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

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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.

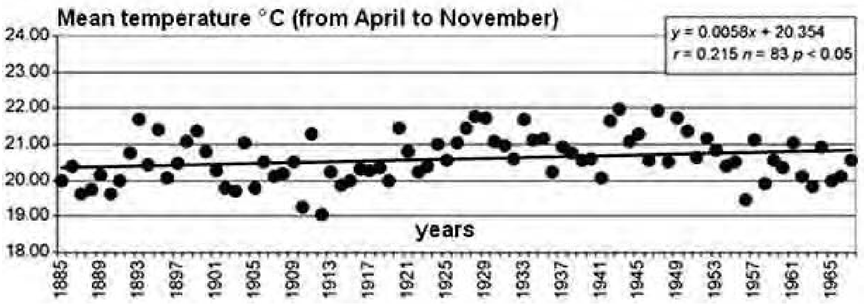

Fig. 1. Yearly mean temperatures (from April to November) over the 1885 - 1967 period, with the representation of the significant positive linear regression (after Romano and Lugrezi, 2007).

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).

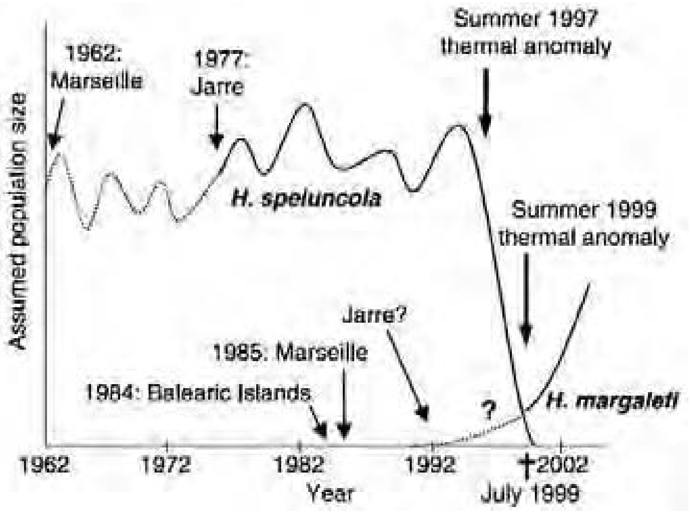

Fig. 2. Proposed scenario of changes in the populations of two Mediterranean species of Mysidacea in the shallow-water marine cave of Jarre Island, near Marseilles, France, over the past 40 years, based on regular observations by SCUBA diving. The years the two species were discovered are also reported, 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).

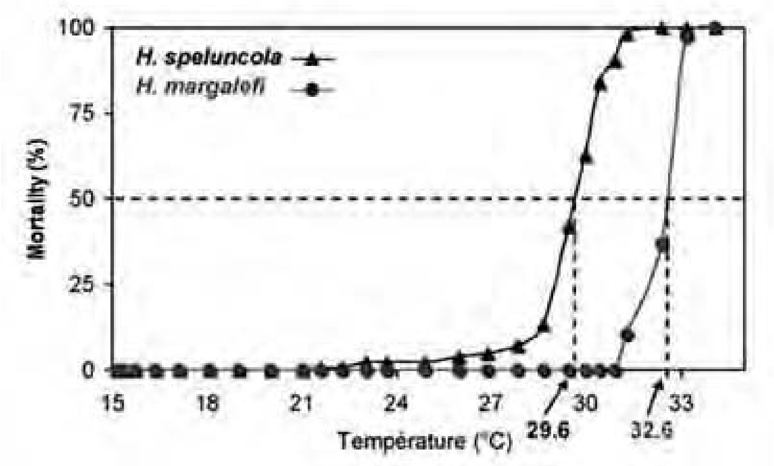

Fig. 3. Ex situ experiment designed to determine the difference of tolerance to an acute thermal stress in *Hemimysis speluncola* and *H. margalefi*, two species of cave mysids with different thermal habitat requirements. Dotted lines indicate the acute LT50 (lethal temperature for 50% of an experimental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

