of Dubrovnik in 2000 (Glamuzina *et al.*, 2002). There is no additional record for this species in the Adriatic.

- *Leiognathus klunzingeri* (Steindachner, 1898) is a Lessepsian migrant, recorded in the Adriatic Sea for the first time in the area of Island of Mljet in 2000 (Dulčić and Pallaoro, 2002). There is no additional record for this species in the Adriatic.

- *Sphyraena chrysotaenia* Klunzinger, 1884 is a Lessepsian migrant, recorded in the Adriatic Sea for the first time in 2000 near Molunat in the Southern Adriatic, caught together with several specimens of *Sphyraena sphyraena* (Pallaoro and Dulčić, 2001). There is no additional record, but it could go unnoticed because of its similarity with *Sphyraena sphyraena*.

- *Siganus rivulatus* Forsskål, 1775 is a Lessepsian migrant, recorded in the Adriatic Sea for the first time in 2000 near Bobara Island in the Southern Adriatic (Dulčić and Pallaoro, 2004). There is no additional record for this species in the Adriatic.

- *Stephanolepis diaspros* Fraser-Brunner, 1940 is a Lessepsian migrant, recorded in the Adriatic Sea for the first time near the coast of Montenegro in 2002 (Pallaoro and Dulčić, 2001). There is no additional record for this species in the Adriatic.

- *Sphyraena viridensis* Cuvier, 1829 is a thermophilic species distributed in the eastern Atlantic and Mediterranean Sea. In the Adriatic Sea, three specimens were caught near Herceg-Novi (Montenegro) in 2004 (Dulčić and Soldo, 2004). There is no additional record for this species in the Adriatic, but it could go unnoticed because of its similarity with *Sphyraena sphyraena*.

- *Lagocephalus lagocephalus lagocephalus* (Linnaeus, 1758) is a thermophilic species distributed in tropical and subtropical waters in the Atlantic, Indian and Pacific Oceans. The first report of the species is from the Southern Adriatic, from the area near Molunat in 2004 (Dulčić and Pallaoro, 2006). There is no additional record for this species in the Adriatic.

- *Fistularia commersonii* Rüppell, 1838 is a Lessepsian migrant, recorded in the Adriatic Sea for the first time in 2007 near Sveti Andrija Island and near the Italian coast. There is a new record from Bar in Montenegro (Dulčić *et al.*, 2008). Based on additional records, there is a possibility of existence of a self-sustaining population in the Adriatic.

- *Terapon theraps* Cuvier, 1829 is a Lessepsian migrant. In the Adriatic Sea one specimen was caught in 2007 in Piran Bay (Lipej *et al.*, in press). There is no additional record for this species in the Adriatic.

Possible climate impacts on the northern Adriatic pelagic ecosystem

Serena Fonda Umani [1] and Alessandra Conversi [2]

[1] *Department of Life Sciences, University of Trieste, Trieste, Italy*
[2] *CNR, ISMAR-La Spezia, Pozzuolo di Lerici (SP), Italy*

Nowadays one of the most challenging questions for both terrestrial and marine ecologists is how climate change will impact a given ecosystem. To forecast the possible responses we need to know how that system behaved in the past under climatic oscillations, which means that we have to look at long time series of data.

For marine scientists the major problem is that biological time series are generally rather short (usually no more than 50 years) compared to terrestrial or atmospheric records. Thanks to paleocologists we are able to reconstruct the far past, but this does not help us to understand the biological characteristics of 100 – 150 years ago. They are a sort of black box. In this paper we examine different long time series collected in the northern Adriatic Sea.

NORTHERN ADRIATIC SEA

The Adriatic Sea is one of the most studied areas of the Mediterranean Sea. The first scientific information dates back at least 400 years (Zavodnik, 1983). Stretching southward for 800 km from the highest Mediterranean latitude (45° 47' N), it consists of three basins (northern, central and southern) of increasing depth, from the shallow north area (usually not exceeding 50 m of depth) to the >1,200 m of the south trench, which is separated by a sill from the central basin. The most important currents are the Eastern Adriatic Current (EAC) flowing northward from the Levantine Basin and the Western Adriatic Current (WAC) that flows southward along the Italian coast. During winter very dense water is produced in the northern area by the cooling caused by the strong ENE wind (Bora), which flows southward as bottom current following the topography of the basin.

The northern Adriatic has been recognized for many years as a region of high marine production at several trophic levels, from phytoplankton to fish. In particular, a region of high but variable phytoplankton biomass and production was quantified off the delta of the Po River, and related to the spreading of its plume (Franco, 1973; Gilmartin and Revelante, 1981). In general, a marked west to east decreasing gradient of biomass and production is observed (Smodlaka and Revelante, 1983).

The longest time series available for the northern Adriatic deals with the mucilage events and dates back to 1729 (Fonda Umani *et al.*, 1989). The word "mucilage" indicates here the huge accumulation of dissolved (colloidal) organic matter that can cover the sea surface for hundreds of square kilometers and underwater can assume the aspect of large clouds up to 6 – 7 m long and > 2 m large. Recently we have demonstrated that mucilage is due to the uncoupling between primary production and bacterial carbon demand and the consequent accumulation of dissolved organic material, which is the proximal source of the aggregates (Fonda Umani *et al.*, 2007).

The time series was reconstructed on the basis of some scientific papers and of several records in old newspapers (Fonda Umani *et al.*, 1989 and references therein) (Figure 1). Mucilage events have been noted in the northern Adriatic (NA) since 1729, followed by events in 1872, 1880, 1903, 1905, 1920, 1930, 1949, possibly 1951, and most recent episodes in 1988, 1989, 1991, 1997, 2000, 2002 and 2004 (Fonda Umani *et al.*, 1989; Precali *et al.*, 2005). In 1976 and 1983, mucilage accumulation was isolated in the Kvarner region (Pucher-Petkovic and Marasovic, 1987). The mucilage events appear to interrupt in the middle of last century and since 1968 red tides, mostly due to dinoflagellates, each year affected the NA.

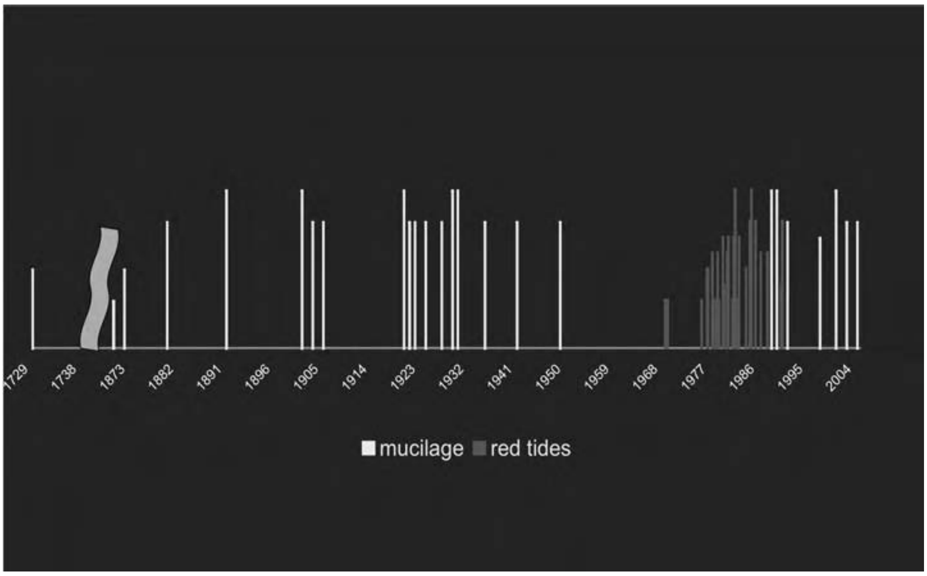

Fig. 1. Long-time series of mucilage and red tide events in the Northern Adriatic.

Dinoflagellate blooms occur most frequently along the western margin of the NA, probably as a consequence of the combined effects of the discharge of buoyant, nutrient-rich water and physical processes that confine the discharges from the Po River and smaller rivers to the western margin under most circumstances. Three bloom periods characterize the region: 1) following the late spring diatom bloom, when surface nutrients are depleted and the water column has become thermally stratified, dinoflagellates are able to bloom by migrating between nutrient-rich, sub-thermocline water and the surface layer where light intensity is higher; 2) during the summer, when surface waters remain nutrient depleted and dinoflagellates rapidly respond to local nutrient enrichment from river discharges or coastal upwelling; 3) after the rainfall-induced freshets in autumn, which lead to brief diatom blooms, followed, as in spring, by blooms of dinoflagellates. The duration of spring and summer blooms appears to be limited by nutrient availability, while autumn events seem more dependent on stable meteorological conditions and perhaps intense recycling of local production (Sellner and Fonda Umani, 1999). Red tides series ended by 1987, and after the reappearing of mucilage, only in 1990 was there another red tides season.

The triggering causes of the mucilage were widely debated by the international scientific community (e.g. Degobbis *et al.*, 1995; 1999). Boero (2001) proposed an articulated model in which jellyfish outbreaks in the early 1980 s played a key role in de-structuring Adriatic food webs as the result of the strong predation impact on fish eggs and mollusks' larvae. His proposal explains the red tides increase by the reduction in efficiency of the grazing food web (diatoms – copepods – fish) and of the filtering benthos population (mollusks). Excess nutrients were used by the opportunistic dinoflagellates, which in turn led to both pelagic and benthos mass mortalities due to anoxic crises. Benthos mortality reduced the yield of commercially important bivalves, inducing fishermen to use more efficient tools to collect them such as hydraulic dredges. The already depleted stock of benthic filter feeders was further impacted by over-fishing. The food webs shifted from the old very productive grazing type to a sort of microbial loop with mucilage as end product. Boero predicted that in a year rich of thaliaceans, and more generally, I would say, of gelatinous filter feeders, mucilage will not occur.

Fonda presented several times a simpler model (Figure 2), taking into account that P - limitation plays a relevant role in mucilage formation, increasing the percentage of exudation by primary producers and limiting the efficiency of bacterial degradative metabolism. In the past P loads in the Adriatic Sea were much higher. The Margalef's Mandala foresees in a turbulent system at high nutrient concentration an efficient grazing food web with high fish production, while at low turbulence (like in the Italian coast belt of the NA confined within the frontal system) red tides occur. Italian law banned P from the detergents in the middle of 1980 s and in the meantime P oxidation of the sewage treatment plants was improved leading to a relevant P reduction in the sea water (while N loads are still increasing). The unbalanced N:P ratio seems to favor small phytoplankton over diatoms and possibly the microbial food web (based on cyanobacteria) over the classic grazing one and, according to Boero (2001), jellyfish as top predators in a turbulent system. In a well-stratified confined system the final product is the less structured one, that is mucilage. The amount of carbon produced does not necessarily change but what changes is the final product from a well structured and appreciated multicellular fish to unicellular dinoflagellates at high P concentration to jellyfish in a mixed water column and just gelatinous amorphous organic slime in stratified calm sea at low P concentration.

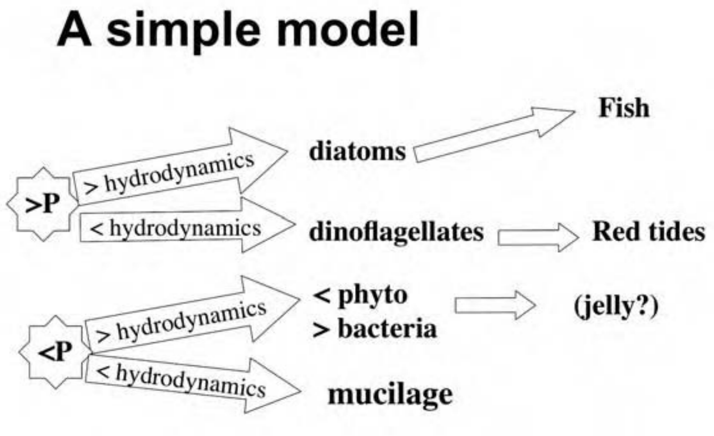

Fig. 2. A simple model of NA pelagic ecosystem functioning at high and low phosphorus loads and hydrodynamic conditions.

Another long biological time series available for the NA is the annual catch of anchovy for the three countries bordering the basin (Italy, Slovenia and Croatia) for the period 1975-2004. For the same time interval, fishing effort data and length frequency and age-length data were available. These data were combined into fish age classes, so that catch-at-age data were used as basic input of Virtual Population Analysis (VPA) by Cingolani *et al.* (2005). Anchovy (*Engraulis encrasicolus* L.) is one of the most important commercial species of the northern and central Adriatic. The mean annual catch of anchovy was estimated in the time interval 1975 – 2001 at 24,000 tonnes (Santojanni *et al.*, 1996). Stock biomass of anchovy dropped at very low level in 1987. After this collapse a slow but continuous recovery of biomass took place. Also in this case the first explanation was overfishing, associated with low levels of recruitment in 1986 and 1987 (Santojanni *et al.*, 2006). Regner (1996) suggested a possible role of mucilage in the anchovies' drop, because mucus aggregates can negatively impact anchovy directly (irritating adult fish and trapping larvae and post larvae) or indirectly (by changing plankton communities' structure). This may be true after 1988, but not before. Santojanni *et al.* (2006) found positive relationships of number of recruits with autumnal SSE and ESE wind stress and both annual and fall Po River runoff, as well as with high frequency of NE winds and positive value of NAO index in the previous autumn.

The most specific long time series for this workshop is confined to the Gulf of Trieste and is constituted by monthly records of copepods' community structure and abundance in the period 1970 – 2005 (with a 5 years gap between 1981 and 1985). The Gulf of Trieste is the northernmost part of the NA, with a surface area of about 600 km^2 (Malej and Malačič, 1995), and a volume of 9.5 km^3 (Olivotti *et al.*, 1986). It is characterized by an overall shallowness (maximum depth around 23 m in the southern part), and 10% of the average bottom depth < 10 m; and by large and variable freshwater inputs (Fonda Umani *et al.*, 1992). The main freshwater input is through the Isonzo River from the north-west coast. Hydrodynamical conditions are forced by the wind regime, characterized by strong, abrupt wind events and by the interaction with the general circulation of the Adriatic Sea. Both salinity and temperature ranges are very wide, spanning from <20 to >38 and from 6°C to >25°C respectively. Highly variable environmental conditions selected over time a peculiar zooplankton community constituted by relatively few highly tolerant species. The copepods' community in the Gulf of Trieste is characterized by approximately 40 coastal and estuarine species (compared to more than 130 in the southern basin), which in turn can exhibit high dominance. Copepods dominate in all months except for June and July, when the cladoceran *Penilia avirostris* takes over (Cataletto *et al.*, 1995). In particular, the calanoid copepod *Acartia clausi* is dominant for most of the year, comprising at some points >80% of the total biomass followed by *P. avirostris*, which can account for >37% in summer (Fonda Umani, 1985). Other species of copepods like *Oithona*, *Clausocalanus*, *Temora*, *Paracalanus*, and more recently *Oncaea*, can be considered relevant (Specchi *et al.*, 1981; Fonda Umani and Ghirardelli, 1988; Fonda Umani *et al.*, 2005; Kamburska and Fonda Umani, 2006). Recently Piontkovoski *et al.* (2006) highlighted the relationship between copepods' abundance in the Gulf of Trieste and the NAO index with a time lag of 0 – 1 year. The first studies on this time series have focused on group associations. Cataletto *et al.* (1995) found, during the first decade of monitoring (1970-80), a regular late spring-summer appearance in a group characterized by *Acartia clausi* and *Temora longicornis*, and a regular autumn-winter appearance in a group characterized by *T. stylifera* and *Oncaea* spp. Two main groups related to spring-summer and winter-autumn prevalence were also identified by Kamburska and Fonda Umani (2006), who found several differences in patterns of abundance between 1970-1980 and 1986-1999 and attributed them to climate changes (NAO, ENSO, EMT, SST increase) in the northern hemisphere from 1987. In the early 1990 s, the same authors noticed also the arrival in the Gulf of *Diaxis pigmoaea*, which earlier was confined to more southern coastal areas of the basin (Fonda Umani *et al.*, 1984; 1994). They also observed a significant increase of *Oncaea* spp., which often prevails in the diet of anchovies, after 1987, when anchovy stock collapsed (Figure 3).

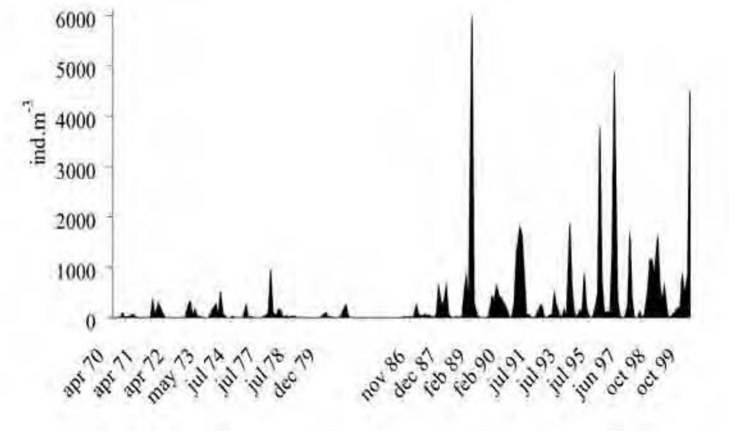

Fig. 3. Mean annual abundances of *Oncaea* spp. in the Gulf of Trieste in the 1970 s and 1980 s (from Kamburska and Fonda Umani, 2006).

The analysis of the long-term copepod records indicates that the whole community underwent a substantial transformation over the 36 year period, which appears to be mainly centered around the end of the 1980s - beginning of the 1990s. Recently our group tried to identify the period of change using the sea surface temperature record in the Gulf of Trieste for the period 1970-2005. SST is used as an indicator of physical change in the ocean and long-term changes in SST have been found to be concurrent to widespread changes in the marine system (Kirby *et al.*, 2007). Overall, in the Gulf of Trieste SST has increased by 0.5°C between 1970 and 2005, but this increase is not equally distributed between seasons, and the spring, summer, as fall temperatures increased by 0.6°C, 1°C, 1.1°C, respectively, while there is no long-term increase in the winter SST. The cumulative sum technique (Beaugrand *et al.*, 2003) has been used to identify whether a year of change in the water column was present.

The cumulative sums of the winter SST indicate that the period of change in the water column starts in 1987, which divides two periods, one from 1970 to 1987, the second from 1988 to 2005. New/ rare species occurrences were noted: the appearance of the southern Adriatic species *Diaixis pygmoea* in the Gulf of Trieste in February 1990, that has persisted since as documented by Kamburska and Fonda Umani (2006). For its part the cyclopoid copepods *Oithona similis* and *O. nana*, occasionally present and in low numbers in the first period, became relatively abundant in the late 1980s - early 1990s. We found a significant ($p < 0.05$) change between the two periods for total copepods, *Paracalanus parvus*, *Oncaea* spp., and *Euterpina acutifrons* (all increasing), *Pseudocalanus elongatus*, *Clausocalanus* spp. and *Ctenocalanus vanus* (declining). The entire species assemblage is also quite different between the two periods: during the years 1970-87 *A. clausi* represents 40% of the total copepod population, followed by *Clausocalanus* spp. (19%; in the second period becomes 5%), and “other copepods” (7%; then 8%), a group which contains the rare species *Candacia* spp., *Nannocalanus minor, Mecynocera clausi*, *Calocalanus* spp., and copepodite stages of Calanoids. In the second period *A. clausi*, while still undoubtedly the most abundant species, represents just 28% of the total copepod population, and the second most abundant taxon becomes *Oncaea* spp. (14%; was 4% during the first period), followed by *P. parvus* (11%; was 5%). Many species present a shift in the timing of the maximum abundance, therefore in their phenology. As example there is a large (84 days) delay in the fall peak of *P. elongatus* (no change in the timing of the spring peak). The fall peak has not only moved forward, but has basically vanished, which is likely to be associated to the 55% decline of this species. The abatement of the major abundance peak during the second period is seen also in *C. vanus* (another cold water species) and in *Clausocalanus* spp., which are both declining taxa. This is consistent with the hypothesis of a restricted season for these species, due to the warming. Edwards and Richardson (2004) observed analogous changes of the phenology of different plankton trophic levels in the central North Sea in response to the general warming of the system.

Using the same data set but exploiting another method (STARS method by Rodionov, 2004) to identify possible shift points in mesozooplankton descriptors Kamburska and Fonda Umani (in press) recognized significant temperature shifts in 1977, 1987 and 1995, which were paralleled by shifts of copepod abundance in 1979, 1987, 1991 and 2002 and of mesozooplankton biomass in 1979, probably in 1987, 1993 and 2001. They applied the same method to the phytoplankton time series of the Gulf of Trieste (1986 – 2005) and detected significant shifts in 1993 and 2001. On a wider geographical scale (the entire NA including the Gulf of Trieste) Camatti *et al.* (in press) observed in 2001 the over-all increase of *P. parvus* and the prolonged period of the *P. avirostris* swarming compared to previous records.

