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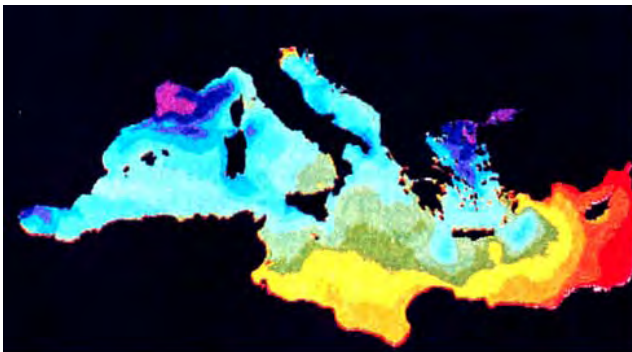


United Nations Environmental Programme

MEDITERRANEAN ACTION PLAN

Regional Activities Centre for Specially Protected Areas

Impact of climate change on biodiversity in the Mediterranean Sea



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For bibliographic purposes this volume may be cited as:

UNEP-MAP-RAC/SPA 2008. Impact of climate change on biodiversity in the Mediterranean Sea. By T. Perez, .RAC/SPA Edit., Tunis : 1-61.

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This document should not be considered as an official United Nations document.

CONTENTS

FOREWORD	2
INTRODUCTION	3
GLOBAL CHANGE IN THE MEDITERRANEAN – THE PROOF!	4
The first signs in deep Mediterranean water	5
Very clear trends in coastal waters.....	5
Increasingly frequent temperature anomalies.....	7
Other factors linked to climate change that will have consequences for the management of coastal areas.....	9
BIOLOGICAL CONSEQUENCES OF CLIMATE WARMING IN THE MEDITERRANEAN	11
Visible signs that the Mediterranean is being southernized	11
Warming of the Mediterranean and biological invasions.....	18
EXTREME CLIMATE EVENTS AND MARINE EPIZOOTICS	22
Necrosis and mass mortality.....	22
Emergence of pathogens.....	28
Effects on the secondary metabolism	30
Short- and medium-term responses by populations	31
EXAMPLES OF EFFECTS ON THE FUNCTIONING OF THE MARINE ECOSYSTEMS	34
CONCLUSION AND PROSPECTS	38
Climate change and the future of Mediterranean biodiversity	38
Lines of research to be pursued	40
Possible adaptation measures and suggested action	41
BIBLIOGRAPHY	48
EXECUTIVE SUMMARY	59

FOREWORD

This study falls within the context of the reflection initiated by the Regional Activity Centre for Specially Protected Areas (RAC/SPA) on the sustainable management of the sea, coast and marine resources, as is written into the Mediterranean Strategy for Sustainable Development and the recommendations made in this context by the Contracting Parties at their 14th Meeting (Portoroz, 2005).

It aims at drawing up a statement on the problems arising, on a regional scale, and at providing valid, up to date scientific information. Furthermore, it constitutes an element of response to the recommendations made by the Contracting Parties at their last Ordinary Meeting (Almeria, 15-18 January 2008), particularly the request that a report be drafted on the situation of biodiversity in the Mediterranean and on the impact of climate change observed.

This document offers an initial appraisal that deserves to be regularly supplemented and updated with information gathered from the countries. It intentionally restricts itself to aspects of Mediterranean marine biodiversity in that this subject has so far been little addressed by the other international organisations, and thus is meant to supplement their approach. Also, even if the evolution of ecosystems in response to impacts observed today is sometimes envisaged, reflection remains restricted to those scientific documents that are accessible at international level.

It does not pretend therefore to be exhaustive. Lastly, there has been very little mention in this first appraisal of measures of adaptation to or reduction of the effects of warming.

A. Gannoun

Director of RAC/SPA

INTRODUCTION

Analysis of the results of the latest report by the Intergovernmental Panel on Climate Change (IPCC 2007; see also the 2002 IPCC Report) has shown that climate change has already had a perceptible effect on world biodiversity and is likely to affect the sustainability of the ecosystems and services that today it supports. Thus, in the context of the Mediterranean Strategy for Sustainable Development, aiming at paying greater attention to the sustainable development of the sea, the coast and marine resources, it appears desirable to make an appraisal of the impact so far known of climate change on Mediterranean marine diversity.

Moreover, it is widely recognised that these changes will continue and even intensify, despite the major steps that are being taken to reduce greenhouse gas emissions. Thus it is becoming necessary to identify how we can help biodiversity, and the human activities that it underpins, to adapt. It thus seems opportune in the context of this study to evaluate measures to adapt to, or reduce, those effects of warming that could be envisaged.

Up to now, many recent or ongoing research programmes have brought to light new data concerning the impact of climate change on Mediterranean marine biodiversity, but many lacunae still exist. Some geographical parts of the Mediterranean have been little, or not at all, studied and certain thematic fields of investigation are still completely untouched. During the past fifteen years, several summaries have been published by French (Laubier, 2001, 2003; Laubier *et al.*, 2003) and Italian (Bianchi, 1997, 2004, 2007; Bianchi and Morri, 1993, 2000; Occhipinti-Ambrogi, 2007) writers, but much data remains unpublished. In 2003, Garrabou *et al.* made a summary on the effects of warming in the north-western Mediterranean using published and unpublished data and also personal communications obtained after surveys in European marine stations. The same approach was used to draft this report, inspired by the existing published summaries and the most recent scientific data. In all, 135 sources were used, 75% of these exclusively Mediterranean.

GLOBAL CHANGE IN THE MEDITERRANEAN – THE PROOF!

Global change, particularly climate warming and the increased frequency of extreme events (e.g. El Niño) affects both terrestrial and marine ecosystems (e.g. Barry *et al.*, 1995; Southward *et al.*, 1995; Petchey *et al.*, 1999; Hughes, 2000; Walther *et al.*, 2002). The present climate change is very clearly a result of the exponential development of human activities and goes far beyond the borders of natural variability (Karl and Trenberth, 2003).