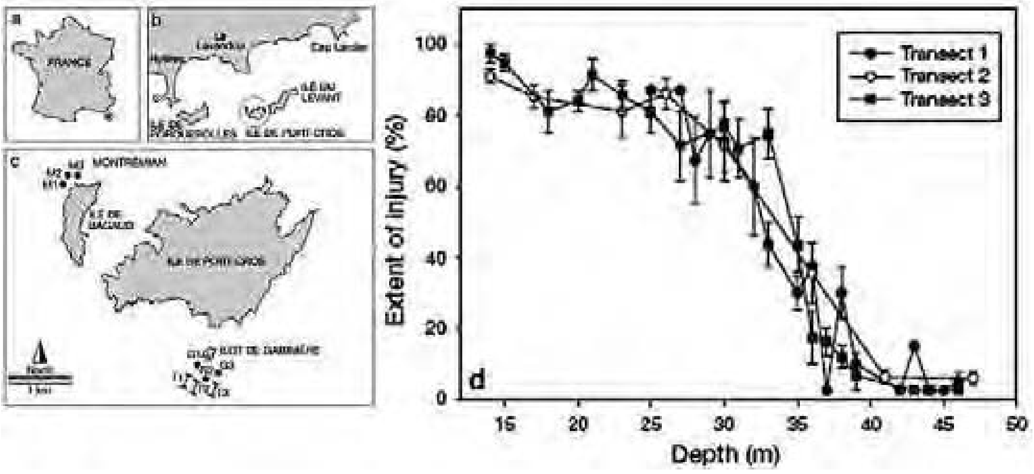

Fig. 4. (a,b) Distribution of the *Paramuricea clavata* shallow population at Port-Cros National Park (NW Mediterranean, France) and location of sampling sites; (c) permanent plots at Montrémian (M1, M2, M3), La Gabinière (G1, G2, G3) and depth transects (T1, T2, T3); (d) effect of depth on partial mortality (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

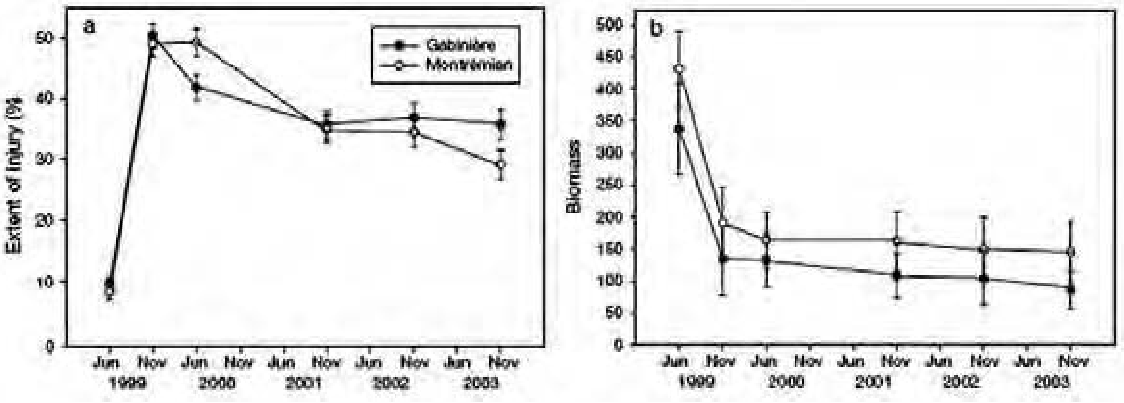

Fig. 5. Changes in: (a) partial mortality (% of injured colony surface) including affected and unaffected *Paramuricea clavata* colonies; (b) biomass (g DM.m^{-2}) over the study period (June 1999 to November 2003) at two locations (Montrémian and La Gabinière). Data are mean ± SE (after Linares *et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

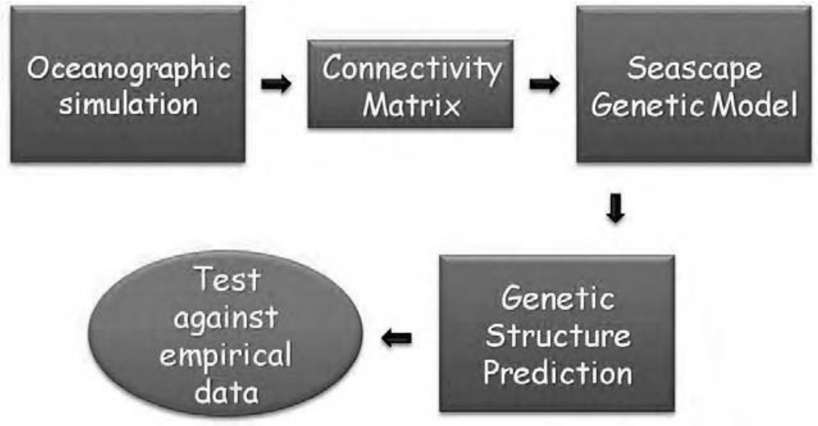

Fig. 6. Conceptual Model of Coupled Oceanographic-Genetic Approach (after Galindo *et al.*, 2006).

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).