In the Gulf of Trieste *P. avirostris* time series (1986 – 2006) highlight relevant differences among decades (Figure 4): from 1986 until 1996 maxima peaked in August and on average were lower than in the following years when high values were reached already in July and remained high in September, and the cladoceran was regularly found, although in low numbers, from March until December. According to Specchi and Fonda (1974) at the beginning of the 1970 s, this warm species in the Gulf of Trieste started its swarming in the last week of June at a temperature of 20.6°C and totally disappeared by the mid of November at a temperature of 13.8°C. Compared to previous reports, it appears that this species, present in the North Adriatic not earlier than 1914 (Leder, 1917), not only became dominant in summer, thanks to its parthenogenetic reproduction, but that the period of its presence is expanding in the entire northern basin.

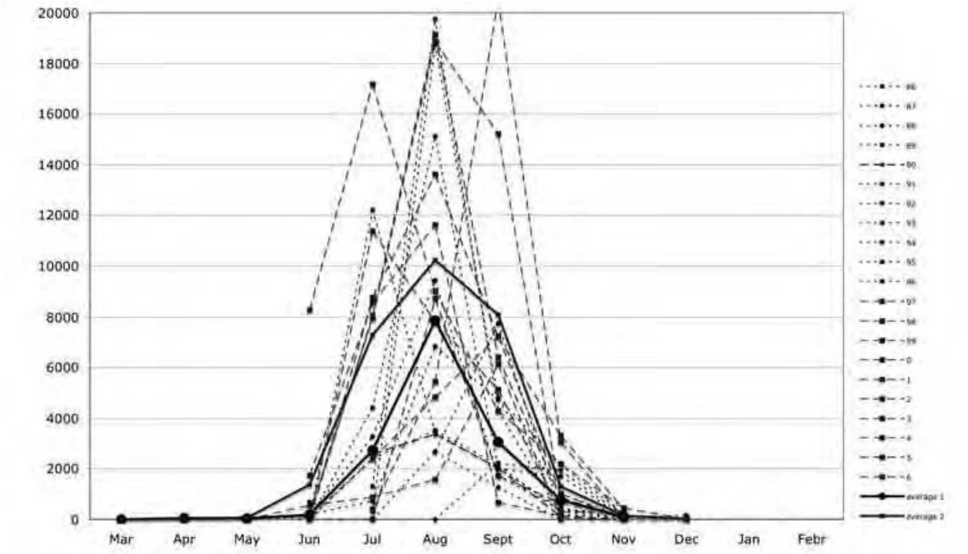

Fig. 4. Abundances and temporal dynamics of *Penilia avirostris* in the Gulf of Trieste in the 1980 s (black) and 1990 s (grey).

Summing up, it appears that in the NA ecosystem:

- 1987 was a year of change in the winter temperature, which affected (or concurred with) the whole pelagic food web, from primary producers up to fish;
- afterward cold species decreased, mostly because their time of presence in the NA was restricted by higher than usual summer/fall temperatures. In the meantime warm species expanded their period of presence and moved northward.

SOME PRELIMINARY CONCLUSIONS

The first consideration is that during the year 1987, marine ecosystems around Europe, not only in the Mediterranean basin, were also modified, albeit in very different ways (Alheit *et al.*, 2005). The abrupt alteration seen in the NA might thus be due to some larger scale climatic influences, which could have so far been hidden by the simultaneous reduction of P loads in the system. This was thought as the primary cause of the ongoing oligotrophication, and consequently of the observed biological changes from mucilage to fish stock collapse.

The second consideration is that the Gulf is a border system being under the influence of the EAC flowing from the south, and rich in nutrient fluvial inputs. Therefore, small climatic fluctuations may cause dramatic shifts in the system, from a mesotrophic situation, similar to the rest of the western Italian coast, to the more oligotrophic characteristics of the eastern coast and the open northern Adriatic waters.

The third consideration is that collecting all information available at different trophic levels is necessary to recognize large scale climate signals, and only after a more or less long time lag. Obviously the first analyses always rely on local environmental conditions or changes, both natural and anthropogenic. We need much more time to realize the biological response to large scale events driven by climatic changes.

Finally, we want to stress the importance of zooplankton long time series, even if in coastal areas, as they seem still capable of reflecting climate impacts. Only the most accurate and specific analyses on zooplankton communities have allowed us to identify a specific year of change in the Gulf of Trieste, which again highlights the crucial role of zooplankton long time series. As noted by Richardson (2008), zooplankton communities can be seen as beacons of climate change, particularly sensitive to global warming. The NA, and especially the Gulf of Trieste, are among the best areas to follow the future evolution of the zooplankton-climate link, because of the paucispecific composition of zooplankton communities, the availability of a long time series, and the high latitude. For example, if the present decreasing trend of cold relic species, such as *Pseudocalanus elongatus*, will continue, those species will totally disappear, being substituted by the warmer species which are already moving northwards.

Benthic marine algae as reflection of environmental changes in the Northern Adriatic Sea

Ivka M. Munda

Scientific Research Centre of the Slovene Academy of Science and Arts, Ljubljana, Slovenia

ABSTRACT

The northern Adriatic Sea is an unstable environment with wide seasonal and also interannual variations of the thermohaline regime, which is allied to the changeable current system and atmospheric conditions. There are likewise changes in the underwater illuminance and sedimentation rate. A complex interplay of these factors is reflected in the benthic algal flora and vegetation both regarding its seasonality and annual changes. There is, however, a highly dynamic situation in the benthic environment, which is overshadowed by anthropogenic disturbances, such as pollution, eutrophication and also mechanical damages. There is a general trend of reduction of fucoid stands, both in the eulittoral (*Fucus virsoides*) and sublittorally (*Cystoseira* and *Sargassum* species), in spite of transitional reinstallments. They are locally replaced by populations of ephemeral species. Several species with boreal affinities have not been found in recent surveys, while certain tropical species have increased in quantity.

Our findings are compared with the historical floristic data of Paul Kuckuck from the end of the 19th century, revealing a drastic reduction in the number of algal species, particularly in the Rhodophyta and Paeophyta.

INTRODUCTION

Marine algae are good descriptors of coastal environments. Changes of their associations, zonation patterns and floristic diversity are obviously linked to habitat modifications due to anthropogenic impact and variations of temperatures and salinities, light conditions as well as other abiotic ecological factors.

The northern Adriatic is a shallow shelf area and is regarded as the most dynamic basin of the entire Mediterranean Sea. It is characterised by a strong river run-off and wide seasonal and interannual variations of temperature and salinity (Russo and Artegiani, 1996; Artegiani *et al.*, 1997). It receives fresh water through the North Italian rivers (Po, Adige, Tagliamento, Isonzo), which carry a heavy load of organic and inorganic pollutants into the shelf. Pollution - and eutrophication - induced changes of the benthic algal flora and vegetation of this area were already reported (Munda, 1982b; 1993a,b; 1996). There are likewise changes related to the sedimentation rate, turbidity, and prevailing currents, which are linked to atmospheric conditions. During the last few years thermohaline properties within the northern Adriatic have changed (c.f. Malačič *et al.*, 2006), which may be linked to the seasonal and interannual variations of the benthic algal flora and vegetation.

STUDY AREA AND ECOLOGICAL CONDITIONS

Algological studies were carried out within the eastern area of the Gulf of Trieste, following others along the Istrian coast (Rovinj with surroundings), see Figure 1.

Fig. 1. Map of the Northern Adriatic coast.

Throughout the shallow Gulf of Trieste soft substrata prevail. There are alluvial Holocene deposits of silt, clay and fine-grained sand. This gulf is isolated from the rest of the northern Adriatic by a shoal, running from Grado to Salvore. It lies on the junction of the Istrian carbonate platform and Karst in the east, and the Friuli plain in the west. Between the river Timava and the town of Trieste extends a nearshore Karst area of Cretaceous limestone, with numerous freshwater springs. Eastwards from an accumulation area at Muggia, the coastal slopes are formed by Paleocene flysch all the way to Salvore. In localities dominated by hard substrata the coast slopes gently to about 9 m depth and from there on steeply towards the sediment bottom.

The bays of Piran and Koper where algological observations were carried out have high sedimentation rates. The detritial material originates from flysch, while the river Isonzo carries limestone material in the form of coarse grained sand and gravel into the western area of the gulf. The depth in its central area does not exceed 25 m and it contains approx. 9 km^3 water (Orožen Adamič, 1981). The tidal range is 97 cm in average, the highest for the entire Adriatic Sea.

The bottom topography within the gulf (Ranke, 1976) is responsible for the course of the main currents (c.f. Zore Armanda, 1968). A regular circular subsurface current transfers river-born and urban pollutants within the gulf (Mosetti, 1972; 1988; Stravisi, 1983; 1988) while local currents of a changing direction were reported by Rajer (1990). There are likewise seasonal and annual variations in the surface circulation. The discharge of the Po river greatly determines the current conditions as well as the physical and chemical gradients within the area, affecting the formation of a peculiar circulation. A line between the Po river mouth and Rovinj separates two gyres, a cyclonic north, and an anticyclonic south of this line (Zore Armanda and Vučak, 1984). Variations in the current system are also highly dependent on the bora wind, which blows in an offshore direction (Mosetti, 1972; Zore Armanda and Gačič, 1987) and are also related to recent changes in the atmospheric circulation.

Hydrographic data within the Gulf of Trieste are currently registered at the Marine Biological Stations at Trieste and Piran on offshore stations. Temperature and salinity data were also collected simultaneously with algal samplings at Piran (Munda, 1993a,b). During the 80-ties salinity values varied in average between 33 and 38 psu with minima between June and August and maxima from January to April. They usually increase with depth. Temperatures within the surface water layers exhibited minima between February and March with values from 6° to 7°C and maxima in July and August with approx. 25°C. During the time of summer stratification water temperatures decreased with depth and the opposite was found during winter. Homeothermic conditions were usually found between April and May (Figure 2a,b). Recent seasonal and annual measurements of temperatures and salinities (Malačič *et al.*, 2006) for the years 1991 to 2003 (Figure 3) revealed a yearly temperature increase from 0,12 to 0,23°C per year for summer at the surface, and of 0,22 to 0,23°C at 10 m depth.

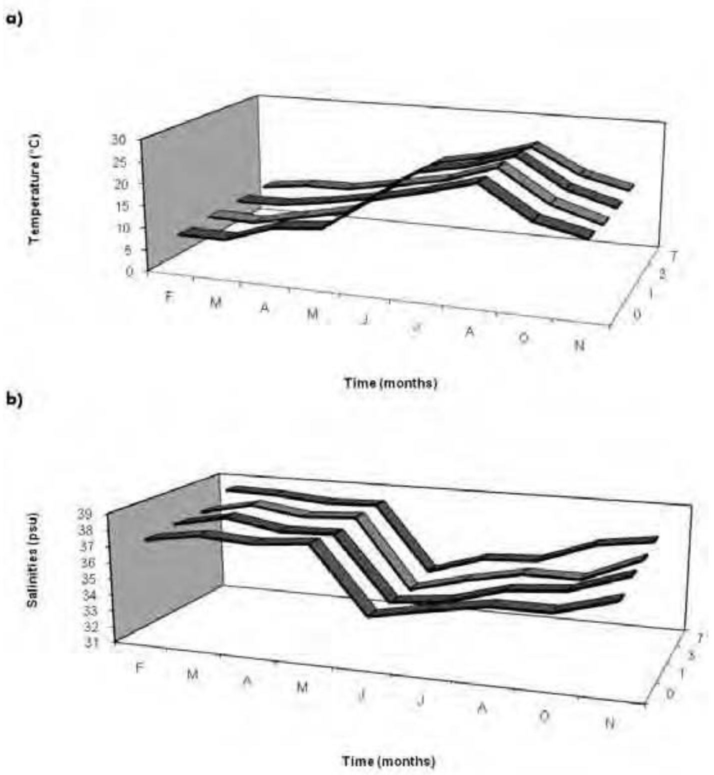

Fig. 2. Seasonal distributions of a) temperature, and b) salinity, at different depths near Piran in the 1980 s.

Winter temperatures showed an increasing trend from zero to 0,1°C per year. Interannual changes of annual temperatures in the surface water layers of the northern Adriatic, as estimated from long-term statistical analyses (Supić *et al.*, 2004), are related to the NAO and solar radiation. Salinity and density values in the surface water are mainly dependent on the major river discharge (Po, Isonzo).

Following recent measurements (Malačič *et al.*, 2006) the average yearly temperature minima increased to 9,19°C at the surface and to 9,17°C at 10 m depth, compared to data found by Munda (1993 a,b) of 7,7°C to 7,8°C during the eighties. Average yearly temperature maxima were reported as 25,0°C for the surface and 22,6°C for 10 m depth. Newer measurements for 2007 revealed, however, a yearly minimum of 10,1°C and a maximum of 26,5°C at the surface (Faganeli, pers. comm.).

Surface salinities show wide seasonal and interannual variations. They are influenced by the Adriatic circulation and changes in the river input. Average salinity values during the last decade ranged between 32,8 psu and 38,0 psu at the surface and 36,7 psu and 38,0 psu at 10 m according to Malačič *et al.* (2006).

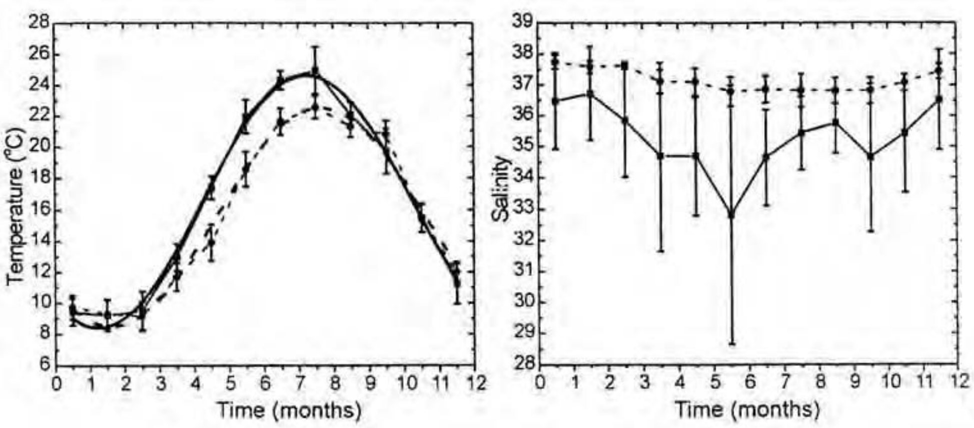

Fig. 3. Monthly temperature and salinity in the period 1991 – 2003 at depth of 0,3 m (solid lines with squares) and 10 m depth (dashed lines with dots) (after Malačič *et al.*, 2006).

SPATIAL, SEASONAL AND INTERANNUAL VARIATIONS OF THE BENTHIC ALGAL FLORA AND VEGETATION

The benthic algal flora and vegetation seems seriously threatened by environmental changes, both abiotic and biotic. Here remains the fundamental question about effects of global warning on the entire benthic environment, in particular on the subsurface habitats. Adverse effects on benthis algae are:

1. a decrease in species richness;
2. disappearance of large, canopy-forming species, first of all fucoids;
3. decrease in stratification;
4. disturbed seasonality.

Transitional recovery processes involve:

1. an increase of taxa;
2. increase of cover and
3. a greater complexity in stratification.

Fucoids, first of all representatives of the genus *Cystoseira*, are the main habitat-forming species in the Adriatic as a whole. *Sargassum* species are limited mainly to the lower water levels, while the endemic fucoid *Fucus virsoides* occupies the narrow eulittoral zone. It is regarded as a glacial relict, with *Fucus spiralis* as its Atlantic counterpart and best represented in the northern Adriatic. Its quantity decreases southwards along the eastern Adriatic coast.

Vegetational changes within the northern Adriatic basin are first of all due to the disappearance and / or reinstallment of the fucoid stands where also the main algal biomass is concentrated. They are rather sensitive indicators of environmental changes. Their disappearance along the Istrian coast in the seventies (c.f. Munda, 1972; 1979; *versus* Munda, 1980; 1993 a,b) was attributed to the drastically increased pollution and eutrophication (Munda, 1996).Within the Gulf of Trieste these vegetational changes were less severe and fucoids exhibited a patchy distribution (Munda, 1991). On the basis of field observation a sensitivity scale for the main fucoids was worked out (Munda, 1982b), ranging from *Fucus virsoides* over *Cystoseira compressa* and *C. barbata* to *C. crinita*, *C. corniculata* and *C. amentacea*, and finally to *Sargassum* species, as the most sensitive to environmental stresses. *In vitro* experiments also revealed a sensitivity of *Cystoseira* species (*C. compressa*, *C. barbata*) higher than *Fucus virsoides* towards decreased salinities, elevated temperatures and nutrient enrichment. Field observations were in agreement with these still partly unpublished findings (c.f. Munda, 1982a).

The zonation patterns and leading algal associations were first of all observed on hard substrata of allochthone limestone rocks and on flysch. The eulittoral slopes are only locally covered by the endemic *Fucus virsoides*, which has a patchy distribution in the area. Schemes of zonation patterns on a shore depleted of *Fucus virsoides* and another dominated by fucoids are presented in Figures 4 and 5.

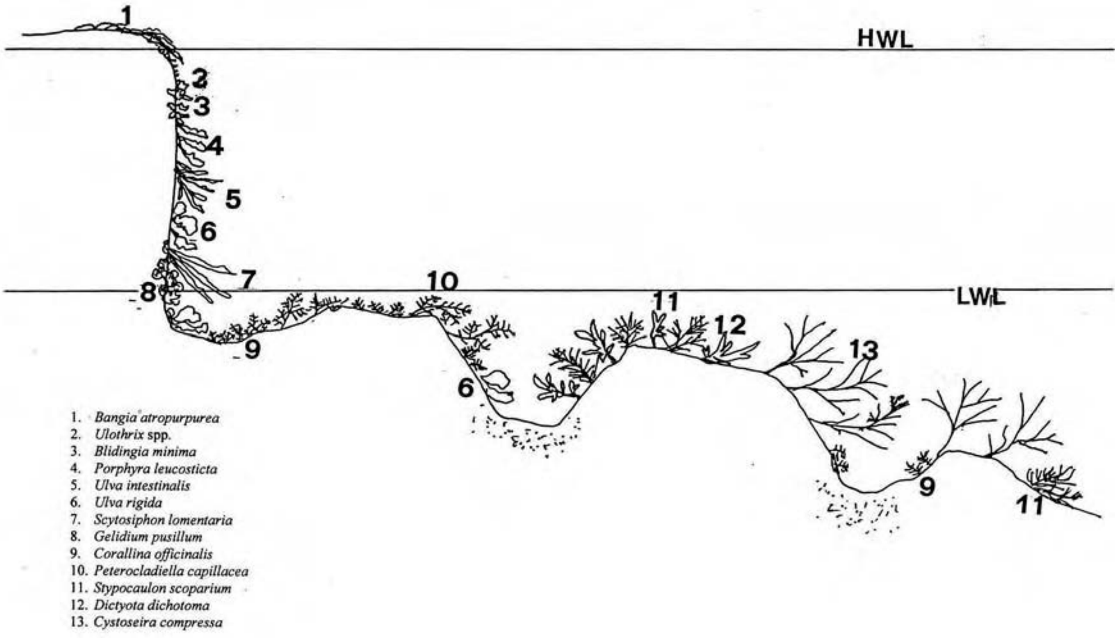

Fig. 4. Algal zonation pattern without *Fucus virsoides*.

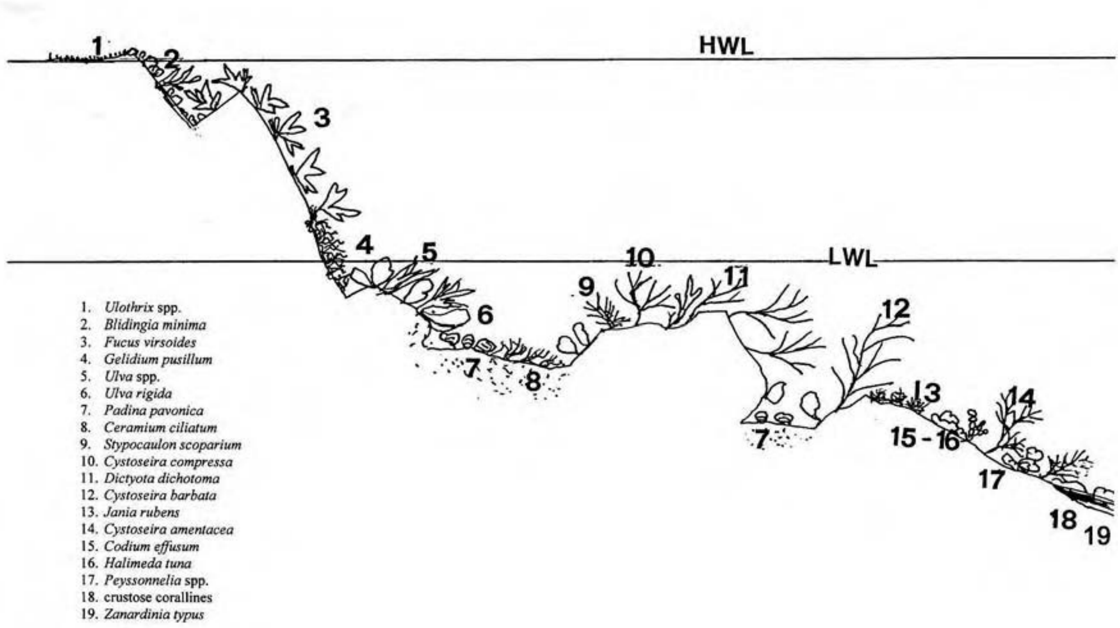

Fig. 5. Algal zonation pattern dominated by *Fucus virsoides*.