The potential effects of global change act at several levels of biological organisation, from the physiological disturbance of individuals to modifications of a community and how it functions, through local extinctions and/or the extinction of certain species (Hughes, 2000; Parmesan and Yohe, 2003; Root *et al.*, 2003). Predictions about the consequences of warming for biodiversity as a whole are very worrying. On the basis of a moderate climate change scenario, a recent estimation, taking into account 20% of the earth's surface, anticipates an extinction of 15-37% of the species that today occupy this area by 2050.

The coastal areas must be given particular attention since they shelter high biological diversity, complex biological systems that are very productive and have a high degree of interaction with human populations. The potential effects of climate change represent new sources of stress and thus fully justify a growing concern for the conservation, and even restoration, of marine coastal ecosystems (Fig. 1).

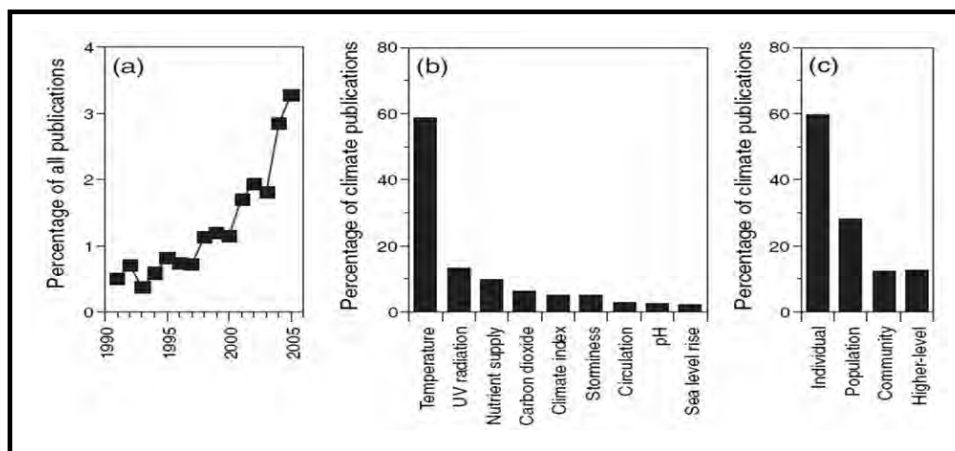


Figure 1 : a) Evolution over time of the number of publications on marine ecology and biology concerning climate warming; b) trend concerning the abiotic variables considered; c) level of biological organisation considered (Harley *et al.*, 2006).

The Mediterranean only represents 0.82% of the oceans' surface area but shelters 4-18% of world marine biodiversity according to the taxonomical groups considered (Bianchi and Morri, 2000). The Mediterranean seems to be one of the regions most sensitive to climate change (Parry, 2000), and the amount of evidence of the warming of the marine water fully justifies a resolute research effort to assess the risks run by Mediterranean marine biodiversity.

The first signs in deep Mediterranean water

The hypothesis of a current warming of the Mediterranean water was advanced for the first time, backed up by proof, by Béthoux *et al.* (1990) using a set of hydrological data acquired between 1959 and 1989 in the north-western Mediterranean. These writers demonstrated the existence of a rise in the temperature of the deeper water of 0.12°C in 30 years, i.e. an average annual rise of 0.004°C. This warming of the deep water, that could be seen as minimal, could have a certain influence on the temperature of the coastal waters, according to the results of modelling. It has been impossible, however, to advance any value, given the very great spatial and temporal variability of the temperature of the coastal water compared to the extreme stability of that of the deep water. Since 1990, the rise in temperature of the latter has continued in an almost linear manner (Béthoux and Gentili, 1999; Béthoux *et al.*, 1999)..

In the eastern part of the Mediterranean basin, there has been no comparable observation. However, it has recently been remarked that exceptionally cold years (1987, 1992-3) or years with very low rainfall (1989-90 and 1992-3) have had the effect of increasing the salinity (from 38.9 to 39.1) and consequently the density (from 29.2 to over 29.3) of the deep water of the eastern Mediterranean; simultaneously, a new area of formation of deep cold water in the eastern basin has appeared in the Aegean Sea (Lascaratos *et al.*, 1999). It has been advanced that this rise in salinity of the deep Mediterranean water could give rise to an increase in the flow of deep water leaving in Gibraltar and moving northward, with part of the Gulf Stream being diverted towards the Labrador sea (Johnson, 1997). If we bear in mind the current warming value, this theory seems fortunately much exaggerated (Béthoux and Gentili, 1999).

At present we do not have any information on the direct effect of this very small rise in temperature on deep sea Mediterranean fauna. It is true that knowledge on Mediterranean deep benthic population dynamics is very small, really insufficient to show a variation, even significant, of the qualitative or quantitative composition of these populations.

Very clear trends in coastal waters

Until very recently, the existence, for Mediterranean coastal waters between the surface and a hundred metres down, of long sets of hydrological measurements was unknown. Francour *et al.* (1994) were the first to mention an exceptional set acquired by J. Pascual, a volunteer working on the Spanish Catalan coast. This set showed a warming of the north-western Mediterranean that went far beyond what Béthoux *et al.* (1998) had allowed. The warming of the coastal water has been a certainty for the last 30 years (1.4°C at 25 m., Salat and Pascual, 2002; Romano, 2003). To this set were added other contemporary sets of data gathered in the north-western Mediterranean along the coast of Provence (SOMLIT-INSU, of Villefranche-sur-mer set, integrating the vertical dimension (0-80 m.), the Île du Levant Navy set, for surface water only). These three sets were examined in detail as to their consistency, regularity and seasonal representativeness in the context of

the programmes of the French Institute of Biodiversity (Boury-Esnault *et al.*, 2006) and of the MEDCHANGE National Research Agency (coord. J. Garrabou), still ongoing. They all confirm the same trend of a warming of some 1°C over the past 30 years for the north-western Mediterranean coast (Fig. 2). To this already exceptional data is added the historical set of the maregraph of Marseilles from 1884 to 1967 (Romano and Lugrezi, 2007). Some measuring faults have been identified by the authors, but the fact that all this data had been acquired according to the same procedure for 83 years permitted their comparison over time. This comparison reveals a warming trend of some 0.7-0.8°C in 100 years (Fig. 3), i.e. a rate three times lower than that stated in the above-mentioned sets that had been started in the early 1970s.

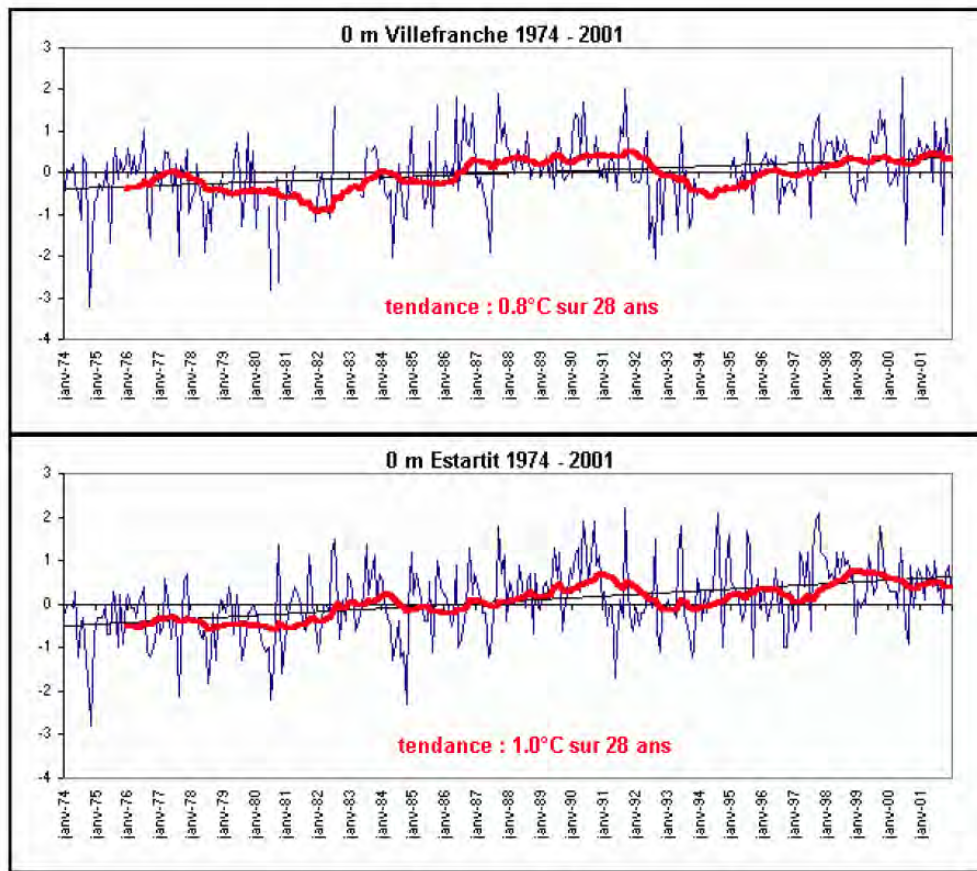


Figure 2: SOMLIT-INSU, Villefranche-sur-mer, set, and Pascual, Estartit, set. Presentation of monthly discrepancies with the pluriannual average (blue) with the sliding average (red) and estimate of a linear trend since 1974 (from Bensoussan and Romano, in Boury-Esnault *et al.*, 2006).

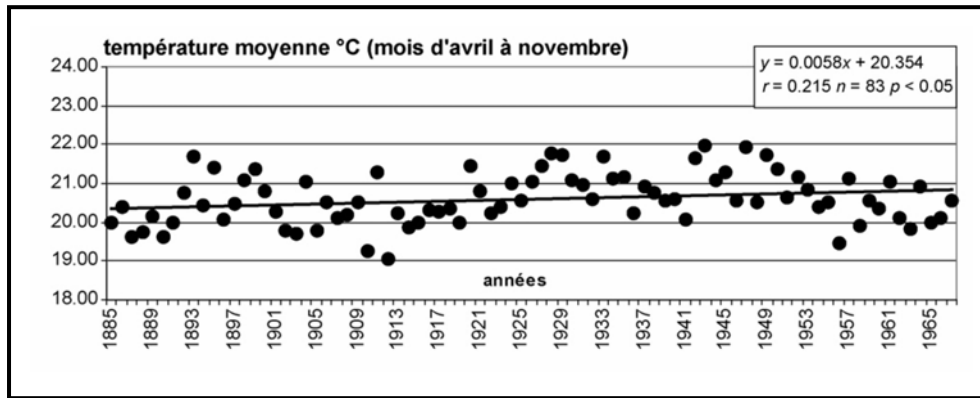


Figure 3 : Average temperatures of the years 1885 to 1967 (calculated over the months from April to November) with positive linear regression over the period as a whole (Romano and Lugrezi, 2007).

Unfortunately, we do not yet have comparable data from the southern or eastern Mediterranean. One can just note the beginning in 1998 of a set on the Lebanese coast (Abboud-Abi *et al.*, 2004) in order to compare over some years the temporal dynamics at the two ends of the Mediterranean (Golfe du Lion and Lebanese shore). At a time when there is increasing observation of northward migrations of species with warm affinities able to replace the temperate species, and when the eastern basin is undergoing the colonization of many biotopes by ‘Lessepsian’ migrants from the Red Sea via the Suez Canal, this kind of comparative study seems, unfortunately, to be too unrepresentative.

Increasingly frequent temperature anomalies

Recent studies have identified a correlation between the North Atlantic Oscillation (particularly positive NAOs*) and climate variability in the north-western Mediterranean (Molinero *et al.*, 2005). As well as the warming trend proven by the few temporal sets exploited, we are also witnessing a trend towards bigger temperature anomalies. This means warmer winters and summers with heatwaves (air and underwater) that are easily perceptible to basic users of the coastal environment, and events also detected using temporal sets such as the Villefranche-sur-mer one (Fig. 4).