Recent algological studies along the eastern area of the Gulf of Trieste revealed both seasonal and annual variations in the benthic algal flora and vegetation. The seasonal and depth distribution of the main algal groups, expressed as number of species, is presented in Figures 6a,b and 7. Conditions along the western area, where soft substrata prevail, are described by Falace and Bressan (2003).

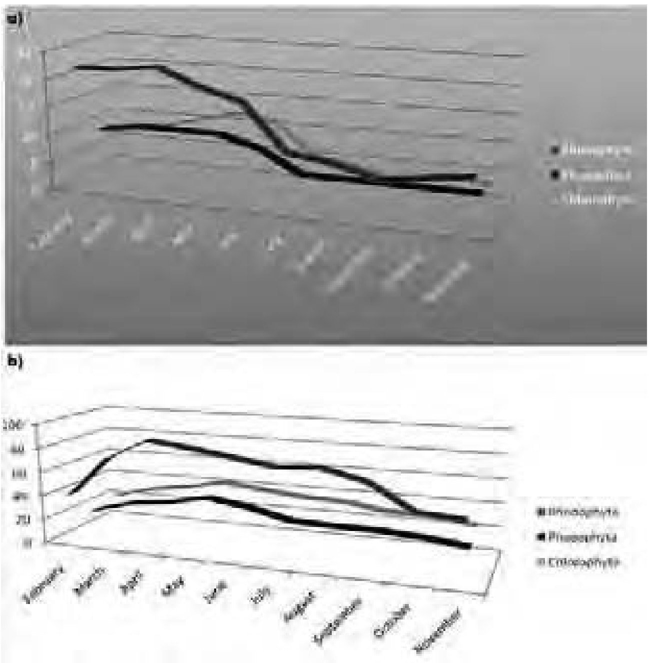

Fig. 6. Number of species – seasonal dynamics a) eulittoral, and b) sublittoral (Gulf of Trieste).

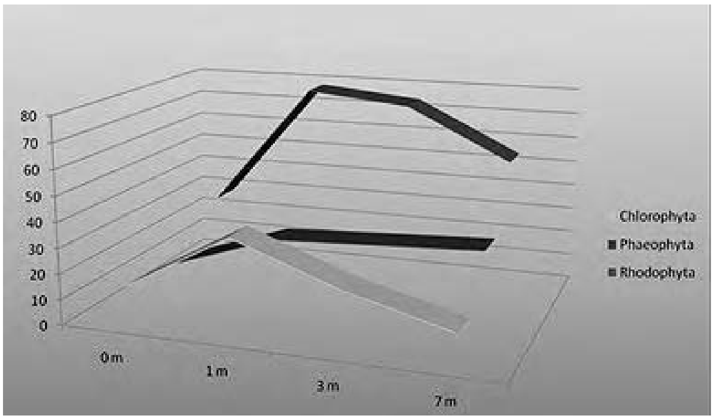

Fig. 7. Number of species in relation to depth (Gulf of Trieste).

In most rocky sites *Fucus virsoides* is replaced by diverse ephemeral species during spring. They form distinct zones with the following vertical sequence: *Bangia atropurpurea*, followed downwards by a belt of *Ulothrix* species, and even lower down by *Porphyra leucosticta*, *Blidingia minima*, a mixed belt of diverse *Ulva* species, *Ulva rigida* and lowermost *Scytosiphon lomentaria*. These slopes are usually clean during summer. *Fucus virsoides*, if present, forms a conspicuous four-layered association (c.f. Zavodnik, l967; Munda, l972), with crustose and dendritic species in the undergrowth, and mainly green algae within the layers of companion species and epiphytes. In some sites it is replaced by perennial turf-like mats of *Gelidium pusillum*.

Around the eulittoral/sublittoral junction a prolific vernal red-algae association occurred in most sites, formed by representatives of the Ceramiales. The dominant species within this conspicuous belt varied annually from e.g. *Ceramium ciliatum*, over *Callithamnion corymbosum* and diverse *Antithamnion* species to *Crouania attenuata*.

This vernal eulittoral vegetation was usually found between January and May and was best developed in April. There was, however, annual translocation in the appearance and disappearance of the individual belts, which cannot be attributed only to the influence a single environmental factor (e.g. the *Porphyra* belt could be absent, the appearance of *Bangia* delayed, the *Scytosiphon* belt joined by *Petalonia* species, the relative proportion of *Callithamnion corymbosum* within the vernal red algae belt increased).

The intertidal *Fucus virsoides* belts recently increased in width and again spread throughout the area. This transitional recovery was followed by a new destruction. The same was true of the sublittoral *Cystoseira* populations. There is, however, a highly dynamic situation in the upper water layers. In spite of transitional reinstallments there is a clear trend of a progressing reduction of fucoid stands in the northern Adriatic. Several stenoecious *Cystoseira* species occurred in this area mainly in patches, in between diverse mixed populations e.g. the endemic Mediterranean *Cystoseira barbara*, *C. amentacea*, *C. crinita* and *C. schiffneri*. Only *Cystoseira compressa*, a species of boreo- Atlantic affinity, was still rather prolific and formed a separate association in the upper sublittoral. It is noteworthy that the same species remained on the Côte des Albères, where all other *Cystoseira* and *Sargassum* species were erradicated (Thibaut *et al.*, 2005). The former *Cystoseira* associations are being replaced by those of diverse cosmopolitic species, with a lower structural capacity, such as by *Dictyota dichotoma*, and *Stypoaculon scoparium*. This succession means a reduction of floristic diversity and decrease in stratification. In some sites the tropical Atlantic species *Alsidium corallinum* formed dense populations in the sublittoral, replacing Cystoseirae, and the same was true of *Halopythis incurvus*.

As an example of interannual variations the appearance and subsequent disappearance of prolific belts of the invasive Atlantic species *Codium fragile* subsp, *tomentosoides* could be mentioned. On some allochthone rocks annual variations were likewise obvious with changes from crustose brown algae to green- algae mats. In a little harbour in Piran free floating algal mats changed yearly from e.g. *Acinetospora crinita*, over *Percursaria percursa* to diverse *Ulva* species (*Ulva intestinalis*, *U. clathrata*, *U. prolifera*) indicating a shift from species with warm water affinity over boreo Atlantic to cosmopolitic ones.

On gently sloping flysch rocks in the eulittoral, continuous mucus mats of diatom colonies locally replaced macroalgae in the spring (dominated by *Licmophora paradoxa*) to be reduced or absent the next year. It is noteworthy, however, that interruptions of the macrophytobenthos by microphytobenthos (diatoms and Cyanobacteria) are characteristic of this part of the northern Adriatic Sea.

In connection with the problem of global warming and the increased water temperatures in the upper water layers, the reappearance of the pantropical *Sargassum* species is noteworthy, as well as the frequency of *Padina pavonica*, *Asperococcus* species, *Hypnea musciformis*, dense sublittoral mats of *Acinetospora crinita*, along with an increased frequency and upward migration of some pantropical green algae (e.g. *Anadyomene stellata*, *Halymeda tuna*, *Valonia* species, *Flabellia petiolata*, *Bryopsis muscosa*). Some tropical Atlantic red algal species, as *Chyllocladia verticillata*, *Botryocladia botryoides*, *Compsothamnion thuyoides*, *Callithamnion corymbosum*, *Mesophyllum lichenoudes*, *Dasya corymbifera* increased in quantity during the last few years and were locally dominant. The invasive species *Asparagopsis armata* appeared as its tetrasporophyte *Falkenbergia rufolanosa*, which forms wide mats in the upper sublittoral and occurs also as an epiphyte on diverse macroalgae, while the gametophyte is limited to the Middle and South Adriatic.

On the other hand, a decrease in species with boreal affinities can be noticed. Several species, still mentioned by e.g. Furnari *et al.* (l999) for the Gulf of Trieste, were not found during recent surveys, such as e.g. *Bonnemaissonia hamifera*, *Aglaothamnion gallicum*, *Bornetia secundiflora*, *Brogniartella byssoides*, *Callithamnion tetragonum*, *Seirospora interrupta*, *Ceramium echinotum*, *Ceramiumn secundatum*, *Callophyllis laciniata*, *Audouinella subpinnata*, *Chondria coerulescens*, *Halarachnion ligulatum*, *Gymnogongrus griffithsiae*, *Erithroglosum sandrianum*, *Sphaerococcus coronopifolius* and some *Polysiphonia* species among the red algae. Fewer brown algal species were likely to disappear: e.g. *Arthrocladia villosa*, *Cladosiphon zosterae*, *Elachista intermedia*, *Herponema velutinum*, *Myriotrichia clavaeformis*, *Petaloia zosterifolia*, *Kuckuckia spinosa*, *Hincksia fuscata*.

It is noteworthy, however, that in this coldest area of the Adriatic Sea numerous species with a boreal affinity are still well represented and conspicuous, first of all representatives of the Corallinales.

LONG-TERM CHANGES

As an example of long-term changes of the benthic algal flora and vegetation, conditions along the Istrian coast (surroundings of Rovinj) will be mentioned. There was a prolific benthic algal flora and vegetation in the sixties (Munda, 1972; 1979) with a regular fucoid zonation (ranging from *Fucus virsoides* over diverse *Cystoseira* species to *Sargassum hornschuchii* and *S. acinarium*), as well as a prolific vernal red-algae vegetation. It was totally deteriorated in the seventies, but a partial reinstallment was found 20 years later.

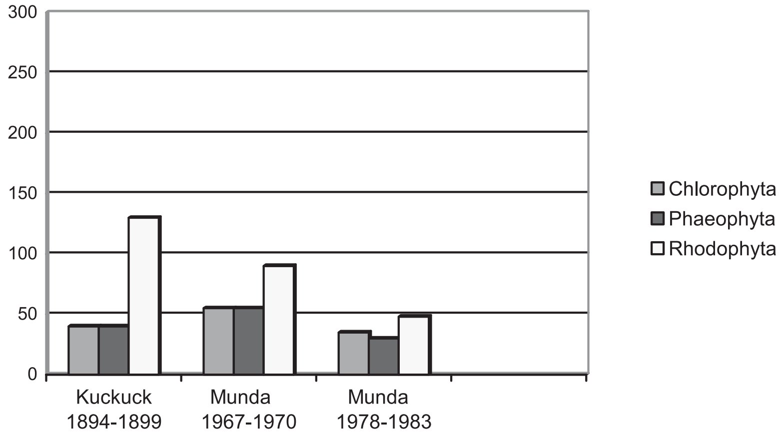

Fig. 8. Number of species recorded in the Rovinj area.

Previously, at the end of the 19th century (l894-l899), the Germain phycologist Paul Kuckuck from Helgoland collected marine algae around Rovinj. From a reconstruction of data from his unpublished diaries (see Munda, 2000) it became obvious that there was a rich algal flora at his time, when the environment was still undisturbed. In comparison with Kuckuck's records a floristic impoverishment occurred from the end of the 19th century to the sixties within all algal groups. About 24 % of the red algae and 30 % of the brown algae recorded by Kuckuck were not found in the sixties, when the vegetation was still prolific and apparently undisturbed. These long-term floristic changes can be, however, attributed to ecological parameters other than pollution and eutrophication or other forms of anthropogenic disturbances. Such decisive parameters are water dynamics, temperature and salinity regimes, sedimentation, turbidity, and sand-movements, resulting from short and long-term climatic changes (e.g. Vatova, 1934; Zore Armanda, 1991; Zore Armanda *et al.*, 1991; Supić *et al.*, 2004; Malačič *et al.*, 2006).

A further drastic reduction of the Rhodophytan flora by about 50 % occurred in the seventies. The main floristic impoverishment was found among the *Ceramiales.* Floristic and vegetational changes between the sixties and seventies were, however, extreme, resulting in a total deterioration of the fucoid populations. In comparison to Kuckuck's times, the overall number of recorded species decreased by more than one half. The Rhodophyta were most strongly affected with a loss of 62 % of the species, followed by the Phaeophyta and Chlorophyta with 53 % and 33 % respectively.

Dead zones: a future worst-case scenario for Northern Adriatic biodiversity

B. Riedel [1], M. Zuschin [2] and M. Stachowitsch [1]

[1] *University of Vienna, Department of Marine Biology, Austria*
[2] *University. of Vienna, Department of Paleontology, Austria*

ABSTRACT

Shallow coastal seas are most endangered (Halpern *et al.*, 2008) and, through a series of impacts ranging from overfishing, eutrophication to coastal development, they are likely to experience the largest change in biodiversity, should present trends in human activity continue (Jenkins, 2003). No other crucial environmental variable has changed more drastically in shallow coastal marine ecosystems worldwide than dissolved oxygen (DO) (Diaz, 2001). “Dead zones”, caused by hypoxia (DO<2.0 ml l^{-1}) and anoxia (no oxygen) in bottom-water layers, top the list of emerging environmental challenges (UNEP, 2004), and the problem is likely to become worse in the coming years (Wu, 2002; Selman *et al.*, 2008).

The Adriatic Sea is the most impacted system of the entire Mediterranean (Danovaro, 2003; Lotze *et al.*, 2006). Over the last decades, increasing nutrient and organic loads have triggered considerable environmental changes, with an enhanced frequency and severity of benthic dystrophic events (Danovaro and Pusceddu, 2007).

We provide here a brief overview of low DO events in the Northern Adriatic and responses from the species to the ecosystem level. The potential coupling between climate factors and coastal eutrophication is discussed.

NORTHERN ADRIATIC HYPOXIA

The Northern Adriatic Sea is a recognized area for long-term decreases in DO concentration and associated benthic community changes and mortalities (Stachowitsch, 1984; 1991; Justić *et al.*, 1987). It combines many features known to be associated with low DO events (Stachowitsch and Avcin, 1988): it is semi-enclosed, shallow (<50 m) and is characterized by soft bottoms, a high riverine input (mainly from the Po River), high productivity and long water residence times (Ott, 1992). As elsewhere in the northern hemisphere, this constellation can be associated with seasonal hypoxia and anoxia in late summer/early fall. Moreover, the combination of certain meteorological and hydrological conditions such as calm weather and/or reduced current circulation (Franco and Michelato, 1992; Malej and Malačič, 1995) can trigger hypoxia/anoxia.

Oxygen depletions, often associated with massive marine snow events, have been noted here periodically for centuries (Crema *et al.*, 1991), but their frequency and severity have markedly increased during recent decades. High anthropogenic input of nutrients into the Northern Adriatic (Justić *et al.*, 1995; Danovaro, 2003; Druon *et al.*, 2004) has led to a higher production and deposition of organic matter than there is oxygen supply to allow its decomposition (Rabalais and Turner, 2001; Bishop *et al.*, 2006). The average long-term decrease in water body transparency here over the 20th century, accompanied by decreasing bottom oxygen concentrations since the 1950s, has been convincingly outlined by Justić (Justić *et al.*, 1987; Justić, 1988). Since the 1980s, severe oxygen deficiencies have been reported here on a regular basis (e.g. Fedra *et al.*, 1976; Stachowitsch, 1984; Hrs-Brenko *et al.*, 1994; Penna *et al.*, 2004). The impacted areas range from restricted zones (several km²; Stachowitsch, 1992) to approx. 250 km² (Faganeli *et al.*, 1985) to 4,000 km² (Stefanon and Boldrin, 1982; Degobbis, pers. comm.), ultimately affecting every region (Figure 1).

The Northern Adriatic is therefore a case study for recurring perturbations involving anoxia and marine snow events and shows profound effects on the species to community level (Šimunović *et al.*, 1999; Barmawidjaja *et al.*, 1995; Benović *et al.*, 2000; Kollmann and Stachowitsch, 2001).

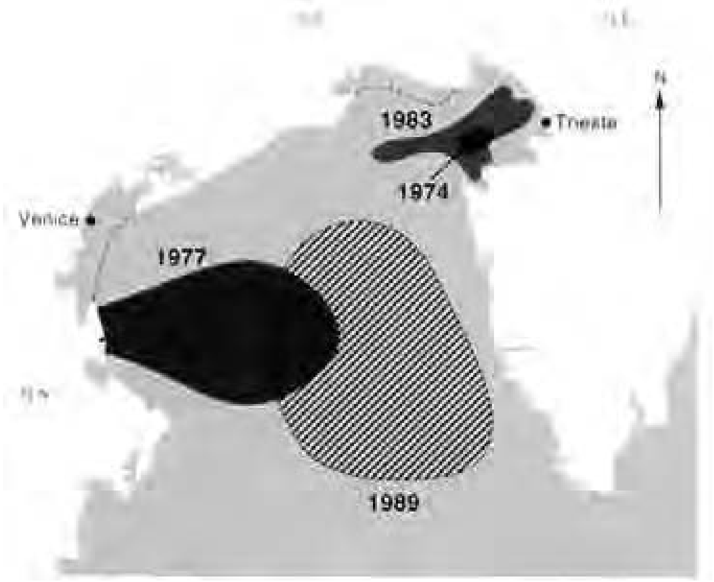

Fig. 1. Bottom anoxias in the Northern Adriatic between 1974 and 1989. Virtually no area is unaffected and the number of unnoticed events is probably much higher (from Ott, 1992).

HIGH-BIOMASS SUSPENSION FEEDERS AND BENTHIC CONTROL

Macroepifauna communities are widely distributed in the Northern Adriatic (Fedra, 1978; Zuschin *et al.*, 1999) and largely consist of decimetre-scale, interspecific, high-biomass aggregations termed multi-species clumps (Fedra *et al.*, 1976) (see Plate B, page 108): one or more shelly hard substrates provide the base for sessile, suspension-feeding colonizers (mostly sponges, ascidians, anemones or bivalves), which in turn serve as an elevated substrate for additional vagile and hemi-sessile organisms (mostly brittle stars and crabs) (Zuschin and Pervesler, 1996). The presence of a well-developed macroinfauna is expressed in the early designations (*Schizaster chiajei*-community) of the benthic communities here by Vatova (1949) and later authors (Gamulin-Brida, 1967; Orel and Menea, 1969; Orel *et al.*, 1987; Occhipinti-Ambrogi *et al.*, 2002).

The predominant, wide-ranging macroepibenthic community was named the ORM- community based on the biomass dominants, the brittle star *Ophiothrix quinquemaculata*, the sponge *Reniera* sp. and the ascidians *Microcosmus* spp. The mean biomass, measured as wet weight, amounted to 370 (±73) g/m² (Fedra *et al.*, 1976).

In the shallow Northern Adriatic, the benthos is not merely a receiving compartment. Rather, complex feedback processes are in operation, with the benthic subsystem controlling and helping dampen oscillations in the pelagic subsystem (Ott, 1992). Ott and Fedra (1977) estimated that the suspension feeders here can remove all the suspended material in the water column every 20 days. This is on the same order of magnitude as calculated for the Oosterschelde (Herman and Scholten, 1990), Swedish waters (Loo and Rosenberg, 1989), the USA (Cloern, 1982) and France (Hily, 1991). Such communities have therefore been termed a “natural eutrophication control” (Officer *et al.*, 1982) and play a key role in the stability of the entire ecosystem.

The repeated low DO events, coupled with commercial fishing activities during recent decades, however, have led to the destruction of epifauna-based benthic communities in many areas (Stachowitsch and Fuchs, 1995; Kollmann and Stachowitsch, 2001; Figure 2). Their loss makes the system more sensitive to perturbations. Other key functional processes for the overall system, such as bioturbation and related sedimentary activities, may also be altered by hypoxia/anoxia and the corresponding loss of biodiversity (Snelgrove, 1998; Rosenberg, 2001; Levin, 2002). The current status of the ORM-community makes it unlikely that it fully fulfils its pre-mortality regulatory capacity.

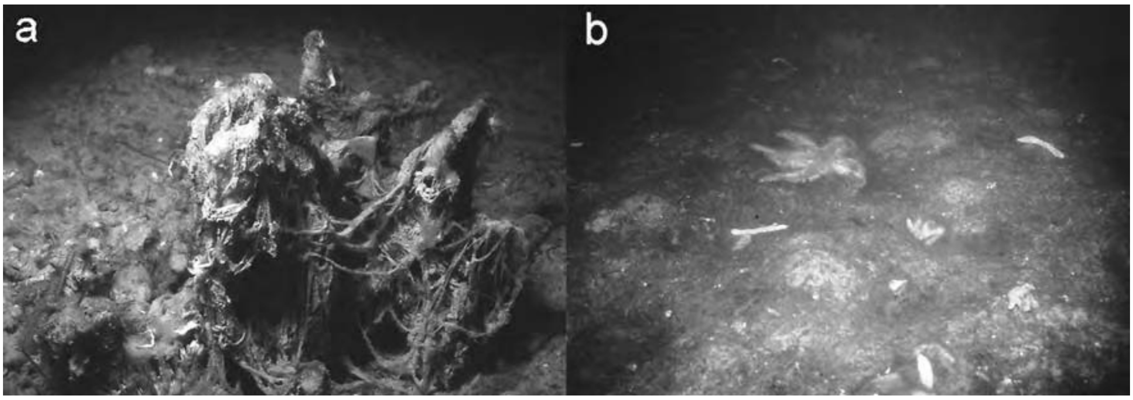

Fig. 2. Mortality scenario after anoxia. a) Decomposing sponge clump with mucus cover and entangled crabs (*Pilumnus spinifer*, *Pisidia longicornis*); b) Typical late aspect of mass mortality. Decomposing sea star *Astropecten bispinosus* and sipunculids. Note lighter sediment mounds [photos: M. Stachowitsch].