In the Mediterranean, the best documented temperature anomaly was that which caused the mass mortality of benthic invertebrates in the Mediterranean (Cerrano *et al.*, 2000; Pérez *et al.*, 2000; Romano *et al.*, 2000). Analysis of the meteorological data of the Marseilles region during the summer of 1999, compared to the average for the dozen previous years (1988-1999), showed that summer 1999 saw a marked drop in the relative frequency of winds from the north-north-west (the *mistral*) between July and October (13-27% instead of 42%) and a drop in the intensity of the gusts (Romano *et al.*, 2000). Furthermore, the

* The North Atlantic Oscillation (NAO) links the intensity of the Iceland depression to that of the Azores high. Its fluctuations have direct consequences on the European, especially western European, climate.

periods of calm were particularly long during the summer of 1999 (125-250 hours per month on average); all these conditions together gave rise to temperature conditions in the water column that had never before been observed. Recordings of sea water temperature made in the bay of Marseilles between the surface and sixty metres down presented, for the summer of 1999, the special feature of a seasonal thermocline that never neared the surface, but in fact plunged progressively down to a depth of 40 metres. At the same time, the temperature of the supra-thermocline water rose to 23-24°C and kept this value for about two months (Fig. 5) (Romano *et al.*, 2000). Autonomous thermographs installed on various parts of the Provençal coast (Pérez *et al.*, 2000) confirmed for the late summer an average temperature 5-6 degrees higher than that of 1998 and 2000 at the same period. Comparable conditions were recorded in Liguria, with a thermocline that in this case plunged to 65 metres (Cerrano *et al.*, 2000). Other accounts of temperature anomaly were received that year from different parts of the Mediterranean (Greece and Tunisia) without their being confirmed by scientific reports.

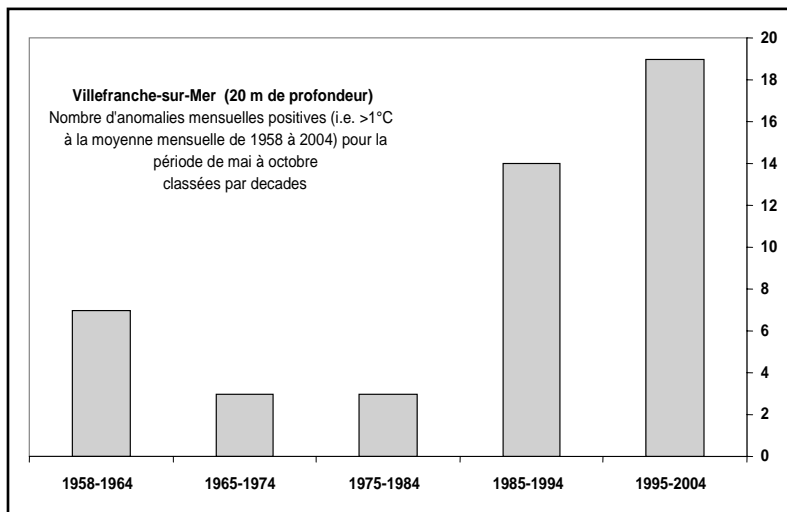


Figure 4: Changes in the number of temperature anomalies found by decade between 1958 and 2004 on the Provence coast (from Bensoussan and Romano, in Boury-Esnault *et al.*, 2006).

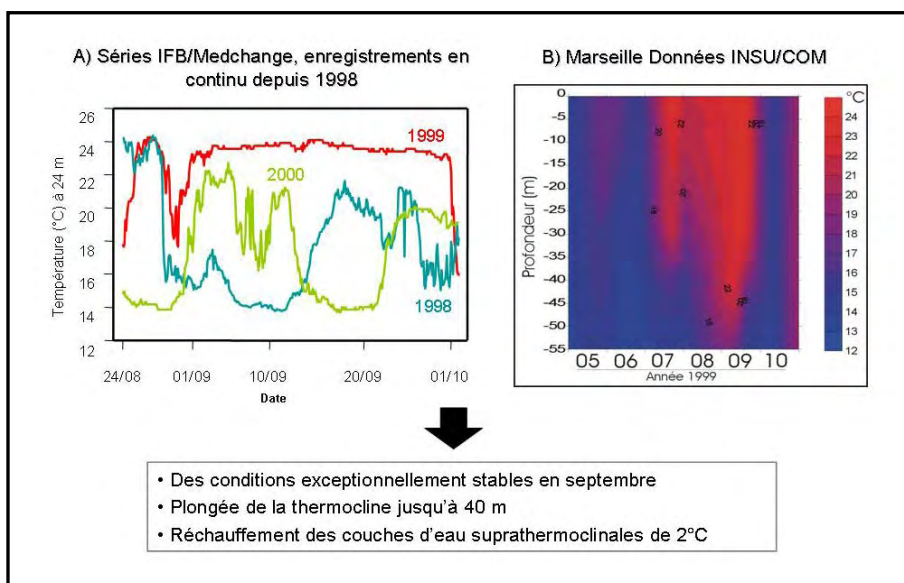


Figure 5: Illustration of the temperature anomaly observed in Provence in late summer 1999 (from Pérez *et al.*, 2000, modified).

The only written account of a comparable phenomenon observed during summer 1999 in the eastern part of the Mediterranean basin comes from a column on Kalymnos sponge fishermen published by a British writer (Warn, 2000).

Since then, another large scale event was recorded in 2003. In this case, the recordings made in six parts of the western Mediterranean (from the Columbretes Islands to Naples), containing the previously-mentioned long-term sets, indicate that the summer of 2003 was the warmest summer in the last thirty years (Marullo and Guarracino, 2003; Harmelin, 2004; Sparnocchia *et al.*, 2006). The temperatures recorded at sea were much higher than those of 1999, but the hot water mass was usually hemmed in at shallow depth (the first 20 metres).

The Mediterranean had experienced comparable phenomena before 1999 and did after 2003. In most cases, these were very local events with little or no effect on the ecosystems. But we are witnessing a rise in the frequency of these events, and it is particularly worrying to see in such a brief period of time a succession of temperature anomalies over ever greater geographical areas.

These events and their ecological consequences have demonstrated the urgent need to obtain reliable sets of temperature data and have led to the setting up of a network of automated temperature recorders (IFB and Medchange programmes) in reference sites for marine biodiversity in the north-western basin (e.g. Port-Cros National Park, the Reserves of Scandola, Cerbères-Banyuls, Cap Creus). It is obvious that this type of easily implemented instrumentation, not very costly and sufficiently reliable to permit the interpretation of ecological phenomena, should be extended to sites in the southern and eastern Mediterranean. Some sites in the Adriatic Sea (Croatia) are already equipped (Bakran-Petricioli, personal comm.)

Other factors linked to climate change that will have consequences for the management of coastal areas

Probable changes in most of the other climate variables remain very uncertain on a local scale, which is obviously the most pertinent for assessing possible ecosystem responses. But there is however a consensus on a certain number of variables which have already caused, or should shortly cause, major effects on the coastal ecosystems (Nicholls and Hoozemansb, 1996).

The first of them is obviously the sea level, which is rising by about 1 mm. per year (Fig. 6), a rise that is small but already threatens the emblematic ecosystems of the Camargue or the Nile delta, for example. The intensity of the rainfall, giving rise to floods and massive entry of earth into the coastal environment, is another factor whose effects on aquatic (and marine) biodiversity have sometimes been measured. Lastly, we are wondering about other variables, whose direction or intensity of change we do not yet know. These, for example, are changes in the currents, the direction and the height of waves, and the frequency of storms, whose effects on the coastal environment we can sometimes very locally measure.

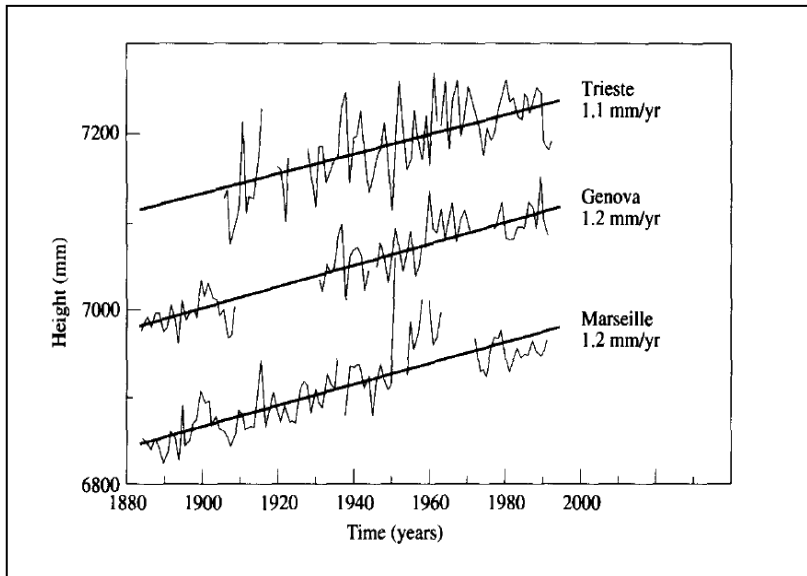


Figure 6: Three sets of data from the western Mediterranean showing the rise in sea level. Data available from the Permanent service for mean sea level (<http://nbi.ac.uk/psmsl/>; Nicholls and Hoozcmans 1996).

BIOLOGICAL CONSEQUENCES OF CLIMATE WARMING IN THE MEDITERRANEAN

A rise in the temperature of the living environment beyond a tolerance limit that varies according to species gives rise to physiological stress; the longer exposure to this temperature lasts, and the nearer the species considered are already to their upper limit of thermotolerance, the more pronounced this is. This stress, if produced regularly, can lead either to changes in the geographical distribution or to modifications of the living cycle and *in situ* adaptation to the new conditions, or lastly, in sessile, or fairly stationary, forms to large-scale mortality accompanied by epizootics and the replacement of the affected species by better armed southern species (Harvell *et al.*, 1999, 2002; Hughes, 2000). These modifications obviously have repercussions on the biodiversity and can markedly modify the aspect of the underwater landscapes.

Visible signs that the Mediterranean is being southernized

In the total absence of long sets of surface water temperature measurements when they started their analysis, Francour *et al.* (1994) chose, to answer the question of a possible rise in the temperature of coastal water, to call on biological warming indicators selected from among plants and animals, i.e. species whose temperature preferences were well-known (thermophilous species, psychrophilous species) (Fig. 7).



Figure 7 : Indicator species of the southernizing of the north-western Mediterranean. A) the ornate wrasse *Thalassoma pavo*; B) the grey trigger fish *Balistes carolinensis*; C) the sea-urchin *Centrostephanus longispinus*; D) the dusky grouper *Epinephelus marginatus*. Photos R. Graille (A), J.G. Harmelin (B) and T. Pérez (C,D)

In this study, these authors considered three geographical areas that have been under regular observation for several decades: the Port-Cros National Park, on the Var coast, the Scandola Nature Reserve, on the western coast of Corsica, and the Golfe du Lion. Among the macrophytes they noticed in Corsica the advance between 1989 and 1992 of two shallows species, *Dasycladus vermicularis* and *Digena simplex*, both absent from the colder parts of the Mediterranean, especially the Golfe du Lion. Conversely, two other species of northern affinity, present up to the British Isles, *Halopitys incurvus* and *Halopteris scoparia* (= *Stypocaulon scoparium*), regressed significantly over the same period (Francour *et al.*, 1994). For invertebrates, these authors particularly mention the case of the Echinodermata. The echinus *Arbacia lixula*, considered as a thermophilous species, saw its density multiplied over tenfold between 1983 and 1992 in Scandola, a nature reserve where fishing is banned on the western coast of Corsica. *Centrostephanus longispinus*, another thermophilous echinus species, long considered as rare in the north-western Mediterranean, has become abundant in Port-Cros and other parts of the Provençal coast. Lastly, the starfish *Ophidiaster ophidianus*, another thermophilous species, was found for the first time in the Scandola Reserve in 1990. For fishes, the examples are even more numerous. The ornate wrasse *Thalassoma pavo*, abundant in the eastern Mediterranean, was considered as rare or even exceptional in the north-western Mediterranean. Its arrival in Scandola dates back to 1988. Since then, its density has risen tenfold, and juveniles were seen for the first time in March 1991. In the Golfe du Lion, the coldest part of the western Mediterranean, the species was observed for the first time in 1990. Today it is thought that its distribution area could have advanced by 1,000 km. Among exploited species, some formerly rare species have become more abundant, while others appear in fishing catch in the north-western Mediterranean. The sea-bream *Diplodus cervinus cervinus* was unknown until 1980; adults and juveniles of this species are commonly found there today. *Pomadasys incisus* has been caught increasingly frequently since 1987. The barracuda *Sphyraena viridensis* is abundant in the three regions studied and is making its appearance on fishmongers' slabs (Fig. 8). The grey trigger fish *Balistes carolinensis* has become very common since 1980 (as on the French Atlantic coast, where it is frequent off Brittany). At the same time as Francour *et al.*, Bianchi and Morri (1993) also gave a list of 20 "southern" species observed for the first time in Liguria. There one can find almost all the species mentioned by Francour *et al.* (1994), but in this case the writers already discuss whether some of them are pertinent as true indicators of Mediterranean warming (Bianchi and Morri, 1993; Astraldi *et al.*, 1995).