CONSEQUENCES ON ALL LEVELS

The point at which benthic animals are affected by low oxygen concentrations varies, but first indications of stress generally appear when oxygen drops below 2.0-3.0 mg l^{-1} (1.4-2.1 ml l^{-1}; Rabalais and Turner, 2001). Direct effects of exposure to hypoxia such as altered behaviour, physical inactivity and mass mortalities are well documented (Stachowitsch, 1984; Buzzelli *et al.*, 2002; Montagna and Ritter, 2006). The larger, mobile benthos, for example, is often able to migrate out of the affected area, whereby the less mobile fauna – unable to escape or avoid hypoxic waters – exhibits a series of behavioural patterns in response to decreasing oxygen concentrations (Mistri, 2004). Infauna, for example, emerges from the sediment. Epifaunal organisms attempt to position themselves above the lowermost hypoxic bottom layer, either by moving onto higher substrates (Stachowitsch, 1991) or raising their bodies (i.e. arm-tipping brittle stars, siphon-stretching bivalves or tiptoeing crustaceans; reviewed by Diaz and Rosenberg, 1995).

Tolerance to hypoxia/anoxia in itself, however, is a question of physiological capacity and adaptability, which varies from species to species (Hagerman, 1998). Two “strategies”, depending on duration and intensity of the low oxygen bout, are possible. The first is to maintain aerobic respiration (e.g. increase in respiration rate, number of red blood cells, flow of blood through respiratory surfaces, or more effective use of respiratory pigments) as long as possible. The second is to resort to anaerobic respiration and reduce overall metabolism (e.g. resting, inactivity, down regulation of protein synthesis and certain regulatory enzymes) if severe hypoxia or anoxia prevails (Hagerman, 1998; Burnett and Stickle, 2001; Wu, 2002).

However, once anaerobic conditions and H_2S develop, mass mortalities of nearly all organisms occur (Stachowitsch, 1984).

Diaz and Rosenberg (1995) reviewed the effects of hypoxia on benthic organisms. In general, fishes are more sensitive than crustaceans and echinoderms, whereby polychaetes and bivalves are the most tolerant. Within each taxon, however, there is considerable variability, dependent on the respective life habits (Gray *et al.*, 2002).

In the Northern Adriatic, sea anemones are particularly tolerant to hypoxia due to a combination of physiological and behavioural adaptations (see Sassaman and Mangum, 1972; Shick, 1991). This is confirmed by other field and laboratory studies (Jørgensen, 1980; Wahl, 1984). In the 1983 mortality, for example, one week after the onset of the event, survivors predominantly included individual anthozoans such as *Ragactis pulchra*, *Cerianthus membranaceus* and *Epizoanthus erinaceus* (Stachowitsch, 1984). In our recent, artificially induced anoxia experiments *in situ*, *Cereus pedunculatus* was among the most tolerant species and survived more than 83 hours of anoxia and a final H_2S concentration of about 160 µM l^{-1}. This information will be synthesized into a catalogue of behaviours, allowing indicator species to be defined and the status of benthic communities to be assessed.

Hypoxia may severely alter community composition by killing sensitive species but favouring a few tolerant forms (Dauer, 1993), and decreasing recruitment and growth (Breitburg 1992; Miller *et al.*, 2002; Stierhoff *et al.*, 2006). This will impact both the apparent and the potential biodiversity, e.g. pelagic resting stages in the sediment – important agents of local re-colonization – will also be decimated (Boero and Bonsdorff, 2007; Danovaro and Pusceddu, 2007). Moreover, changes in functional types/groups (including ecosystem engineers; Crain and Bertness, 2006) occur along hypoxic gradients, influencing overall ecosystem properties (Pearson and Rosenberg, 1978; Diaz and Rosenberg, 1995): suspension feeders might be replaced by deposit feeders, macrobenthos by meiobenthos, bioturbators may be lost, phytoplankton communities can become dominated by nanoplankton and microflagellates. The result is an unbalanced community dynamics, altering both function and composition in unforeseen ways (Grall and Chauvaud, 2002).

Beyond these direct effects, there is increasing evidence for indirect effects (Eby *et al.*, 2005). These include altered competition and predator-prey interactions, whereby predation rates increase or decrease depending on the relative tolerances of predator and prey to anoxia (Breitburg *et al.*, 1994; Sagasti *et al.*, 2001; Decker *et al.*, 2004; Riedel *et al.*, 2008). Thus, hypoxia also affects the trophodynamics of marine ecosystems. Wu (2002) suggests a general shift from *K*-selected to *r*-selected species, and from complex to simple food chains.

Such scenarios, which are increasingly unfolding in shallow coastal waters around the world (Selman *et al.*, 2008), represent undisputable worst-case situations for biodiversity and ecosystem function. The result is local extinction (Solan *et al.*, 2004) and large-scale homogenization at the lowest possible level (Sala and Knowlton, 2006). The ultimate reflection will be a total loss of ecosystem services beyond the seas as navigational highways.

CLIMATE CHANGE – ADDING INSULT TO INJURY?

For the Mediterranean, many models predict a temperature increase by an average 3°C until the end of the 21st century, with a larger warming in summer than the global average. Mean precipitation is expected to decrease, especially in summer, mainly due to the northward extension of the descending branch of the subtropical Hadley circulation (Li *et al.*, 2006). However, future impacts on the coastal system will vary greatly at regional scales (Scavia *et al.*, 2002). Clearly, the trends will be determined by complex interactions between temperature, precipitation, runoff, currents, salinity and wind.

Climate change will influence hypoxia/anoxia both directly and indirectly. The mechanism involves changes in coastal eutrophication by two major pathways (Figure 3):
1) Temperature-related changes in atmospheric circulation patterns will alter hydrological cycles, leading to shifts in precipitation, evapotranspiration and subsequent changes in river quantity and quality regimes (Miller and Russell, 1992). Specifically, changes in the magnitude and seasonal patterns of freshwater and terrestrially derived nutrient inputs will profoundly affect coastal salinity, turbidity, water residence time and primary production (Justic *et al.*, 2005; Harley *et al.*, 2006). Prolonged residence times during low-flow conditions will promote algal blooms (Relexans *et al.*, 1988), whereas storm-related high river flows result in higher nutrient inputs and stronger vertical

salinity gradients. Both conditions favour the development of hypoxia/anoxia in bottom waters (Paerl *et al.*, 1998; Scavia *et al.*, 2002).

2) A warmer atmosphere leads to warmer water temperatures, which have a lower oxygen content available for respiration by aquatic organisms. Moreover, increased summertime surface temperatures, especially if coincident with reduced winds, will lead to more persistent stratification. This is a prerequisite for prolonged hypoxia/anoxia. (Justic *et al.*, 2007; Thuiller, 2007). Finally, both photosynthesis and respiration are temperature-dependent processes and thus the rates of production, decomposition, and nutrient cycling are likely to increase (Kennedy *et al.*, 2002; Harley *et al.*, 2006).

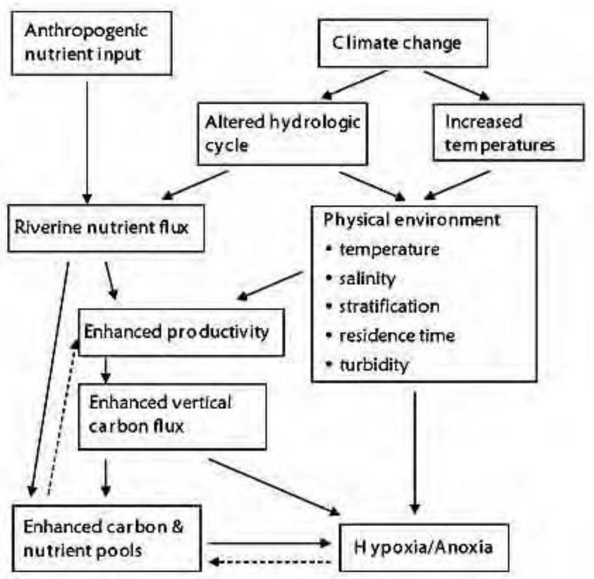

Fig. 3. Coupling between climate variables and eutrophication. Possible pathways for the development of hypoxia and anoxia in shallow coastal areas. Broken arrows indicate feedback control (adapted from Justić *et al.*, 2007).

In one of the few available models for the Northern Adriatic, Vichi *et al.* (2003) predicted precisely such an overall enhancement of the water-column stratification on an annual basis, with stronger intensification during the summer. The diffusion of oxygen and nutrients between surface and bottom layers was reduced, and the transfer of organic matter through the food web shifted towards the smaller components of the microbial web.

Benthic and pelagic species will therefore be exposed to unusual temperature, salinity, and oxygen conditions. These factors will take most of the fauna to their physiological limits. Such stressed organisms, coupled with hypoxia-related denuded areas, will provide little resistance to disease and the immigration of alien species (Harvell *et al.*, 2002; Osovitz and Hofmann, 2007).

PERSPECTIVES

Ecosystem stability is a crucial topic in modern ecology. In the Northern Adriatic, instability has been introduced by recurring perturbations involving anoxia and marine snow events along with intensive dredging and trawling activities. Currently, the frequency of such disturbances greatly exceeds the duration of recolonization process. The situation in the Northern Adriatic has been described as "rapid death, slow recovery" (Stachowitsch, 1991).

Climate change is likely to affect hypoxia and anoxia in myriad ways and on different levels. Most of the anticipated changes will involve increased hypoxia/anoxia. Our current research (Stachowitsch *et al.*, 2007) on artificially induced oxygen depletion events on the sea floor – including time-lapse documentation – provides a foretaste of what mass mortality, biodiversity loss and local extinction here will look like (<www.marine-hypoxia.com>).

Are climate changes already threatening sessile species (or species with low mobility) in the North-Western Mediterranean Sea? Vulnerability of coastal ecosystems.

Jean-Pierre Féral

Centre Océanologique de Marseille, Station Marine d'Endoume, Marseille, France

1. ABSTRACT

Climate changes are an important additional source of stress for erected Mediterranean species and communities (coralligenous). They affect all levels of ecological organization: from population and life-history changes to shifts in species distribution and composition, and in the structure and function of ecosystems. The effects, immediate and delayed, of positive thermal anomalies are analyzed: shifts on the distribution range, local extinctions, mass mortalities and disease outbreaks. Life history traits (e.g. reproduction), plasticity, population dynamics and population genetics (genetic structure associated with dispersal features) are required for modeling and for restoration, prediction and conservation.

2. CLIMATE CHANGES *VS.* GLOBAL CHANGE

Stigmatized by major Conferences organized by the U.N., starting with the 1972 Stockholm conference, the ecological crisis is closely related to six large components of what is refered to as global change:
a) the demographic dynamics of mankind (6 billion currently, 9 billion in 2050),
b) the destruction, the deterioration and the fragmentation of the habitats,
c) the generalized use of the chemical intrants,
d) the invasion of our ecosystems by alien species and genes,
e) the climate changes, in particular increase in the average temperature of the planet with which an increase of the level of the world Ocean is associated, and
f) finally the erosion of biological diversity.
This paper will mainly deal with sections e) and f).

3. A WARMING TREND IN THE NORTH-WESTERN MEDITERRANEAN?

3.1. Deep waters

Long term hydrological changes have been reported in CIESM Monograph n°16 (2002b). The first signs of a global warming in the North-Western basin of Mediterranean were provided either by deep-water temperature measurements (Bethoux *et al.*, 1990; 1998), by inflow-outflow water budgets and models of general circulation (Bethoux and Gentili, 1996), or meteorological data compilations (Metaxas *et al.*, 1991). In the Mediterranean, major water masses exhibit a 40-year trend of increasing temperature and salinity (Roether *et al.*, 1996).

3.2. Coastal waters

Only few long-term temperature series in coastal waters possess the three qualities that are of prime importance to deduce a reliable trend from their high level of seasonal variability: accuracy, adapted frequency and sufficient duration of the measurements. Since 1974 and three-to-five times a month, seawater temperatures are measured from the surface to 80m depth at the same Spanish site offshore (Estartit-Medes Islands) (see Francour *et al*., 1994). During 31 years this series has been conducted by the same operator (J. Pascual), using certified equipment (Richter and Wiese regularly controlled reversing-thermometers). This series constitutes the longest available one concerning Mediterranean coastal waters. The result is an estimate of the coastal water warming trend, which overpasses by a factor two or three the trend previously estimated for the deep water (Salat and Pascual, 2002).

A warming trend (about 1.4°C) of the coastal waters (surface to 80 m depth) has been observed for the last 30 years. In 2007, Romano and Lugrezi (Figure 1) published complementary historical data sets from the tide gauge of Marseilles (1885 to 1967). These data were recorded following the same protocol during 83 years and thus can be compared. The statistical treatment of this series exhibits a significant warming trend, which can be estimated to + 0.7°C by a century, and + 0.8°C when only the warmest months (June to September) are taken into account. There is a difference rate of more than four times between the 1884-1967 data set and that of 1974-2005 evidencing an acceleration of the warming trend.

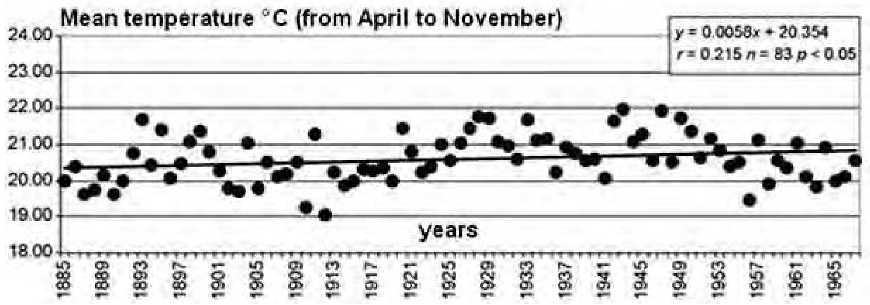

Fig. 1. Yearly mean temperatures (from April to November) over the 1885 - 1967 period, with the representation of the significant positive linear regression (after Romano and Lugrezi, 2007).

3.3. Thermal anomalies in the North-Western Mediterranean basin

Over a 28-year period (1974-2001), the warming rate was estimated at respectively 1.0°C and 0.8°C for both longer series Estartit and Villefranche-sur-mer (Boury-Esnault *et al*., 2006). This trend is higher at 20m depth (1.4°C) than at 80m depth (0.7°C). From shorter series (Marseilles, since 1994 [long term monitoring of the Marine Station at Endoume] and Banyuls-sur-mer since 1998 [Observatoire Océanologique]) one detects in all these series the presence of concordant positive thermal anomalies.

Such events also happened during the years 1982, 1990, 1994, 1997, 1999, 2003 and 2006 (see Plate D, page 110), including at least two consecutive months, and even three in 1997. Certain descriptions of organisms' mortality, before 1999 can be correlated with these positive thermal anomalies (1994-1997). These anomalies of sea water temperature are statistically more frequent since the beginning of the 1990s, occurring between May and October, especially between 0 and 30m depth. It should be noted that as one goes deeper the more these anomalies are shifted towards the autumn. The comparison of the vertical thermal structure (0 with 50m) during the anomalies of 1999 and 2003 makes it possible to distinguish two types of situations: (1) a variation (about 2°C) with the multiannual averages is prolonged and related to a layer of water of several tens of meters and (2) the event is shorter and confined in the upper layer (10 m) but the variations are more important (4 to 5°C). Both scenarios resulted in massive mortalities, but confined within the layers concerned. This confirms the impact, direct or indirect, of these thermal anomalies on the fauna and flora (Boury-Esnault *et al*., 2006).

These continuous records show that in summer, with a very marked thermocline, the depth between 15 and 35m undergoes a very strong thermal variability with an amplitude sometimes reaching 10°C in a few hours.

3.4. Longer term variations

After the 1856-2000 Mediterranean Sea Surface Temperature compilation by Moron (2003), over the period 1900-1996, one notes a rise of temperature of almost 1°C on the Western part of the Mediterranean, and ranging between +0.2 (Levantine Basin) and +0.8°C elsewhere. The contemporary warming (since 1978-1980) is definitely more intense on the West of the basin than on the East. The taking into account of the longest period (1856-2000) largely minimizes this increasing tendency, because of the presence of an abnormally hot phase, compared to the long-term average, between 1870 and 1885. An irregular variation within a period of 65-70 years (Schlesinger and Ramankutty, 1994), appears in fact more important than the long-term tendency, with variations which can reach 0.3 to 0.6°C in about fifteen years. It is considered that such oscillations may have obscured the greenhouse warming signal.

This means that even if the present warming trend is unequivocal (IPCC, 2007), accurate prediction of future temperature change requires an understanding of the causes of this variability; possibilities include external factors, such as increasing greenhouse-gas concentrations and anthropogenic sulphate aerosols, and internal factors, both predictable (such as El Niño) and unpredictable (noise).

4. CLIMATE CHANGES AND IMPACTS OF HUMAN ACTIVITIES (AN IMPACT ON THE IMPACT?)

Climate changes can act synergistically with other changes due to the consequences of the main human activities and pressures, such as:
- Demography;
- Tourism;
- Agriculture (eutrophication);
- Fishing and aquaculture (cf. CIESM Monographs n°5, 1998; n°7, 1999a; n°12, 2000b; n°32, 2007);
- Invasion of exotic species (cf. CIESM Monograph n°20, 2002a and CIESM Atlases of Exotic Species in the Mediterranean <http://www.ciesm.org/online/atlas/index.htm>);
- Industry;
- Maritime traffic / hydrocarbon and oil spill pollution;
- Sewage outfalls and urban runoff (cf. CIESM Monograph n°30, 2006);
- Discharge via rivers (cf. CIESM Monograph n°30, 2006).

5. GEOGRAPHICALLY RANGE-CHANGING SPECIES

It is sometimes claimed that it takes centuries for ocean temperatures to fully adjust to climate changes. The effects of global warming on ocean temperature would be then rather small, and changes in sea surface temperature are insufficient to explain the appearance or disappearance of marine species. However, Francour *et al*. (1994), working in marine protected areas (no harvest - hunting or fishing, minimal local pollution) in the North-Western Mediterranean have observed obvious changes in the composition of organisms assemblages within some years. Thermophilic species were (and are) increasingly abundant or newly observed, including juveniles, making evident local reproduction process. Unusual occurrence in marine life may then be used as indicator of changing ocean conditions (Mearns, 1988).

The environmental conditions at the limit of distribution of a species may change (temperature, salinity) and become favorable or not to the species. In consequence, the area of distribution expands or diminishes. Environmental conditions may change in part(s) of the area of distribution of a species and create conditions where the species may proliferate to the detriment of others. This concerns all species within a given area (Francour *et al*., 1994; Féral *et al*., 2003; Laubier *et al*., 2003; Perez, 2008).

In the Western Mediterranean, short term climate changes influence the boundaries of biogeographic regions, with some warm water species extending their ranges and colonizing new regions where they were previously absent. The northward migration of species with a warmer affinity has been demonstrated in several regions (see papers by Azzuro and Moschella about meridionalization and tropicalization, this volume).

The Ligurian Sea, one of the coldest areas in the Mediterranean Sea, has a lower number of subtropical species and a higher abundance of species characteristic of cold-temperate waters. The warming of the Ligurian Sea has favored the penetration of warm-water species, including for example the ornate wrasse *Thalassoma pavo*, which from 1985 onward established large and stable populations (Bianchi and Morri, 1994).

6. MASS MORTALITY AND DISEASES OUTBREAKS

6.1. Sea water warming and mass mortalities

The 1999 and 2003 mortality events are the best documented. They affected at least 30 invertebrate species (hard-bottom communities) over several hundred kilometers of coastline between France and Italy, and some places in Spain (Bavestrello *et al*., 1994; Cerrano *et al*., 2000; 2005; 2006; Coma *et al*., 2004; 2006; Garrabou *et al*., 2001; Laubier, 2003; Laubier *et al*., 2003; Linares, 2006; Linares *et al*., 2005; 2008a,b; Perez *et al*., 2000; Perez, 2008; Rodolfo-Metalpa *et al*., 2005) after positive temperature anomalies. The organisms mainly affected were the same in 1999 and in 2003. The sponges, including bath sponges and the gorgonians, (see Plate E, page 110) including the red coral, were the most impacted. This strongly suggests that temperature anomalies, even of short duration, can, directly or indirectly, dramatically change Mediterranean faunal diversity.

In fact, “alarm signals“ already occurred years before: sponges’ disease across the Mediterranean Sea during the 1980s (Vacelet, 1994), gorgonian necroses (Harmelin and Marinopoulos, 1994), bleaching of *Oculina patagonica* from the Eastern Mediterranean (Kushmaro *et al.*, 1996).