Emblem Mediterranean species benefit from the warming trend. The case of the dusky grouper *Epinephelus marginatus* is one of the best examples. This fish, which had long been a favourite target of underwater fishers, had become very rare on the north-western Mediterranean coast in the 1970s. Also, since the rare individuals observed were big (and usually male) it was thought that they had been born and had grown up in the warmer water of the southern Mediterranean. In the late 1980s, some medium-sized (30-40 cm.) dusky groupers started to make their appearance, perhaps coming from North Africa, and gradually the proportion of males to females in dusky grouper populations along the coast

of Provence recovered a balance, enabling (or allowing hope for) reproduction. The warming of the water could have facilitated the development of eggs and juveniles. In the early 1990s, very small groupers were observed in Provence, and then reproduction behaviour was observed on the Spanish Catalan coast (Zabala *et al.*, 1997a and b). Today, reproduction behaviour is often observed in all the Marine Protected Areas of the north-western Mediterranean. Enjoying protection in France from harpoon fishing since 1993, and then from hook fishing, the numbers of dusky groupers are constantly increasing both inside and outside the Marine Protected Areas, and very little individuals are regularly observed, indicating with almost total certainty that the species is reproducing in the north-western Mediterranean (Grouper Study Group Observations; Harmelin and Robert, 2001; Bodilis *et al.*, 2003).

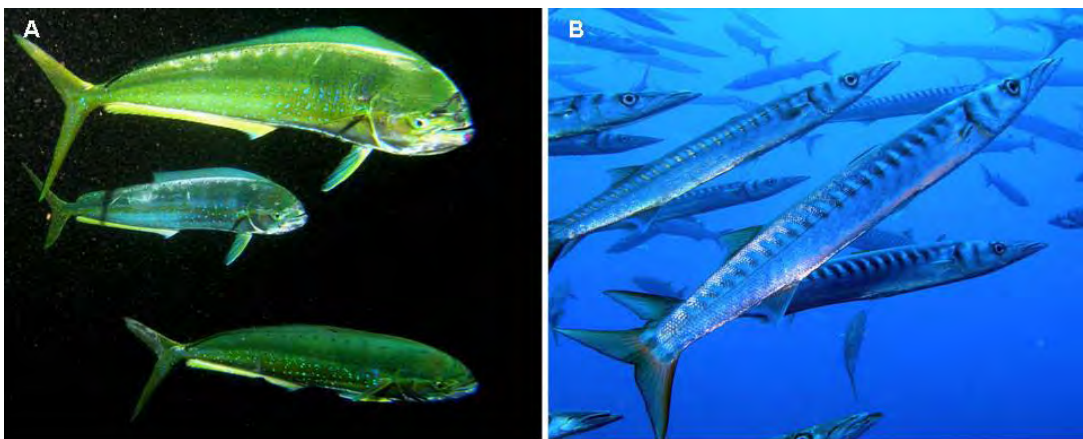


Figure 8 : Southern-origin (even tropical - A) fishes that have made their appearance on the fishmongers' slabs of the north-western Mediterranean: A) *Coryphaena hippurus*; B) *Sphvraena viridensis* (Photos by T. Pérez).

For these very mobile species, short-term modifications of the ichthyological populations reflect in almost real time, in any case on the scale of one generation, changes in hydrological conditions (Garrabou *et al.*, 2003). According to Stephens *et al.* (1988), temperature is the most important variable explaining the changes in geographical distribution. On the French coasts, the northwards advance of southern forms has followed the usual model: firstly there is the immigration of a small number of adult animals, the first sign of a change in physicochemical conditions, and secondly reproduction happens there and juveniles are observed (the case of the ornate wrasse *T. pavo* or the barracuda *S. viridensis*). In 2003, after a survey done by Garrabou *et al.*, the arrival or increased abundance of thermophilous species in the north-western Mediterranean (Fig. 9) and/or the disappearance or reduced abundance of “cold” species, was shown. In all, 46 significant changes of distribution were noted, over 50% of which concerned fishes and over 2/3 of which very mobile species (Garrabou *et al.*, 2003). This information was obtained from a review of the literature, including technical reports, and through information provided by various Mediterranean marine laboratories. Mostly these were species that were easy to identify (fishes, macroinvertebrates and macrophytes), which ensured the reliability of the

information. Today, this information even comes from “non-professional” users of the marine environment, like anglers or divers. Among today’s happy encounters, the coryphene *Coryphaena hippurus* (Fig. 8), basically tropical or subtropical, used to be extremely rare in the north of the basin, whereas it could be caught by specialist fishermen in the south (Tunisia, Libya). Today it is caught fairly frequently by fishermen in the north-western Mediterranean and is found on fishmongers’ slabs.