Most published studies concern the North-Western Mediterranean coasts. On the Tunisian coast, Ben Mustapha and El Abed (2000) have reported cases of mass mortality of gorgonians (*Eunicella singularis*) and sponges in summer 1999, linked to a temperature anomaly and the sinking of the thermocline down to more than 60 meters depth.

6.2. Extinction or shift?

Hemimysis speluncola, known since the beginning of the 1960s in the Marseilles area, has long been the dominant, even unique, mysid species in the dark submarine caves until the 1990s. Its rapid disappearance, between 1997 and 1999, and its progressive replacement by *H. margalefi* (Figure 2) were monitored (Chevaldonné and Lejeusne, 2003). Between 1999 and 2002 virtually all the caves were exclusively inhabited by *H. margalefi*. The only exception was a cave which presents special geomorphological features trapping cold water at the bottom all year round. The geographical distribution of *H. speluncola* confirms that this species has a rather cold water affinity, while *H. margalefi* has been described living in the warmer waters of the Balearic Islands or of Malta. In Marseilles, the replacement of the one species by the other coincided with two successive positive thermal anomalies during the summers 1997 and 1999 (Pérez *et al*., 2000; Romano *et al*., 2000), the second more intense and longer lasting, probably finishing off the (local) extinction of the remaining local populations of *H. speluncola* (Chevaldonné and Lejeusne, 2003). Ecophysiological experiments on the two species has shown that the lethal temperature (LT_{50}) is different of 3°C (Figure 3), strengthening the hypothesis of a species replacement as a consequence of the warming of the North-Western Mediterranean (Chevaldonné and Lejeusne, 2003).

The likely increase in frequency of thermal anomalies in the context of global climate change, and signs already detectable show that the general temperature of the Mediterranean Sea is increasing, and that *Hemimysis speluncola* might soon be driven to (local) extinction, as many other temperate components of North-Western Mediterranean marine biodiversity (see also papers by Despalatovic *et al.* and Munda, this volume). In contrast, species considered as indicators of the warmer parts of the Mediterranean are gradually becoming more frequent and widespread (Bianchi and Morri, 1994; Francour *et al*., 1994; Féral *et al*., 2003). The particular geographical context of the Mediterranean Sea makes it impossible for shallow-water temperate species, already trapped in the coldest parts of the basin, to migrate or disperse northward to accommodate temperature changes. Potential refuges for such thermophilic species exist, where low temperature can be maintained even in the summer period. Such refuges include some caves with topographical peculiarities which maintain a low temperature throughout the year, or habitats situated below the summer thermocline (Chevaldonné and Lejeusne, 2003).

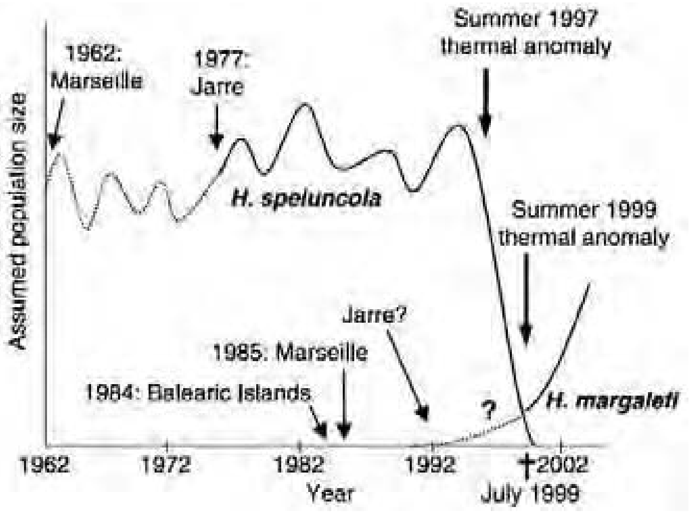

Fig. 2. Proposed scenario of changes in the populations of two Mediterranean species of Mysidacea in the shallow-water marine cave of Jarre Island, near Marseilles, France, over the past 40 years, based on regular observations by SCUBA diving. The years the two species were discovered are also reported, as well as the first report of *Hemimysis margalefi* in the Marseilles area. Since, actual population sizes were impossible to measure or even estimate, this figure is mostly based on presence absence data (after Chevaldonné and Lejeusne, 2003).

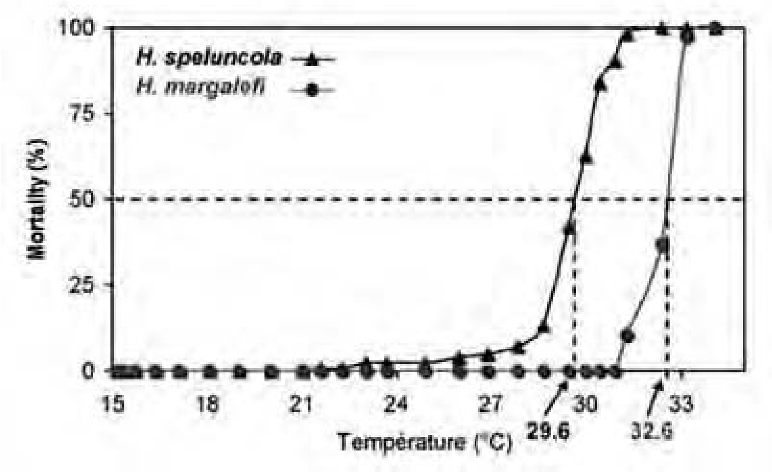

Fig. 3. Ex situ experiment designed to determine the difference of tolerance to an acute thermal stress in *Hemimysis speluncola* and *H. margalefi*, two species of cave mysids with different thermal habitat requirements. Dotted lines indicate the acute LT50 (lethal temperature for 50% of an experimental population) determined for each species (after Chevaldonné and Lejeusne, 2003).

Special environmental conditions found in some shallow-water Mediterranean submarine caves make it possible for some deep Mediterranean species to live in, to the extent that these are often seen as mesocosms of the great depths (Harmelin and Vacelet, 1997). In the case of caves where the water temperature increases, sponges species like *Asbestopluma hypogea* and *Oopsacas minuta*, which are strictly stenotherm, are decreasing in number in some places and disappearing in others.

6.3. Stress, mortality and epizooties induced by temperature

In the Mediterranean Sea, many episodes of mass disease and/or mortality have been reported over the past 30 years, particularly during this last decade in the North-Western basin (*Eunicella singularis* – Weinberg, 1975; sponges – Vacelet, 1990; 1991; 1994; Ben Mustapha and Vacelet, 1991; Gaino *et al*., 1992; *Paramuricea clavata* – Harmelin and Marinopoulos, 1994; see also Boury-Esnault *et al*., 2006). The affected taxa are mostly Porifera and Cnidaria, then Bryozoa, Mollusca and Tunicata. The species most often affected are Mediterranean endemics, among them some species of commercial value (*Corallium rubrum*, *Spongia* spp. and *Hippospongia communis*). These authors hypothesized that abnormally high temperature may cause the observed diseases and death.

As most pathogens are temperature sensitive, climate change in the Mediterranean also favors epidemiological outbreaks. Studies performed on the coral *Oculina patagonica* identified the coral-bleaching bacteria *Vibrio shiloi* as an agent involved in the Mediterranean mass mortalities of coral (Kushmaro *et al*., 1996; 1998; 2001).

Paramunicea clavata colonies at a bad necrosis stage show grayish coenenchyme remains and a totally denuded axis. After several weeks, numerous sessile organisms colonized the axes of gorgonians (epizootie). Mass mortalities of the gorgonian *P. clavata*, scleractinian corals, zoanthids, and sponges observed in 1999 in the Ligurian Sea were indeed by a temperature shift, in conjunction with the growth of opportunistic pathogens (including some fungi and protozoans - Cerrano *et al*., 2000).

Mass mortality by tissue necrosis of several species of gorgonians was observed during the 1999 late summer on the Liguro-Provençal Mediterranean coast. Martin *et al*. (2002) have investigated the occurrence of vibrios on necrosis-affected gorgonians *Paramuricea clavata* and *Eunicella cavolinii*, and their ability to induce tissue necrosis. Among the 11 strains tested, only five, belonging to species *Vibrio splendidus*, *V. pelagius* and *V. campbellii*, were able to induce tissue necrosis in a few days. Temperature experiments carried out at 11°C, 18°C and 23°C showed that necrotic disease may occur only at the higher temperature tested. Statistical analysis suggested that, for these temperature conditions, marine *Vibrio* strains can significantly speed up the necrotic crisis.

One of the most affected species during the 2003 climatic anomalies was *Paramuricea clavata*. From diseased *P. clavata* colonies, culturable bacteria associated to tissue lesions were isolated in order to investigate their potential as pathogens. Inoculation of four bacterial isolates onto healthy *P. clavata* in aquaria caused disease signs similar to those observed during the 2003 mortality event (see Plate F, page 110). The infection process was dependent on elevated seawater temperatures, in a range of values consistent with recordings performed in the field during the climatic anomalies. Among the four isolates, a *Vibrio coralliilyticus* strain that showed virulence to *P. clavata* was identified. *V. coralliilyticus* had been previously identified as a thermodependent pathogen of a tropical coral species, emphasizing a causal role of this infectious agent in the *P. clavata* disease. Taking into consideration predicted global warming over the coming decades, a better understanding of the factors and mechanisms that affect the disease process will be of critical importance in predicting future threats to temperate gorgonians communities in the Mediterranean Sea (Bally and Garrabou, 2007).

7. CLUE TO IMMEDIATE AND DELAYED EFFECTS: MEDITERRANEAN HARD-BOTTOM ECOSYSTEM RESILIENCE?

In this section the case of *Paramuricea clavata* will be taken as an example. Some years after the summer 1999, according to the parameters followed by Linares *et al.* (2005) and other authors, the consequences of the mortality events were assessed in various ways. Spatial patterns showed decreasing mortality with increasing depth between 0 and 50 m at La Gabinière, Port-Cros (Figure 4), as well as high local variability (Linares *et al.*, 2005).

Several years after the mass mortality of 1999, the average size of *P. clavata* colonies fell significantly in the populations studied, whatever the region considered (Cerrano *et al*., 2005; Linares *et al*., 2005; Bianchimani, 2006; Boury-Esnault *et al*., 2006; Perez, 2008). At the Port-

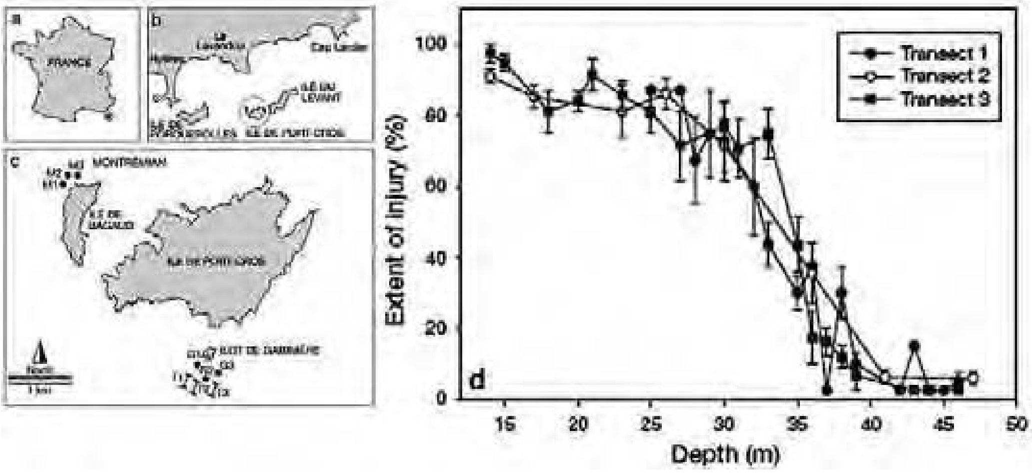

Fig. 4. (a,b) Distribution of the *Paramuricea clavata* shallow population at Port-Cros National Park (NW Mediterranean, France) and location of sampling sites; (c) permanent plots at Montrémian (M1, M2, M3), La Gabinière (G1, G2, G3) and depth transects (T1, T2, T3); (d) effect of depth on partial mortality (extent of injury, mean ± SE) of affected and unaffected colonies along three depths transects at La Gabinière (after Linares *et al*., 2005).

Cros National Park, the temporal pattern was characterized by a sharp decrease in biomass (58%) shortly after the event caused by the combined effect of colony death and an increase in the extent of colony injury (from 9% before the event to 52% shortly after it). After four years, the monitoring indicated a large delayed effect of the event. Population density decreased continuously after November 1999, and by November 2003 the accumulated density decrease was 48% of the initial population (Figure 5). This decrease was mainly due to the death of colonies subjected to extensive injury, and because recruitment did not always offset mortality (Linares *et al*., 2005). After November 1999, biomass continued to decrease at a slow rate, becoming almost constant after November 2001. Overall, the delayed effect of the event accounted for a 70% loss in *Paramuricea clavata* biomass. Given the low dynamics of *P. clavata* and its role as a habitat former, the delayed effect of the mass mortality event indicates the relevant role that disturbance can play on the population dynamics of this species and as a community structuring force on the coralligenous community (Linares *et al*., 2005). In Italy the drop in population density was compensated for by a major recruitment of new colonies (Cerrano *et al*., 2005). In time, a recovery due to the gradual decline in the colonies'rate of necrosis is visible. It is the result of the regenerative capacity of certain colonies (Cerrano *et al*., 2005), and also of the breaking of necrosed branches under the weight of colonizing organisms (epizootie) (Pérez *et al*., 2000; Bianchimani, 2006). The disappearance of these dead colonies, explains the very great reduction in the biomass within the

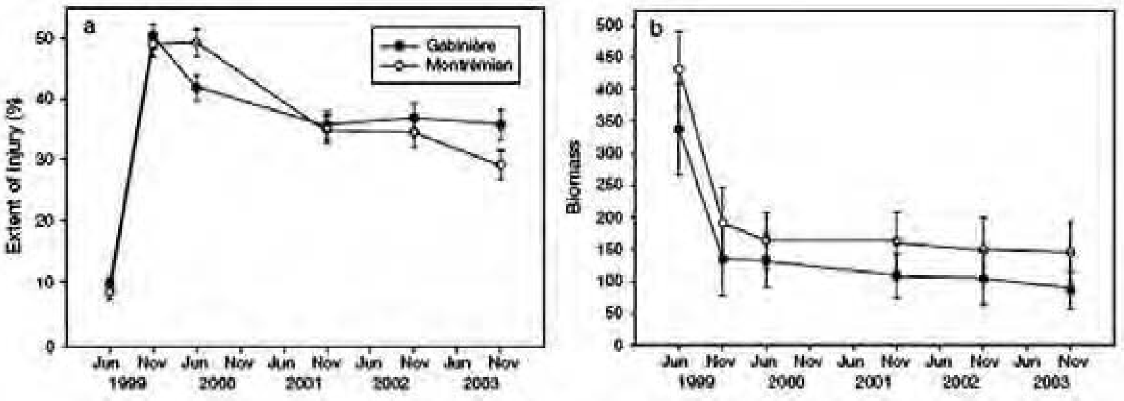

Fig. 5. Changes in: (a) partial mortality (% of injured colony surface) including affected and unaffected *Paramuricea clavata* colonies; (b) biomass (g DM.m^{-2}) over the study period (June 1999 to November 2003) at two locations (Montrémian and La Gabinière). Data are mean ± SE (after Linares *et al*., 2005).

gorgonian populations (Linares *et al*., 2005; Bianchimani, 2006). This last parameter, which integrates demographic structure data and population density, shows that several years after the 1999 mortality the populations had still not recovered (Harmelin and Garrabou, 2005; Bianchimani, 2006).

Linares *et al*. (2008a) tried to determine the impact of mass mortality events on the reproduction of *Paramuricea clavata*, and examine the effect of the damage one year (June 2000) and two years (June 2001) following the event. The reproductive parameters of female colonies were more affected than those of males. In female colonies that were moderately or severely damaged, the proportion of fertile polyps decreased by about 22-35%, whilst in the worst affected males there was only a 12% decrease. Female colonies showed a progressive decrease in gonadal biomass with increasing damage to a maximum reduction of 73-75% of oocyte production. In contrast, in males, the reduction in sperm production amounted to 49-64%. The same pattern of decrease in gonadal output compared to the extent of the injury was observed in 2001, two years after the mass mortality event. This indicates that the observed pattern was a response to the extent of the injury rather than a direct effect of the event. These severe effects on the reproduction of the red gorgonian species have implications for the recovery of affected populations in the long-term (Linares *et al*., 2008a).

8. CONCLUSIVE REMARKS: RESTORATION AND CONSERVATION

Divers, anchors, fishing lines and the development of filamentous algae have been considered the main human-induced sources of red gorgonian mortality (Harmelin and Marinopoulus, 1994; Bavestrello *et al.*, 1997; Coma *et al*., 2004; Giuliani *et al*., 2005). But this consideration has changed since the occurrence of mass mortality events in recent years in the North-Western Mediterranean Sea. As long-term consequences of the 1999 event, the recovery of populations of *P. muricea* can be likely measured on the order of decades (Linares, 2006).

As ecosystems engineers, species like gorgonians play an important role in the structural complexity, and hence, their conservation may be essential to maintain the biodiversity of the communities where they inhabit. Effective responses to the important threats that are affecting many long-lived marine species will require that their life-history traits, and in particular their low resilience to periodic disturbance, be considered in tandem with the interacting threats facing them if effective conservation plans are to be made (Linares, 2006).

Global warming is an important additional source of stress for species and communities which is affecting all levels of ecological organization: from population and life-history changes to shifts in the species composition and in the structure and function of ecosystems. As noted by Bianchi (2007): “Present-day warming ultimately favours the spread of warmwater species through direct and indirect effects, and especially by changing water circulation. It is impossible at present to foresee to what extent the exuberance of warm-water species will affect the trophic web and the functioning of marine ecosystems in the Mediterranean Sea of tomorrow”. Although we are only at an early stage in the projected trends of global warming, ecological responses to recent climate change are already clearly visible. Synergistic effects between climate and other anthropogenic variables will likely exacerbate climate-induced changes (Hughes, 2000; McCarty, 2001; Walther *et al.*, 2002; Harley *et al.*, 2006). Knowledge of life history traits should be a priority to better understand the effect of human-induced mortalities on long-lived species, and to predict population recovery/extinction risks and trajectories.

Several basic questions need to be addressed for the conservation of threatened species such as,

- Is the population under study in decline?
- What are the factors that determine the viability of the population?
- How high is the growth rate?
- How high is the fecundity?
- Are the populations fragmented?
- Is the connectivity between populations efficient?
- What is the dispersal capacity?
- What is the size of the neighborhood?
- What life stage is most critical for the viability of the population?

- Is legal protection of the habitat alone a sufficient measure to maintain population viability or is a more active intervention needed?
- Which management strategy offers the greatest chances for facilitating the survival of the population?

Answers generally exist concerning the ecology and the general biology of the species; sometimes data exist on its dynamics, but rarely on population genetics and all questions on fragmentation, connectivity, dispersal are almost without response. A work such as Linares's on reproduction, mortality, survival and growth rates, allows envisaging population dynamics modeling (Linares, 2006; Linares *et al.*, 2008a). This kind of approach will in time enable predictions to be made concerning the populations of gorgonians according to different scenarios of climate warming and combinations of effects with other factors of disturbance. However, genetic data are still lacking in many cases.

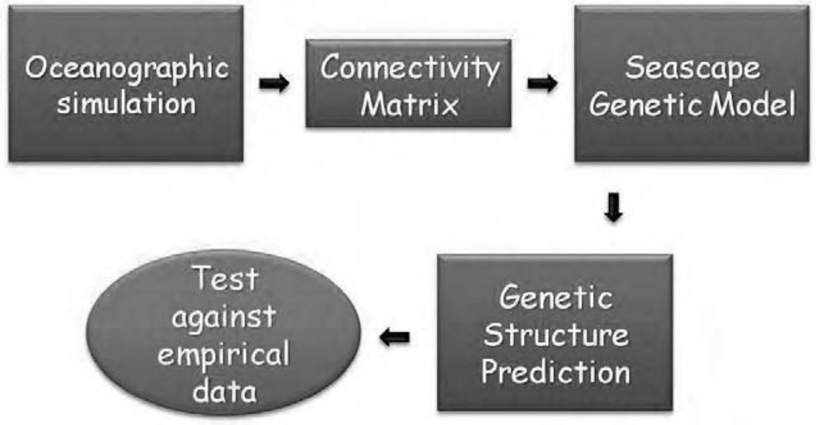

Fig. 6. Conceptual Model of Coupled Oceanographic-Genetic Approach (after Galindo *et al.*, 2006).

Population genetics is a powerful tool for measuring important larval connections between marine populations. Similarly, oceanographic models based on environmental data can simulate particle movements in ocean currents and make possible quantitative estimates of larval connections between populations. However, these two powerful approaches have remained disconnected because no general models currently provide a means of directly comparing dispersal predictions with empirical genetic data. The concept of such a model, proposed by Galindo *et al.* (2006), is depicted Figure 6. Obviously population genetics will provide essential tools for designing Marine Protected Area (Gerber *et al.*, 2003; Palumbi, 2003; 2004).