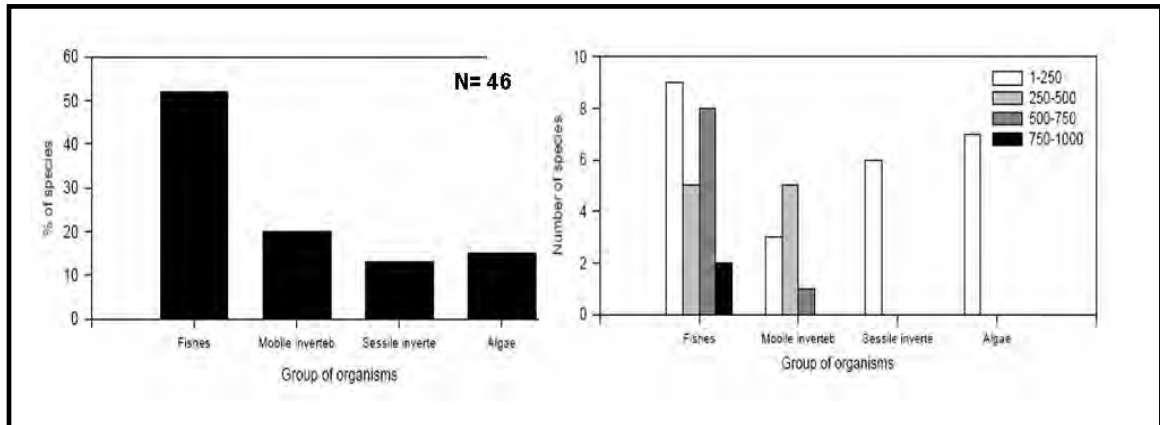


Figure 9: Assessment of movements of southern species towards the north-western basin of the Mediterranean, spatial scale (in km.) of the northward advance (Boury-Esnault *et al.*, 2006).

Very recently, Sabates *et al.* (2006) showed with supporting figures how the warming of the western basin could favour a fishing ground. This work dealt with the analysis of spatio-temporal data (4 zones along the Spanish coast; 50 years) on the abundance and distribution of the round sardinella *Sardinella aurita* when related to temperature variations. Firstly, they established a positive relationship between catch of *Sardinella* and air temperature anomalies (Fig. 10). The writers also showed a relationship between the slow warming of the water along the Spanish coast, the northward advance of this species, and very successful reproduction.

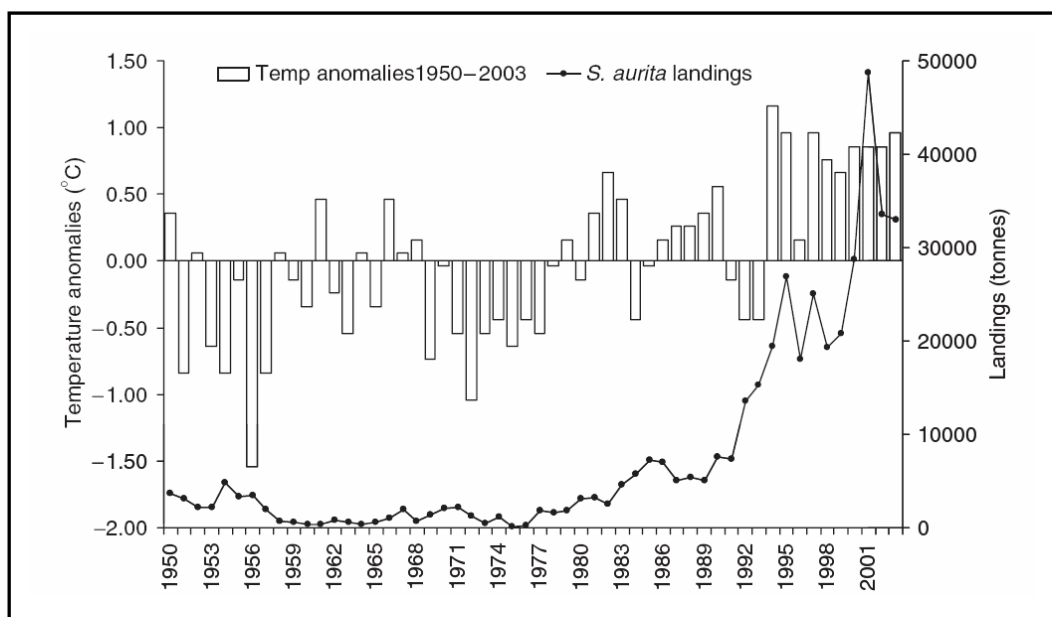


Figure 10: Relationship between yearly catches of round sardinella in the western Mediterranean and air temperature anomalies between 1950 and 2003 (Sabates *et al.*, 2006).

The most spectacular result was the explanation of the variability of annual catch of sardinellas by the average surface water temperature in the April of the previous year (Fig. 11), thus offering prospects of predicting the quality of fishing one year in advance.

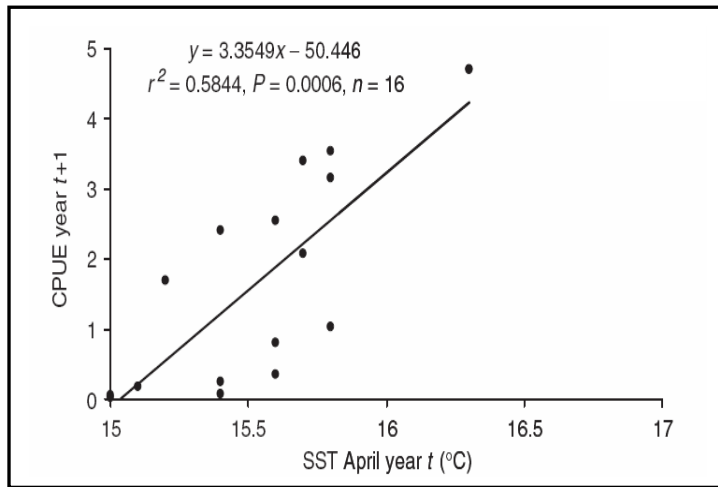


Figure 11: Linear relationship between average sea surface temperatures (SST) in April (year t) and catch of *Sardinella* per fishing unit the following year (year t+1) (Sabates *et al.*, 2006).

Unfortunately, such “positive” results of the warming for fisheries can be somewhat offset by the disappearance of northern forms. For example, the sprat *Sprattus sprattus*, which used to abound in the Golfe du Lion, has become very rare, although it was not particularly sought after by commercial fishermen (Francour *et al.*, 1994). The Adriatic, known for its stocks of small pelagics, also experienced a major decline in sprat stocks between 1992 and 1995 (Bombace, 2001). In the 1980s, in a period of positive NAOs, anchovy stocks dropped considerably, from a biomass peak of 640,000 tonnes in 1978 to about 16,000 tonnes in 1987. According to Bombace, the collapse of this fishing cannot be linked to overfishing but rather to changes in the trophic network, and, especially, hydroclimatic conditions (Salat, 1996) that may have affected the survival rate of anchovy eggs and larvae.