Méditerranée : mixité ethnique et coexistence pacifique ? Cas du golfe de Tunis.

Jeanne Zaouali

INAT, Salammbô, Tunisia

1. L’Influence du réchauffement climatique dans les eaux marines tunisiennes – Pourquoi le golfe de Tunis ?

• Du point de vue géographique : le golfe de Tunis (Figure 1), situé à la jonction entre les bassins occidental et oriental, occupe une position clé en Méditerranée méridionale.

Fig. 1. Le golfe de Tunis.

• Du point de vue des pressions anthropiques : le golfe subit un ensemble de contraintes majeures avec la concentration sur ses rives :

- de près du cinquième de la population nationale (2 millions d’habitants) ;

- de l’essentiel du tissu industriel national (85%) ;
- des ports les plus importants ;
- des rejets en mer des eaux de refroidissement de quatre centrales thermo électriques ;
- des décharges en mer de deux grosses stations d’épuration qui centralisent le rejet d’eaux, purifiées du point de vue bactériologique, mais, encore très fortement chargées en matières nutritives ;
- d’un énorme effort de pêche se traduisant par le raclage systématique des fonds par des chaluts très agressifs (pratique aujourd’hui, fort heureusement, en voie de nette régression).

• Du point de vue biologique :
- Nous avons une connaissance des biotopes et des biocénoses, ancienne et relativement bien documentée permettant de faire des comparaisons spatio-temporelles pertinentes. Ce qui n’est pas le cas pour d’autres zones du littoral tunisien.
- Les connaissances acquises sont, par la force des choses, l’objet d’une réactualisation fréquente liée à la surveillance d’un milieu sous stress permanent et, en de nombreux points, en voie de fort déséquilibre.

• Du point de vue écologique :
- Le golfe de Tunis est, pour toutes les raisons qui viennent d’être invoquées, un milieu particulièrement vulnérable.
- La partie ouest de la baie de Tunis qui est très fortement eutrophisée constitue un « maillon faible » de l’écosystème.
- Satellite de la baie de Tunis, le lac de Tunis a été l’objet après la réhabilitation environnementale de sa partie sud durant cinq années (de 2002 à 2007), d’un suivi mensuel de la qualité physico-chimique et biologique de ses eaux.

2. LES ESPÈCES ALLOGÈNES EN TANT QUE MACRODESCRIPTEURS

Les espèces allogènes (NIS) en Méditerranée sont particulièrement bien suivies (voir CIESM Atlas) et ont fait l’objet d’un grand nombre de contributions (Por, 1978 ; Galil, 1994 ; Galil, 2000 ; Boudouresque, 2005 ; Zenetos *et al.*, 2005 ; Rapport AEE, 2006 ; Galil, 2007a, etc.) notre approche pour les eaux marines tunisiennes sera plus pragmatique que théorique. Nous avons donc opté, en vue d’une meilleure efficacité, pour une étude de type écologique : option du choix de « macrodescripteurs » selon Boero (2007).

Dans le cadre de cette contribution, seront considérés les seules NIS macrobenthiques présentant de fortes biomasses et/ou de fortes densités et représentées par toutes les classes d’âge (ceci, afin d’éviter l’écueil de la citation « orpheline » qui prête à contreverses et n’a pas de signification écologique). Les espèces benthiques sessiles ou peu mobiles, obligées de se reproduire dans un milieu géographiquement strictement limité, peuvent, en effet, être considérées comme des bio indicateurs pertinents non seulement de la moyenne des températures, mais, surtout de l’importance de leurs écarts à la moyenne.

Les poissons, quant à eux, seront laissés de côté car ils peuvent, par définition, choisir leur lieu de reproduction, et, de ce fait leur domaine d’expansion géographique est vaste et mouvant. Cependant l’étendue de leur aire de dispersion donne des indications quant aux températures moyennes des zones fréquentées.

2.1 Les NIS dans l’écosystème du lac Sud de Tunis

Située sur le littoral ouest du fond de la baie de Tunis, cette lagune a, depuis les temps les plus reculés, subit l’impact d’une très forte anthropisation se traduisant par une dystrophie et des nuisances quasi permanentes. Aussi, dans les années 80 furent entrepris de gigantesques travaux de restauration environnementale dans un premier temps, de la partie nord de la lagune (le lac Nord en 1988, ben Charrada, 1992 ; 1995), et, dans un second temps (2001), de la partie sud (le lac Sud).

Dans le lac Sud, la restauration environnementale a abouti à une véritable mise à zéro biologique de l’ensemble du plan d’eau, ce qui a offert une opportunité unique de surveillance écologique. C’est ainsi que dans un délai de quelques mois après la fin des travaux on a pu constater une revivification très rapide (voire quasi instantanée) de l'écosystème qui s'est traduite par une complète modification des biocénoses en place avec l'apparition d'espèces qui, pour la plupart d'entre elles, n'appartenaient pas au peuplement lagunaire antérieur : peuplement LEE (ben Souissi, 2002). On a ainsi enregistré le passage de l'écosystème antérieur à un écosystème de type « estuarien » et l'installation de nombreuses NIS, dont la grande majorité n'était pas présente avant les travaux et n'avait pas été répertoriée dans le golfe de Tunis ou même en Tunisie, voire en Méditerranée[1].

2.1.1 Etude cinétique du repeuplement du lac Sud : les modalités de la cohabitation

Dans ce qui suit nous passerons en revue les situations les plus représentatives. Dès la réouverture du canal à la mer (2001), canal qui avait été fermé pendant les travaux de dragage des fonds, les constatations suivantes purent être faites :

• Installation immédiate, avec une très importante biomasse, du Cardiidae indo pacifique *Fulvia fragilis*. Cette NIS lessepsienne connue jusqu'alors du seul golfe de Gabès (Enzeross and Enzeross, 2002) où elle s'était implantée il y a plus d'une quinzaine d'années montrait une forte aptitude à la compétition en évinçant l'espèce cosmopolite, pionnière classique des milieux lagunaires peu profonds (espèce LEE) *Cerastoderma glaucum*, espèce dont la biomasse était la plus forte avant les travaux. En fait, *F. fragilis*, espèce endogée, considérée comme très « polluo tolérante » était, vraisemblablement, en réserve au fond de la baie de Tunis où elle n'avait pas, jusqu'alors, été détectée.

Ses larves restant vulnérables, ceci, s'est traduit, dans le lac Sud, par un retour progressif de son « binôme » indigène *C. glaucum* avec, toutefois, des proportions réciproques très fluctuantes selon les localisations dans la lagune et les saisons.

• Pénétration, au bout de quelques mois, de crustacés benthiques trouvant refuge dans des paquets d'algues ou dans des infractuosités rocheuses.

- Avec, l'apparition de l'isopode cosmopolite, originaire de l'océan Indo Pacifique, *Sphaeroma walkeri*, qui se substituait partiellement au « couple mixte » *S. serratum* - *Paradella dianae*[2] autrefois abondant dans la lagune (Bey *et al.*, 2001 ; ben Souissi *et al.*, 2003).
- Ces introductions ont été rapidement suivies par l'apparition d'un autre sphaerome, celui-ci d'origine « sénégalienne », *Sphaeroma venustissimum*, espèce non encore répertoriée dans les eaux tunisiennes (ben Souissi *et al.*, 2005) et connue, en dehors de son biotope initial (côtes de Mauritanie et du Maroc), que sur les côtes espagnoles atlantiques (Junoy and Castello, 2003).

Aujourd'hui le « complexe » *Sphaeroma serratum*, *Paradella dianae*, *S. walkeri* et *S. venustissimum* perdure, mais leurs proportions respectives sont très variables à l'échelle spatio-temporelle.

• Substitution progressive du crabe *Brachynotus sexdentatus* installé dans le lac Sud dès la restauration du milieu (l'espèce présente avant les travaux était *Carcinus aestuarii*) par le Goneplacidae lessepsien, *Eucrate crenata* (Zaouali, 1993). Dès 2003, ce crabe indo-pacifique est devenu abondant dans le lac Sud où son acclimatation semble être forte puisqu'on ne constate pas de reprise de la dominance par son « binôme » antérieur.

Présent sur l'ensemble des côtes du golfe de Gabès depuis plus de 15 ans, il est remonté (brutalement ?) vers le nord jusque dans la zone de Bizerte.

• *Musculista senhousia*. Cette moule lessepsienne a fait sa première apparition dans le lac Sud en 2004 (ben Souissi *et al.*, 2004 ; 2005). Elle est entrée assez vite en compétition avec *Mytilus galloprovincialis* qui, elle, a toutefois très rapidement rétrogradé (mortalités juvéniles en masse). Elle a, immédiatement, été très abondante et le reste encore, mais de façon intermittente. Préexistait-elle dans le golfe de Tunis où elle est aujourd'hui largement représentée ? comme elle l'est d'ailleurs dans la zone de Kerkena ou de Jerba.

La colonisation excessivement rapide du lac Sud par ces NIS et le hiatus entre la colonisation primitive au niveau du golfe de Gabès et, celle, plus tardive, au niveau du golfe de Tunis, suggérerait

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[1] Température moyenne des eaux de la lagune en 2001 de 19,3°C, en 2006 de 20,5°C – Salinité moyenne en 2001 de 37,7 psu et en 2006 de 36,7 psu.

[2] *Sphaeroma serratum* est une espèce atlanto-méditerranéenne ; *Paradella dianae*, originaire des côtes mexicaines du Pacifique est une espèce déjà très largement répandue en Méditerranée.

le rôle prépondérant du trafic maritime (le port commercial de Tunis est établi dans le canal central du lac de Tunis), mais est il le seul vecteur ?

2.1.2. Les apports de cette étude

L'observation de la cinétique du repeuplement de la lagune de Tunis a montré :
• Qu'elle pouvait jouer le rôle d'un véritable laboratoire d'étude de la biodiversité du fait de ses dimensions relativement modestes (900 hectares) permettant un suivi spatio-temporel très efficace.
• Que le nombre d'espèces NIS présentes dans le lac Sud est passé, en 7 ans, de 5 à 17. En 2000, les NIS présents dans la lagune étaient toutes des espèces à diffusion ancienne et très large en Méditerranée, cosmopolites et majoritairement caractéristiques des milieux fortement eutrophisés. Alors que les nouvelles recrues (NIS) sont, à l'exception du serpulidé *Hydroïdes dianthus* (que l'on trouve avant et après travaux), des espèces de diffusion relativement plus restreinte et sous des contraintes thermiques liées à leur biotope original.
• Que ce sont des espèces para tropicales et tropicales dont l'origine est, aussi bien, occidentale (15%) qu'orientale (85%), alors qu'à Tunis, le trafic maritime est essentiellement originaire de l'Europe (92% du trafic, notamment avec l'Italie, la France, l'Espagne).

De manière plus globale, l'observation des intrusions des NIS dans le lac Sud met en évidence :
1) Le « tropisme » exercé sur les NIS par un milieu où la concurrence est faible (cas de toutes zones où il y a écroulement des biocénoses en place) c'est-à-dire dans un écosystème déstructuré, désertifié où les lois normales de la cohabitation ne peuvent plus jouer faute de « cohabitants ».
2) Une forte compétitivité vis-à-vis des espèces indigènes, ce qui pourrait s'expliquer par le fait que seules les espèces exotiques les plus tolérantes sont en mesure de vaincre les obstacles de l'émigration.
3) L'importante augmentation du nombre de ces NIS, quelle que soit leur origine :
- apport par des navires, fouling et clinging = « parachutage » avec des aires d'occupation très discontinues,
- transport par les courants littoraux = « contagion » c'est-à-dire dispersion marginale plus ou moins continue et rapide à partir des points sources ouest et est.
4) Une cinétique invasive bien différente selon les « routes » suivies :
- cinétique lente, sans à coups majeurs (contagion) pour les organismes suivant la route maghrébine d'ouest en est, route ancienne déjà largement balisée (en quelque sorte « regroupements familiaux effectués depuis longtemps !) ;
- cinétique en évolution rapide et chaotique (parachutage, et, le temps passant, éventuellement, « contagion ») avec une accélération très brutale à partir des années 60 pour les espèces orientales passant de l'est à l'ouest.
5) Pour les espèces lessepsiennes, l'accélération de cette cinétique, aussi bien dans l'espace que dans le temps, avec le franchissement sans problème du « verrou » du cap Bon, alors que ce passage semble encore difficile (voir impossible ?) pour les espèces sénégaliennes.

2.2 Les peuplements du golfe de Tunis

Situé au point de confluence des flux occidentaux et orientaux, le golfe de Tunis présente un intérêt particulier dans l'étude de la cinétique d'établissement des NIS[3].

2.2.1 Les espèces d'origine occidentale

Ce sont essentiellement des espèces tropicales**,** sénégaliennes. Nous citerons :
• *Perna perna*
Cette moule que nous rangerons dans la catégorie des « archéoNIS » est mentionnée en de nombreux points des côtes marocaines et algériennes. Dans les années 60 toutefois, selon Pérès and Picard (1964) elle ne dépasse pas Philipeville = Skikda). En Tunisie, après un hiatus correspondant à la portion littorale nord, elle est présente au début des années 70 dans les zones « péri portuaires » des villes de Bizerte (Zaouali, 1973) et, quelques années plus tard, de Tunis où on la trouve conjointement à *Mytilus galloprovincialis*.

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[3] Dans ce qui suit, nous traiterons de quelques espèces n'ayant pas colonisé le lac de Tunis ou ne s'y étant établi qu'à titre transitoire dans la zone sous influence marine maximale.

Son implantation en Méditerranée qui est exclusivement nord africaine, obéit à un schéma d'expansion cohérente d'ouest en est, mais, elle n'a pas, tout comme son binôme *Mytilus galloprovincialis*, progressé vers le sud et n'a pas franchi le Cap Bon. Tout, donc, porte à croire, qu'à ce niveau, l'extension de l'aire de ces deux espèces est arrêtée à la fois par une barrière thermique et aussi, et, surtout, par une barrière « haline » (moyennes supérieures aux exigences de température et salinité compatibles à la survie des larves).

• *Eastonia rugosa*

Eastonia rugosa, est une espèce sénégalienne dont l'installation en Tunisie pourrait être datée des environs des années 50 à 60 avec une distribution contemporaine, à l'origine, limitée à la seule partie aval du canal central[4] du lac de Tunis (Zaouali, 1971). Elle est le témoin (espèce relicte ?) d'un peuplement tyrrhénien notamment, dans les régions de Monastir et Jerba où ce bivalve forme de larges bancs fossiles. A ce propos, Seurat (1929a) qui mentionne *E. (Standella) rugosa*, en tant que fossile à Jerba, insiste sur le fait qu'elle n'est trouvée vivante, au début du 20e siècle, que sur les côtes algériennes et du sud de l'Espagne. En effet, *Eastonia rugosa* tout comme *Perna perna* n'apparaît dans aucun des inventaires très minutieux de la faune malacologique du littoral tunisien faits par Dautzenberg (1895) ou Pallary (1904 ; 1906 ; 1914).

Jusqu'au milieu des années 1990 ce bivalve est resté exclusivement concentré dans le canal central du lac de Tunis où il était présent, conjointement à *Venerupis decussatus*. Mais, depuis une dizaine d'années, il a gagné énormément de terrain et on le retrouve, avec de très fortes biomasses, tout au long des côtes ouest de la baie de Tunis dans les fonds sablo vaseux entre 2 et 5 mètres où il s'est en grande partie substitué à *Venerupis decussatus*.

Comme *Perna perna*, *Eastonia rugosa* n'a pas franchi la barrière du Cap Bon mais contrairement à *Perna perna* qui reste cantonnée aux côtes africaines, *E. rugosa* a, à l'heure actuelle, progressé vers le nord avec une première implantation en Sicile, suivie d'une poche d'expansion dans la région de Rome (dispersion par le trafic maritime ? ou, peut être, par le reparquage de palourdes tunisiennes exportées à des fins commerciales?).

• *Siphonaria pectinata*

Cette « patelle pulmonée » est, en date, un des derniers témoins en Tunisie de l'influence du courant atlantique dans le golfe de Tunis. Jusqu'alors citée des côtes algériennes et du sud de l'Espagne, elle a fait son apparition en 2005 à la frontière algérienne et on la trouve, aujourd'hui (Antit *et al.*, 2007), de Tabarka, où elle est relativement abondante, à Tunis où elle est encore très rare.

2.2.2 Les espèces d'origine orientale, lessepsiennes

En dehors des espèces déjà mentionnées dans le cadre de l'étude du lac Sud nous citerons :

• *Pinctada radiata*

Ce bivalve serait la première espèce lessepsienne à avoir franchi le seuil du canal de Suez (inauguré en 1869). Il peut donc être considéré comme une espèce pionnière dans la catégorie des migrants « parachutés » dans les eaux tunisiennes, puisque sa première signalisation qui date de 1890 indique sa présence au niveau du port de Gabès ainsi que près des côtes jerbiennes, c'est-à-dire à quelque 2,500 km de distance des côtes méditerranéennes égyptiennes où elle serait apparu pour la première fois en 1874 (Zenetos *et al.*, 2003) ! En 1929 elle est mentionnée sur l'ensemble du golfe de Gabès par Seurat (1929b), elle y reste cantonnée jusqu'à la fin du 20e siècle.

A l'heure actuelle, elle a très largement gagné du terrain. Elle est loin d'être rare dans le Sahel (région de Monastir) et, depuis un peu moins de cinq ans, elle a franchi la barrière du cap Bon et est remontée jusque dans le golfe de Tunis où, néanmoins, elle ne représente pas encore une forte biomasse.

A l'échelle méditerranéenne (Figure 2) *Pinctada radiata* a connu une expansion tout particulièrement rapide avec des citations d'implantations nouvelles se multipliant à partir des années 70. Mais, bien qu'elle soit aujourd'hui largement distribuée (sans que l'on ait d'idées précises quant aux valeurs des biomasses) elle reste (à quelques exceptions près) cantonnée au bassin oriental.

L'observation de l'extension actuelle de l'aire de répartition de *Pinctada radiata* est intéressante car on peut noter qu'elle s'est faite :

- avec une coupure nette entre les bassins oriental et occidental, à peu près au niveau de 10° E,

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[4] Canal qui a séparé, à la fin du 19è siècle, le lac en deux parties.

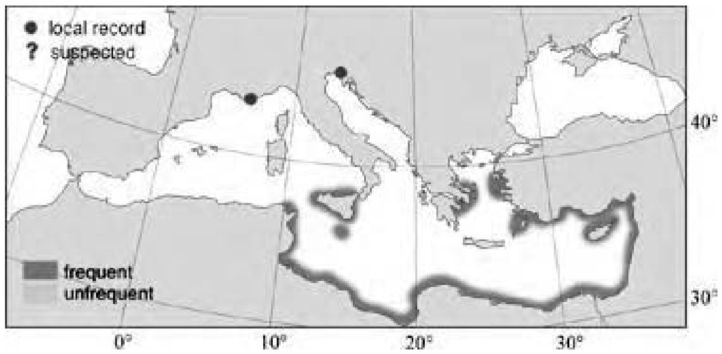

Fig. 2. Aire de la répartition de *Pinctada radiata* en Méditerranée (CIESM Atlas of Exotic Species in the Mediterranean Vol. 3 Zenetos *et al.*, 2003).

- et une seconde coupure au niveau de 38° N, en dehors d'intrusions très sporadiques vers le Nord. Cette configuration montrerait une colonisation par contagion liée au réchauffement des eaux, mais, peut être, aussi, à une qualité de l'eau qui serait assez proche de celle des eaux de mer Rouge, en d'autre termes, cette extension pourrait, en quelque sorte, matérialiser la zone d'influence actuelle du courant oriental.

• *Caulerpa racemosa* et *Caulerpa taxifolia*

Ces deux chlorobiontes d'origine indo pacifique ont été mentionnées, pour la première fois en Méditerranée dans la zone portuaire de Sousse, en 1920 (Hamel, 1926) pour la première et en 2000 pour la seconde (introduction d'une souche différente de celle présente en Méditerranée septentrionale, Boudouresque, 2005).

Alors que *C. racemosa* est restée cantonnée, pendant près de 70 ans, au sud de la Tunisie (Hamza *et al.*, 1995), elle a depuis une dizaine d'années (Djeloulli, 2000) envahi l'ensemble des côtes jusque dans la région bizertine montrant une vitalité expansive très nettement supérieure à celle de *C. taxifolia* qui reste, à l'heure actuelle, cantonnée à la péninsule du Cap Bon (ces deux caulerpes invasives sont présentes dans la zone du port de Sidi Daoud - partie nord est du golfe de Tunis).

Le fait qu'il n'y ait pas eu, pour le moment, de colonisation de *Caulerpa taxifolia* vers l'est du bassin oriental (en dehors de la Croatie, limite de 15°E ?), alors que cette espèce est, au départ, typiquement indo pacifique pourrait être mis en relation avec le fait que l'espèce colonisatrice a / aurait ? des exigences bien différentes de l'espèce exotique. De même pour *C. racemosa* dont on a mis en évidence une mutation (hybridation) *C. racemosa* var. *cylindracea* (Verlaque *et al.*, 2005) introduite par une autre voie que celle du canal de Suez.

3. QUELQUES RÉFLEXIONS À PROPOS DES NIS MACRODESCRIPTEURS

3.1 Des cinétiques d'implantation très différentes - Classification des NIS

La liste des NIS dans les eaux marines tunisiennes peut être subdivisée en deux groupes ayant, dans leur grande majorité, les mêmes affinités tropicales mais demeurant néanmoins très nettement différents.

• Les « NIS sénégaliennes » dont l'implantation concerne des espèces peu eurybiontes, pour ne pas dire sténobiontes (espèces sensibles, de stratégie « K ») ce qui, jusqu'à aujourd'hui, à de rares exceptions près, les a cantonnés dans le bassin occidental avec une progression d'ouest sans explosion démographique. Cette progression, qui est très lente, semble, jusqu'à aujourd'hui, être arrêtée par le « verrou » du cap Bon.

La progression de ces espèces est principalement de type « contagieux » (expansion latérale), elle est, essentiellement, sous influence des courants littoraux ouest, est.

Leur liste dans les eaux tunisiennes, relativement courte, est toutefois depuis une dizaine d'années en rapide progression.

• Les « NIS lessepsiennes » qui sont des espèces, dans leur grande majorité, fortement polluo-tolérantes (espèces opportunistes de stratégie « r »). Leur implantation est accompagnée le plus souvent d'une explosion démographique, vraisemblablement favorisée par une coïncidence de plus en plus marquée entre leurs conditions optimales de vie en mer Rouge et en Méditerranée méridionale.

Leur progression subit une très forte accélération, à la fois, dans le temps et dans l'espace. Elle n'est pas arrêtée par la barrière du cap Bon.

Leur expansion se ferait, dans la plupart des cas, en deux étapes :

1) Introduction liée au trafic maritime à mettre au compte du fouling ou /et du clinging et se traduisant, au départ, par de larges discontinuités géographiques.

2) Expansion géographique cohérente sud nord se traduisant, après un temps de latence et d'adaptation (naturalisation), par une extension plus ou moins rapide de leur aire de colonisation.

Le vecteur d'introduction des « NIS orientaux », dans les eaux tunisiennes, en raison des hiatus constatés entre leur présence dans les eaux égyptiennes et celles du golfe de Gabès, tout comme entre les eaux des golfes de Gabès et de Tunis, est, dans l'état actuel de nos connaissances des biocénoses littorales de la grande Syrte et d'une grande partie des côtes est de la Tunisie, très difficile à retracer.

3.2 Les raisons de l'accélération actuelle de l'installation des NIS en Tunisie ?

L'afflux accru des NIS en Tunisie depuis une dizaine d'années, et notamment leur très rapide remontée vers le golfe de Tunis pourraient être mis en parallèle avec les faits suivants :

- Depuis le début des années 70, l'effacement progressif de la barrière dessalée que constituait le rejet des eaux du Nil avant la construction du haut barrage d'Assouan et qui était à l'origine de la mortalité des larves d'origine lessepsienne ou de leur dispersion en direction des côtes du Moyen Orient.
- Une homogénéisation graduelle des eaux de part et d'autre du canal de Suez favorisant l'installation des espèces lessepsiennes avec la coïncidence, de plus en plus marquée, entre leurs conditions optimales de vie en mer Rouge et en Méditerranée méridionale.

4. PEUT ON RETENIR LE TERME DE « TROPICALISATION » DES EAUX MÉDITERRANÉENNES ?

Les importantes modifications actuelles de la biodiversité observées sur les côtes du Levant, de la Turquie, et, dans une moindre mesure, de la Grèce, comme sur celles de la Méditerranée méridionale orientale (bien que ces dernières soient restées à quelques exceptions près pratiquement vierges de toute observation) nous montrent que, de façon inexorable, les biocénoses qui caractérisaient ces milieux ont, dans les points d'impact les plus vulnérables, subi de très profondes transformations.

4.1 Les zones portuaires de la partie ouest de la grande Syrte - « Importation » de biocénoses allogènes tropicales

Dans la partie méridionale du bassin oriental l'ampleur de ces transformations pu être mise en évidence dans les zones portuaires du sud ouest du bassin oriental (partie sud de la petite Syrte et partie ouest de la grande Syrte).

Au niveau des ports de Tripoli (Libye) et Zarzis (Tunisie), en effet a été observé un phénomène inédit dans cette partie de la Méditerranée qui est la « naturalisation » non pas d'une ou deux espèces mais d'un complexe spécifique entier et totalement cohérent, c'est à dire l'importation non pas d'individus mais de toute une biocénose allochtone ?

C'est ainsi que l'on retrouve à quelque 2,000 km du canal de Suez, une biocénose apparemment « naturalisée » (zone intertidale de substrat dur) constituée de NIS qui, toutes, ont été récoltées à de très nombreux exemplaires comportant des individus de toutes classes de taille (Zaouali *et al.*, 2007a,b ; ben Souissi *et al.*, 2007).

Cette biocénose (see Plate G, page 111) dans la zone proche du port de Tripoli (Libye) est composée de la balane *Tetraclita squamosa rufotincta,* de l'ophiure *Ophiocoma scolopendrina* et du crabe *Grapsus granulosus,* toutes espèces qui n'avaient jamais été signalées en Méditerranée, ainsi que du polyplacophore *Acanthopleura gemmata,* de la patelle *Cellana rota*[5] signalée en Israël

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[5] Dans la zone de Zarzis qui est la seule où l'on dispose de documents antérieurs, *Cellana rota* a supplanté *Patella caerulea* (Seurat, 1929a) et les grapsidae exotiques ont supplanté le grapsidé *Pachygrapsus marmoratus.*

en 1961, et du crabe *Plagusia tuberculata* dont on n'avait à cette date mentionné qu'un seul spécimen dans les eaux libanaises.

Un peu plus à l'ouest, à Zarzis (Tunisie) cette même biocénose, légèrement appauvrie, est présente mais il manque *Acanthopleura gemmata*, *Tetraclita squamosa rufotincta* et *Ophiocoma scolopendrina*. On note, toutefois, en surplus, un autre crabe appartenant à la même biocénose, *Pachygrapsus transversus*[6].

Les espèces composant cet ensemble (Hullings, 1992) que l'on rencontre dans ce qui a été appelé la « Tetraclita zone » à Eilat en Israël par Safriel and Lipkin (1964) sont, toutes, réputées comme étant caractéristiques de l'étage médiolittoral de la mer Rouge.

Comment un tel ensemble a-t-il pu s'implanter ? Il faut, en effet, pour que l'introduction soit réussie qu'il y ait, selon la loi des probabilités, une somme de « coïncidences écologiques » qui ne peuvent, en principe, se trouver que si le milieu receveur est très, sinon tout à fait, en phase avec le milieu originel des espèces « exportées » !

Cette exportation de groupe, si elle est le fait du transport maritime, a-t-elle été facilitée par le biais de transferts, depuis l'Océan Indien, de plateformes pétrolières porteuses de communautés intertidales cohérentes ?

4.2 Sur la présence de Cyprées emblématiquement tropicales

Dans la zone sud du bassin oriental, aux cyprées méditerranéennes sont venues s'ajouter des espèces appartenant typiquement à des biocénoses tropicales, à savoir :
- la percée fulgurante faite par *Erosaria turdus* (ben Souissi *et al.*, 2005) avec la récolte d'individus vivants au large des port de Zarzis de Tripoli, et, de l'île de Jerba ;
- la colonisation de la partie du nord du plâtier kerkenien par *Cyprea (Monetaria) annulus* (ben Souissi *et al.*, 2007) et de la zone des herbiers au large de Tripoli.

Cette Cyprée Indo Pacifique (voir Figure 3), dont c'est la première signalisation méditerranéenne portant sur des individus vivants, a été trouvée en 2006 dans la zone des herbiers de *Cymodocea nodosa,* herbiers qui caractérisent les hauts fonds kerkeniens. Quelle serait l'origine de cette insolite transplantation ? Il serait, peut être, possible de penser à une introduction liée à un éventuel transport de plateformes pétrolières (installations off shore du champ pétrolier « Cercina » à Kerkena, séjour d'une plateforme dans la zone tripolitaine ?).

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[6] *Plagusia squamosa* et *Pachygrapsus transversus* avaient déjà fait leur entrée (sans lendemain) dans le port de Marseille en 1873 à bord du trois mâts « Karikal » qui venait de l'Inde (Zaouali *et al.*, 2007a), mais étaient-ils arrivés vivants ? Si oui, cette destination, non « tropicalisée », n'était pas à leur convenance !

4.3 Continuité géographique - Continuité génétique ? Quels modes de transport ?

La colonisation par la faune ichtyque des eaux de la grande et la petite Syrte ne peut pas être mise au compte du trafic maritime. En effet, malgré des lacunes dans nos connaissances elle montre indubitablement une continuité géographique.

Ne pourrait-il, dans certains cas, en être de même pour les organismes benthiques ? Leur installation en zone portuaire ne pourrait-elle pas suivre la même cinétique que celle suivie par les poissons ? Ne pourrait-elle être, plus simplement, due aux circonstances environnementales particulières qui caractérisent les ports, et, notamment la nécessité pour les espèces qui s'y établissent d'être très compétitives, ce qui est le cas d'une grande partie des NIS ?

5. Les NIS peuvent-elles être envisagées comme des bio indicateurs fiables du réchauffement climatique ? Quels outils ?

5.1 L'étude des écosystèmes – Priorité aux écosystèmes les plus sensibles

Afin de mieux cerner l'impact du réchauffement global sur le milieu marin il semble pertinent de contrôler l'évolution des populations et des peuplements les plus directement exposés à la contrainte thermique à savoir ceux de l'étage « inter tidal » de substrat solide.

Dans cette perspective, les études très poussées qui ont été faites au niveau des îles britanniques dans le cadre du projet MarClim (Micszkowska *et al.*, 2005) ont mis en évidence la pertinence de cette démarche. En d'autres termes, il serait judicieux de suivre cette même approche pour les eaux méditerranéennes au niveau de points clés qui resteraient à déterminer tels :
- Les milieux ayant fait l'objet d'études biocénotiques antérieures très complètes pouvant permettre d'établir des comparaisons quantitatives et qualitatives.
- Les milieux où des modifications très significatives ont déjà pu être notées. Nous pouvons citer, à titre d'exemple, pour la Tunisie, la zone de Zarzis.

5.2 Les espèces « thermo indicatrices »

Afin d'essayer de quantifier l'impact du changement climatique il serait bon de prendre pour espèces « cibles » des espèces très facilement repérables et identifiables par le maximum d'intervenants et cela dans les délais les plus courts.
Dans cette optique il serait opportun :
• De suivre au plus près la cinétique
- de l'avance du bivalve lessepsien *Pinctada radiata* en direction des côtes maghrébines, tout comme sa progression éventuelle vers l'ouest en Méditerranée septentrionale ;
- de la montée vers le Nord du gastéropode lessepsien *Cellana rota*, espèce, à la fois, facilement repérable et identifiable (étage intertidal).
• De procéder à une étude comparative de l'évolution spatio-temporelle des biocénoses des substrats durs des points clés de convergence entre bassin occidental et oriental que sont les îles de la Galite, de Pantelleria et de Lampedusa.
• De procéder à des études génétiques comparatives des NIS installés en Méditerranée et dans leur milieu originel afin de pouvoir apporter des réponses quant aux dérives génétiques éventuelles liées à l'acclimatation des populations allogènes naturalisées.

5.3 Suivi à l'échelle régionale – « Quid » de la partie méridionale du bassin oriental ?

Il est très difficile de statuer sur l'impact et sur la signification écologique des invasions allogènes détectées quand les points d'éventuelles comparaisons sont éloignés de plusieurs milliers de kilomètres ! Ce qui est le cas de la partie méridionale du bassin oriental !

Les observations faites montrent de façon évidente que cette vaste portion maritime mérite au moins la même attention que celle qui a jusqu'à aujourd'hui été portée à la zone du Levant et à la partie nord de ce même bassin.

Il faut, en d'autres termes, essayer de combler rapidement cette importante lacune. En effet, tout porte à croire qu'une étude minutieuse des biocénoses en place le long des côtes égyptiennes et libyennes apportera de précieux éléments de réponse à de nombreuses questions quant à l'influence du réchauffement climatique en Méditerranée.

6. LES NIS, ENRICHISSEMENT DE LA BIODIVERSITÉ ?

Par définition, la Méditerranée a été, et, est un « melting pot » capable d'accueillir et, à la longue, de naturaliser les émigrants, au cas par cas, mais, aussi, à l'échelle « tribale » (biocénose).

Les observations faites sur les eaux littorales tunisiennes ont montré que, dans de nombreuses circonstances, les poussées invasives allogènes aboutissent à plus ou moins longue échéance à un compromis entre émigrant et résident.

Nous l'avons vu, entre autres, pour *Perna perna* ou *Fulvia fragilis* dans le golfe de Tunis, tout comme, cela est vrai, au niveau du golfe de Gabès, pour les crevettes Penaeides de mer Rouge telle *Metapenaeus monoceros* et la crevette méditerranéenne *Penaeus kerathurus* (*Melicertus kerathurus*) dans le golfe de Gabès[7].

En définitive, il est certain que la Méditerranée de demain ne sera pas celle que nous connaissons aujourd'hui, mais, il semble, malgré tout, possible de penser qu'elle sera à l'image de ses peuples riverains qui ont, depuis des millénaires, été enrichis par leurs échanges (plus ou moins paisibles) sans pour autant perdre leur identité.

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[7] Il faut signaler, toutefois, une exception notoire qui est le cas du crabe nord américain *Libinia dubia* ; espèce, très certainement, arrivée par déballastage au niveau du port pétrolier de la Skhira. Ce majidae aux affinités tropicales, dont on sait qu'il est arrivé dans le golfe de Gabès dans les années 2000 (Enzross and Enzeross, 2000), peut être considéré comme une des espèces introduites invasives dans les eaux marines tunisiennes la plus fortement nocive. Toutefois, non pas tant au niveau bio-compétitif qu'au niveau socio économique !

En effet, à l'heure actuelle, du fait de sa prolifération et de sa grande taille, les pêcheurs côtiers, notamment dans la zone sfaxienne, estiment qu'il est un véritable fléau car il rend leur travail difficile en encombrant et déchirant leurs filets maillants.

Helgoland Roads time series: learning from long-term marine data sets

Karen Helen Wiltshire and Heinz-Dieter Franke

Biologische Anstalt Helgoland, Alfred-Wegener-Institute for Polar and Marine Research, Helgoland, Germany

ABSTRACT

Helgoland Roads time series, especially the pelagic time series, serve here as an example of how important continuous time series are for understanding marine ecosystems. Using these data sets the problems associated with long term data acquisition and analyses are elucidated, including quality control examples as well as error examples. The need to differentiate between trends and shifts is discussed. We show the need for having a vigilant unbiased view of the occurrence and persistence of new species.

The greatest challenges with long term marine data are identified as:

- producing a reliable quality-controlled data set,
- posing relevant unbiased hypotheses and
- finding the correct points of analyses and analytical methods.

INTRODUCTION

In times of rapid change and increased pressure on resources, as many of our marine systems are currently experiencing, the foresight shown by scientists, naturalists and managers with the introduction and continuation of Long Term monitoring programmes is laudable.

We are fortunate in particular that in shelf seas and basins many data sets exist. These are increasingly taken out of the closets and subjected to scientific scrutiny. These data sets range from spatially gigantic (such as the CPR) data series (Reid *et al.*, 1998) highly temporally resolved such as the Helgoland Roads time series (Wiltshire *et al.*, 2008), including very old Benthic time series at Helgoland showing gaps of tens of years (Bartsch *et al.*, 2004).

A good long term data set can be a mine of information and the temptation may be large to analyse it indiscriminately, for example to look for climate induced changes. Yet a good dose of scepticism and meta data analyses are needed. In particular, when data come from systems such as the North Sea which in the last 100 years has experienced repeated overfishing, large scale dredging, coastal defence and dyke construction, increased and decreased pollutant loading as well as warming, hypotheses on changes in ecosystem structure and function cannot be based on single factors alone. When dealing with trophic cascades and food webs it is important to involve these complex interactions into ones´ considerations.

Here we present and discuss examples of long term data characteristics, problems and results, based on the temporally highly resolved Helgoland time series both in the pelagic and benthos, to a lesser extent.

DATA

The data sets of the Helgoland long-time sampling series are potentially the richest temporal marine data sets available. They include daily surface water sampling. resulting in a pelagic data set of the Helgoland time series comprising phytoplankton, salinity, Secchi and nutrients analyses from 1962 until the present day. Concurrently the biological parameters zooplankton, rocky shore macroalgae and macro-zoobenthos and bacteria were sampled discontinuously until the 1990s and only recently have been sampled again on a regular basis.

These data sets are used for many purposes, e.g., monitoring the pollution status of the German Bight and the North Sea or, providing ground truth information for Remote Sensing activities. They are implemented as forcing for predictive ecosystem and climate models and they used as a basis for governmental decisions and directives such as the EU ‘Water Framework Directive’.

Because of the potentially high profile which data sets acquire in management strategies, quality assurance and archival are of paramount importance.

While the pelagic parameters have been extensively quality-controlled, the benthic data sets are difficult to check due to lack of consistent long term records and reference sites. Indeed for the rocky shore benthic time series a large amount of time and effort has been invested in trying to link up different data sources. Due to differences in sampling strategies, nomenclature and recording techniques, it proved next to impossible to carry out comparisons between old and new data sets beyond looking at presence and absence of species. However, the pressure is on with regard to the distinction between climate and other signals in coastal seas often leaving the user little time for quality assurance.

Quality and accuracy of data is a major issue in producing and using long-time series data. Unfortunately in practice, this is frequently overlooked and rigorous data control is rarely in evidence.

The pelagic time series of Helgoland Roads (with the exception of zooplankton data that are currently being revised) have been successfully amalgamated into an open access data bank (<www.Pangaea.de>), cross-checked with other data sets from the same water bodies and reference data sets for the North Sea (Wiltshire and Dürselen, 2004; Raabe and Wiltshire, 2008). With this, the pelagic data sets are now sufficiently understood, and corrections, problems and errors have been documented. Thus, they may be used confidently to assess long term changes to the North Sea pelagic ecosystem. The primary sampling at Helgoland Roads is carried out as it always has, with the introduction of a highly resolved automated monitoring system (FERRYBOX) has been introduced in order to understand the temporal variability on an hourly basis of temperature, salinity, nutrients and fluorescence at the site. Every two days light penetration is measured and compared with Secchi and chlorophyll measurements at the sampling site. Phytoplankton species lists are updated and an open access taxonomic database Plankton* Net (<www.planktonnet.eu>) has been established and is cared for by the AWI.

For the rocky intertidal long term monitoring at Helgoland, reliable and consistent intertidal sampling programmes associated with extensive mapping programmes have been introduced recently both for flora and fauna (Bartsch *et al.*, 2004; Reichert *et al.*, in press). The monitoring authorities have taken over a large proportion of the difficult sublittoral monitoring (Boos *et al.*, 2004) which should ensure continuum and comparable long term data for the future. In the meantime because of the need to react to special situations − for example new species entering the system (both as introduced neobiota and as immigrants) − specialised sampling is carried out e.g. for several isopods and amphipods (Franke and Gutow, 2004) and for the ctenophore *Mnemiopsis* (Boersma *et al.*, 2007).

Examples of problems in long-term data analyses

Nutrient data variability

All the nutrient data from Helgoland Roads are measured by colorimetric chemistry and photometers. These measurements, though standard, are not trivial. Lamps and optical filters as well as standards and calibrations have to be checked regularly and the knowledge on how rigorous this needs to be has developed over the years. Consequently, we spent a lot of effort in ensuring that the methods and calibrations used in the past were up to standard and that the data archived were usable and comparable over time. Perhaps the best way to demonstrate the type of problems encountered in long term nutrient analyses is using the silicate data from Helgoland Roads.

Figure 1 shows the silicate values from 1962 to 2005. What stands out is the fact that there is a large jump in the data set around 1987. Over the years this was thought to have been due to inaccurate calibration. However, the continuous decline in values observed thereafter, symptomatic of a system which had a large nutrient input subsequently sequestered, led us to further investigate this jump in the data. As described in Raabe and Wiltshire (in press) a time period was chosen when normally nutrient remineralisation is almost over (even for silicate) while microalgal activity is still at its minimum, i.e. the mid winter month- February. Additionally, in February, the river discharge into the German Bight also would not have reached its maximum and thus, the nutrient concentrations at Helgoland Roads should not have been affected much by phytoplankton growth and/or river discharges extending into the German Bight.

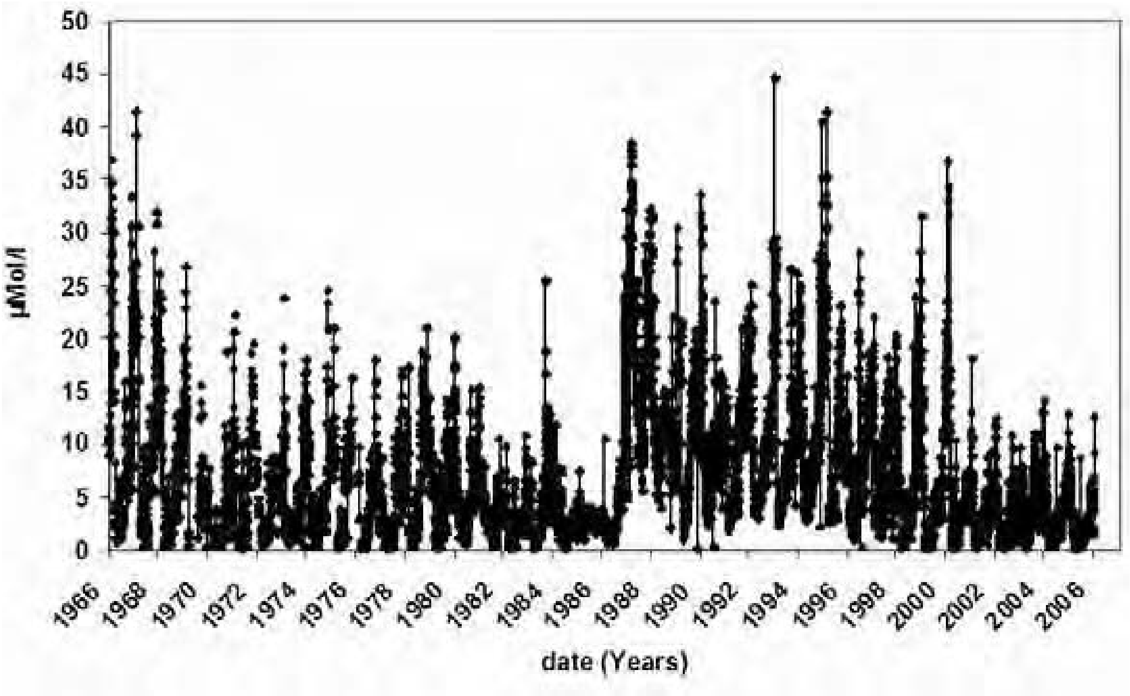

Fig. 1. Silicate values-Helgoland Roads.

Raabe and Wiltshire (in press) showed that from 1966 to 1986, a significant decrease from almost 15 µM down to < 5 µM was observed in February medians. In 1987, the February median increased, culminating in a peak of > 25 µM in 1988. Thereafter, the medians of silicate concentrations slowly decreased again, but did not reach the low level of < 5 µM that had been registered before 2003. Regression analysis for the years 1990 through 1999 gave a highly significant linear correlation ($p < 0.001$), with a winter silicate decrease of 0.75 µM year^{-1}.

We compared these German North Sea data, Raabe and Wiltshire (in press) data from British research cruises of the same time downloaded from the ICES database. The results showed a clear upwards trend from 1985 to 1987, when the overall silicate concentrations reached > 20 µM in coastal waters. All the cruise data values were very similar, confirming the good quality of the independently sampled and analysed data. Starting with concentrations of 5 µM in 1984, the means reached almost 8 µM in 1987, and then dropped back to a nearly constant level of < 5 µM from 1988 through 1991. This clearly indicates a strong silicate input into the North Sea during the year 1987.

After 1990 the Helgoland Roads silicate values never dropped back to the very low concentrations recorded in the early 1980s, although it seems that the silicate is slowly being sequestered in the system, indicated by a steady downward trend in concentrations.

Detailed analyses of the literature and hydrographic conditions regarding inflow from rivers as well as a sudden shift in a whole array of biological parameters in 1987-88, lead us to accept this “hike” in silicate values as real.

Reid *et al.* (2001) reported that “phytoplankton colour”, a visual estimate of chlorophyll from the CPR, increased in the North Sea after 1987 thus conforting these observations. Many phytoplankton and zooplankton species showed marked changes in abundance. Catches of horse mackerel (*Trachurus trachurus* L.) increased, indicating a northerly range expansion from the Bay of Biscay into the North Sea after 1987. Wiltshire *et al.* (2008) show a marked increase in microalgal densities around this time. Edwards *et al.* (2006) investigated the long-term spatial variability of Harmful Algal Blooms (HABs) in the northeast Atlantic and the North Sea using data from the Continuous Plankton Recorder (CPR) and showed unusually high values for the inter-annual bloom frequencies in the late 1980s. They related this to the North Atlantic Oscillation (NAO).

Counting organisms and species identification

Perhaps one of the greatest problems when maintaining a long term data set is the enumeration and identification of species. The Helgoland Roads Phytoplankton time series provides a good example of the problems incurred.

The main difficulty is to achieve conformity when identifying species. This is made more difficult when there are diverse people involved. At Helgoland Roads ten people counted over the time period 1962 through 2007. Although every effort was made to have counting overlap and species intercalibrations along the way, we know from our detailed analyses of the data (Wiltshire and Dürselen, 2004) that there are many problems which can be related to changes in counters.

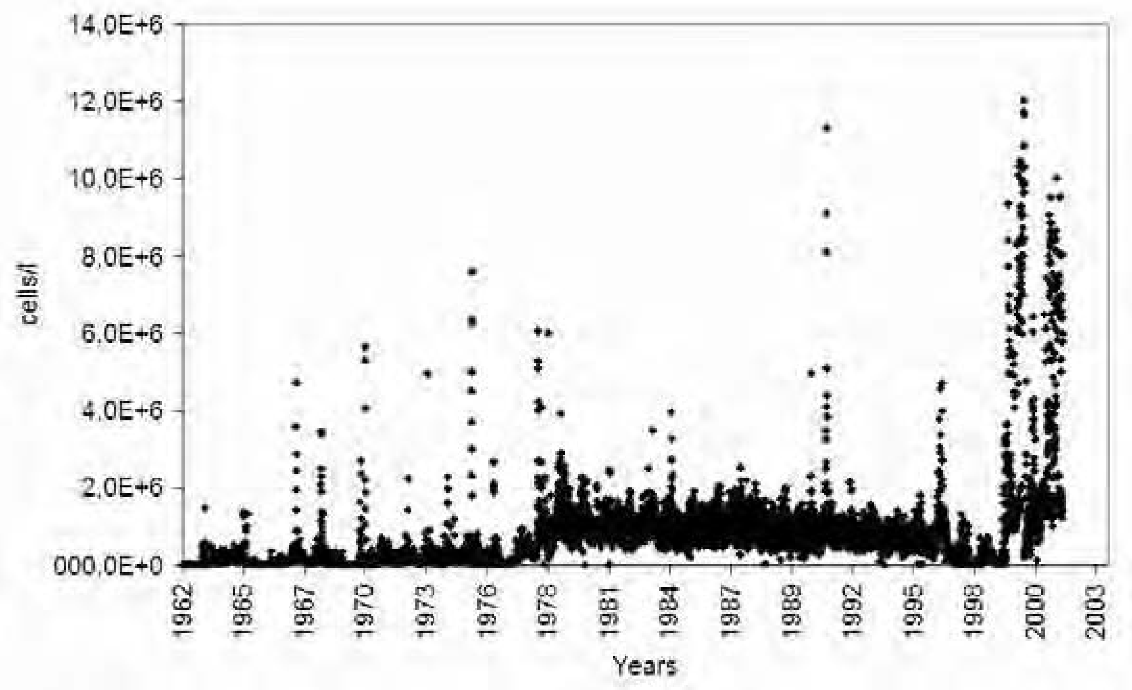

Fig. 2. Flagellate cell numbers-Helgoland Roads.

An example was given in Wiltshire and Dürselen (2004) which we cite again here: Is the observed increase in flagellate numbers in 1976-1978 (Figure 2) really related to increased nutrient input due to eutrophication, or related to a change in hydrographical regime, or is it rather related to the involvement of a new counter? One thing is for sure: the enormous increase in flagellate counts in 1998 is related to the purchase of a new microscope. Interestingly such problems seem to have been negligible for the larger and more easily identifiable diatoms. Thus, one really has to save and use the meta-information related to counting persons carefully.

Experience shows that here it is already difficult to count and analyse small organisms even only as general classes under the microscope, It is next to impossible to achieve undisputed accuracy to species level. In the Helgoland Roads data set this is in evidence on a daily basis, for example with small dinoflagellates where we usually just get it down to genus (e.g. *Protoperidinium* spp. and *Gyrodinium* spp.). We now document this clearly and make type slides of our phytoplankton on a monthly basis. We also pick out previously unclearly identified species and try to get them into culture, also using molecular techniques (e.g. most recently *Peridiniella danica* and *Thalassiosira* species). In the past a few problems have arisen due to the fact that species were not clearly identified. The best example is the diatom *Coscinodiscus wailesii* which was "found" in the Helgoland Roads lists at least two years before it was recorded elsewhere in the North Sea. As no type material was archived and the paper notes are ambiguous, it was likely erroneous. As a result we currently not only take daily samples for Utermöhl counting, but also weekly samples for "species hunts" using nets of different mesh sizes. We try to even take pico and nano phytoplankton into our sampling regime at regular intervals because we are aware of the fact that although we can only identify them with optical and molecular tools, they may be of pivotal importance to the lower part of the food web.

Similar problems exist for zooplankton. Many species, including important indicator species such as the copepods *Calanus hegolandicus vs. Calanus finmarchicus*, have only been identified to genus level. This is frustrating as we now really need them to confirm some of the hydrographic shifts and related trophic changes observed in the North Sea. Thus, we now take more time to differentiate them and are examining ways to reanalyse old data. Although we are absolutely certain that we have found *Mnemiopsis leyidii* in 2006 (Boersma *et al.*, 2007), it is distinctly possible that this organism has been there for longer: as suggested by Faasse and Bayaha (2006) it could have been mixed up with *Bolinopsis* for quite a while because nobody was expecting it and/or had the knowledge to recognise it. Thus, for zooplankton a new analyses regime has to be introduced as well as a stringent documentation of the status quo in the coming months. As for the phytoplankton we have begun to sample size classes that are consequently difficult to identify- e.g. ciliates and mesoplankton in general over the past three years. The outcome was as expected: they are very abundant, voracious feeders and we have identified many species which should not be ignored in long term marine observations.

Among the Helgoland hard-bottom macrofauna some 30 species which had never been reported before for the German Bight or even the North Sea, were registered as permanent elements of the community over the past three decades. As far as these species are conspicuous in phenotype and easy to classify, they may represent true newcomers, e.g. the isopod *Idotea metallica* (Franke *et al.*, 1999), the crab *Liocarcinus depurator* and the hermit crab *Diogenes pugilator* (Franke and Gutow, 2004). Some "new" species, however, particularly amphipods and polychaetes, may have been overlooked or confused with other species in former times. This may apply to *Jassa herdmanni* (Amphipoda), the most abundant species of the genus, which may not have been differentiated from its similar congener *J. falcata* previously (Franke, unpublished). The Japanese skeleton shrimp (*Caprella mutica*) is a true newcomer to the North Sea; it probably already arrived at Helgoland in the mid 1990s, but went unnoticed for a number of years when it was considered to be the native *Caprella linearis* (Buschbaum and Gutow, 2005; Cook *et al.*, 2007).

Knowing what one wants: trends vs. shifts

The current true long term data sets (over 20 years), were often set up with a naturalist´ curiosity as the driving force. Earlier oceanography realised the need for taking many repeated samples over very long time periods and large scales (see CPR data set for example) in the world's oceans.

At the beginning of the previous century it was realised that rapid change, mostly anthropogenically induced, could also affect marine systems. In order to assess changes, monitoring time series were set up. Helgoland Roads is an example. The number of questions to which data sets are applied has grown over time. At Helgoland Roads we have many more questions then the original questions posed, for example:

- How did/does overfishing affect the system?
- How does the introduction/occurrence of new species/aliens affect the system?
- How does climate change influence the system?
- How does changing hydrography affect the system?

Because the system is multi-layered, with countless trophic interactions and input variables, the questions posed above cannot be seen in isolation. Thus, one has to go beyond simple cause and effect analyses based on linear assumptions and must venture into multi-variate statistics and non-linear modelling.

One of the most common problems associated with time series is their time span: after how many years can one use them for prognoses? Geologists, for example, often maintain that only geological time scales are important. This may indeed be the case if one does not consider human-induced changes to an ecosystem. One of the most common assumptions made with the conservative variable temperature is that one can make decent prognoses from a mere ten years of data. An example of how the ten year blocks for Helgoland Roads look like relative to the overall prognosis based on the 45 years of time series is given in Figure 3. There one clearly sees that the linear regressions, all significant trends, for ten year blocks are very different and deviate substantially from the linear trend for all 45 years (Figure 4). None of these would have provided a simple and accurate prognosis for the subsequent 20 years let alone 100 years. On the other hand, it is important to compare different climatic blocks of data- as in cold year blocks versus warm year blocks. Sudden shifts in temperature are also important, e.g. warm to cold shifts as seen in 1986-89 and 1996, since these can cause sharp shifts in biological systems and even reset a system (Reid *et al.*, 1998; Edwards *et al.*, 2002; Straile, 2002; Weijerman *et al.*, 2005; etc.).

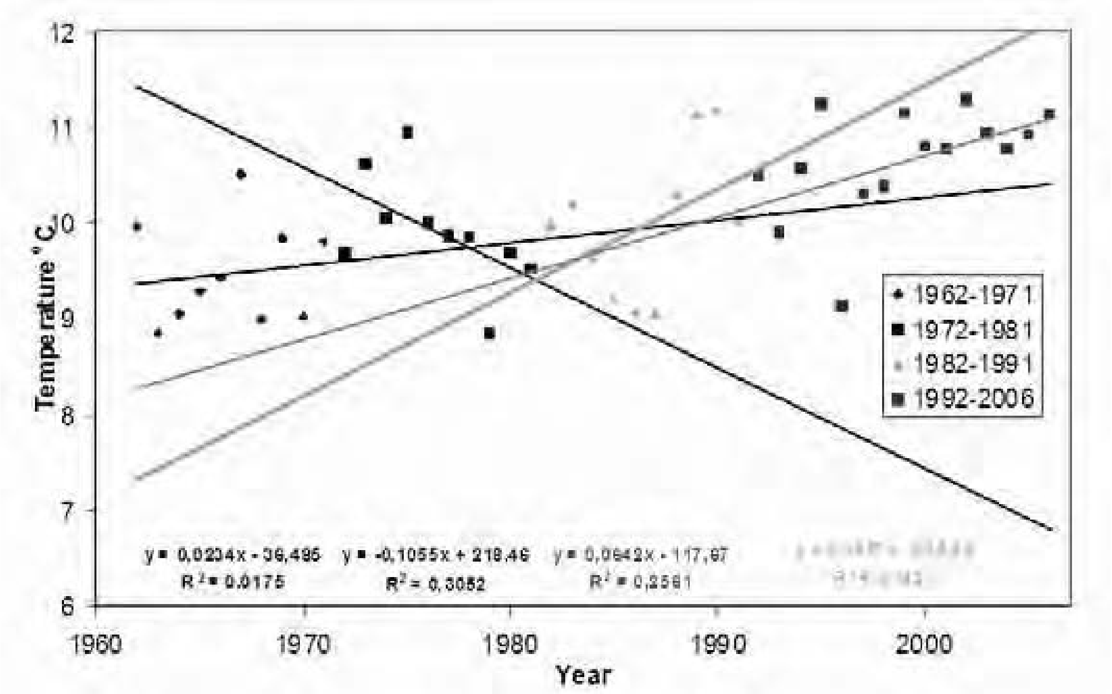

Fig. 3. Temperature trends for separate 10 year mean blocks-Helgoland Roads.

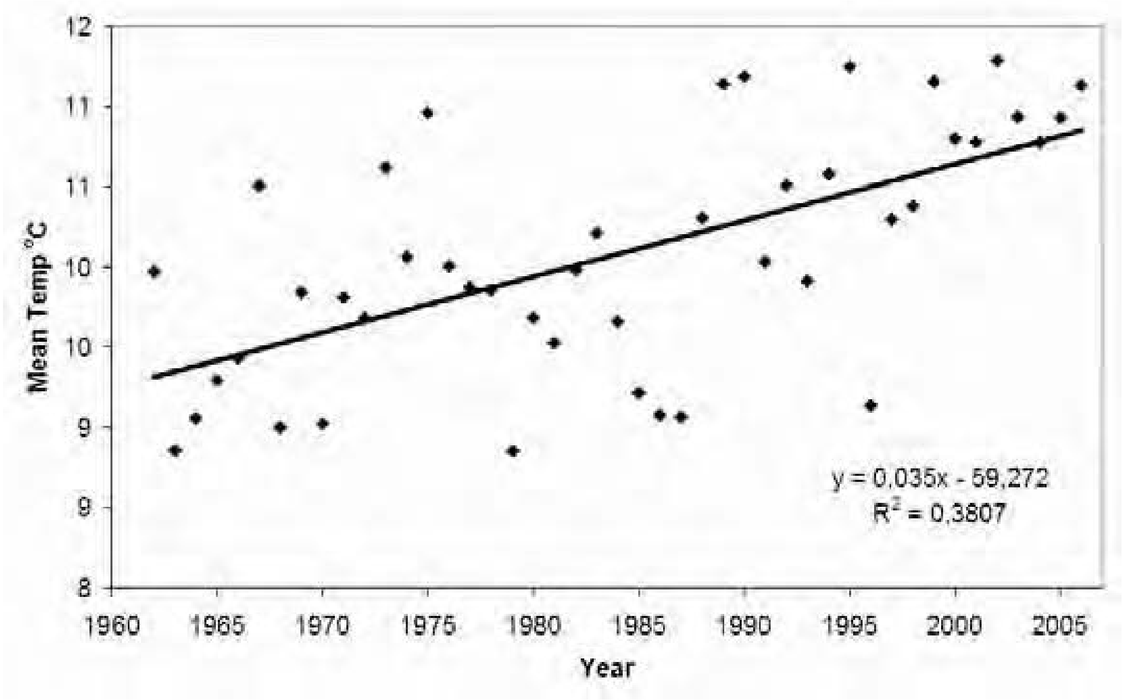

Fig. 4. Mean yearly temperature trend-Helgoland Roads.

Thus one needs to differentiate the effects of trends versus sudden changes or repetitive shifts in the system (see Ottersen *et al.*, 2005).

Simple biological questions such as: does temperature affect the timing of the spring bloom of microalgae? become a challenge in systems like the German Bight which is differentially affected by coastal and marine currents depending on larger weather patterns (see Radach, 1998; Wiltshire *et al.*, 2008; etc.). Indeed the longer a time series, the more interesting such questions become because the more likely we are to understand what is really going on. At Helgoland Roads an analysis of older data until 2000 showed that in general the spring bloom came later related to warmer autumns and potentially due to top down control by surviving herbivores (Wiltshire and Manly, 2004). However, once later data were included this trend was no longer clear and the timing of the spring bloom now appears related only to temperature, it is now coming earlier rather than later. This shift in trend means that overall nothing has changed in timing over the 45 years, statistically speaking, but it is certain that the first thirty years behaved differently from the past 15 years. We went to considerable lengths to evaluate this (Wiltshire *et al.*, 2008) with the data available to us and are at the stage where we need to model interactions to understand the governing parameters in the timing of the bloom. Here again it is important to differentiate out sudden shifts, clearly seen for the spring bloom data in the time period 1975-1979 (Wiltshire and Manly, 2004), versus trends.

Unbiased views: introduced species

New species are continuously arriving in marine systems both naturally as immigrants and through human input. Some of the most controversial introductions in the past have been via ship ballast water, including toxic microalgae into the Northern North Sea, or the introduction of the voracious comb jelly *Mnemiopsis leidyi* to the Caspian Sea with disastrous consequences. The North Sea has been subject to many species introductions such as the Pacific Oyster into the Wadden Sea which is becoming extremely extensive and which is likely to have had an effect on the planktonic organisms due to heightened filtering of the water column in the German Wadden Sea (Kochmann *et al.*, 2008) not to speak of the concrete-like substrate which it induces in a habitat which used to be dominated by *Mytilus edulis*. In the phytoplankton new species have arrived from all over the world in the past 40 years at Helgoland Roads, such as *Concinodiscus wailesii* and *Odontella* *sinensis* to name but two. As yet we do not know whether these two species have had any effect on the planktonic system.

An aspect of great concern in climatically affected systems such as the North Sea is the introduction of “warm climate aliens”, or rather species that have arrived in the system and normally would die off under colder conditions but which now can persist and multiply. Many examples of these at Helgoland Roads are found in the larger organisms, including the brown seaweed *Sargassum muticum* (Reichert and Buchholz, 2006) and the isopod *Idotea metallica* (Gutow and Franke, 2001). As a geologically young ecosystem, the southern part of the North Sea may be expected to be ecologically ‘unsaturated’, able of supporting much more species than at present.

Introductions are normally considered as being negative- however, this is a rather biased assumption- often based on very negative examples. *Sargassum muticum* for example, a recent introduction into the German Wadden Sea is a refuge for small fish and a gathering point for plankton- seemingly making it a positive introduction to the Wadden Sea by increasing habit at value (Polte and Buschbaum, 2008).

The whole issue of introduced species is understandably sensitive in systems which have been dramatically affected by these. However, at present although we are vigilant at Helgoland Roads we try to keep an open mind on the subject as most of these introductions over the past 45 years (certainly in the phytoplankton) seem to have been absorbed into the system.