In some cases, the effects on fisheries can result in changes in the life cycle. This phenomenon particularly concerns species that used to migrate in the autumn to their winter habitats but today stay longer in the northern and central Mediterranean (Bombace, 2001). This is the case, for example, of the amberjack *Seriola dumerlii*, whose winter quarters are usually in the southern Mediterranean, with a northward migration in the summer. Today, it happens increasingly frequently that this big pelagic remains until the winter in the northern basin. Similarly, the tuna *Thunnus thynnus*, a migrant from the Atlantic, today remains an increasingly long time in the north and the centre of the Adriatic Sea, thus offering itself to local fisheries over longer periods (Bombace, 2001).

Certain hemmed in biotopes also witness the replacement of species. The underwater cave communities, with their endemic, specialist species, are particularly threatened, for they are naturally fragmented and more sensitive to disturbance. The best documented example concerns two mysidacean crustaceans dependent on the dark underwater Mediterranean caves, both belonging to the *Hemimysis* genus (Chevaldonné and Lejeune, 2003). In the

Marseilles region, *Hemimysis speluncola*, described in 1963, has long been the dominant, even unique, species in the dark caves where it formed vast swarms up to the 1990s. A precise monitoring of mycidacean populations has allowed us to see the rapid disappearance of *H. speluncola* between 1997 and 1999, and the installation in the now vacant ecological niche of *H. margalefi* (Fig. 12). Exploration of the many caves in the Marseilles region between 1999 and 2002 showed that all of them except one were then exclusively inhabited by *H. margalefi*. The single exception was a cave near La Ciotat, the “3PPs”, which presents special geomorphological features that enable cold water to be trapped all year round at the bottom of the cave. On a Mediterranean scale, the geographical distribution of *H. speluncola* confirms that this is a species with cold affinity, while *H. margalefi* has been described in the Balearics and found in Malta. In Marseilles, the replacement of one species by the other happened between January 1997 and May 1998, these two dates being just before and after the first major summer anomaly observed in the Marseilles region, in summer 1997. The mass, but not total, mortality of *H. speluncola* probably happened during this event; then, two years later, the September 1999 anomaly (Pérez *et al.*, 2000; Romano *et al.*, 2000), more intense and longer lasting, probably finished off the extinction of the residual *H. speluncola* populations, except, of course, the inhabitants of the “3PPs” cave (Chevaldonné and Lejeusne, 2003). Ecophysiological experimenting has shown that the lethal temperature is probably 3°C different for the two species (Fig. 12), thus enabling us to confirm the hypothesis of a species replacement sparked off by the warming of the north-western Mediterranean (Chevaldonné and Lejeusne, 2003).

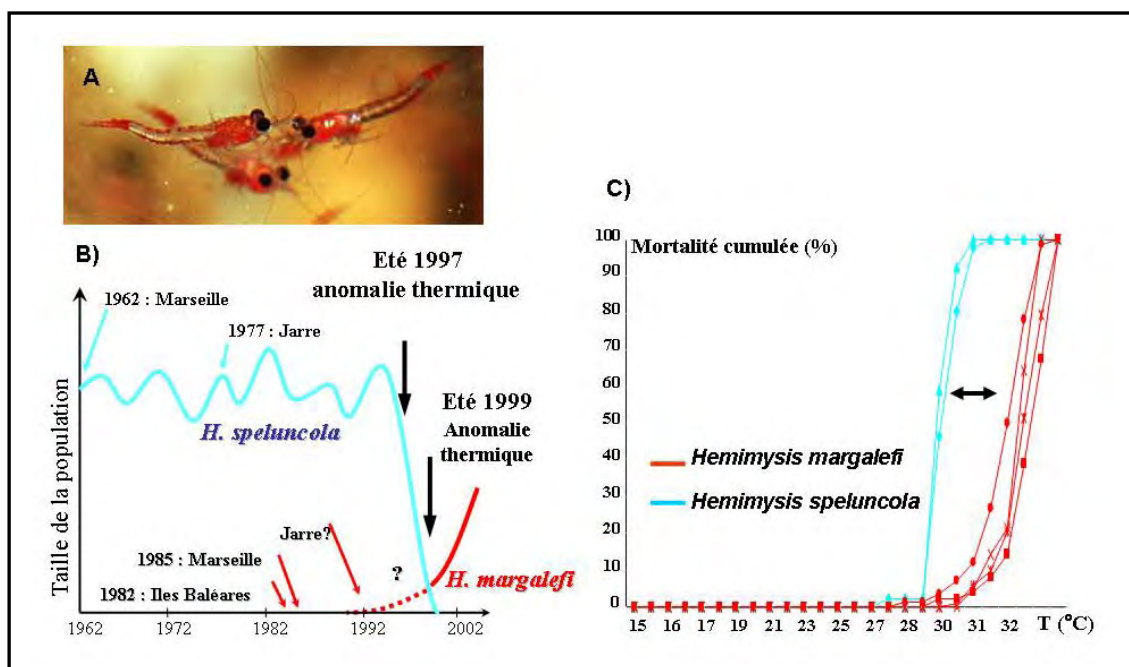


Figure 12: A) *Hemimysis margalefi*, a species that has become dominant in most of the dark Mediterranean caves after the local extinctions of *H. speluncola*. The latter is now only present in cold water caves. B) Illustration of population fluctuations in the Marseilles caves related to the temperature anomalies of the late 1990s. C) Comparative thermotolerance experiments (from Chevaldonné and Lejeusne, 2003, modified). Photo by R. Graille.

The environmental conditions found there mean that the populations of the underwater caves share many faunistic elements with deep Mediterranean ecosystems, to the extent that these are often seen as mesocosms of the great depths (for a review, see for example Harmelin and Vacelet, 1997). There exist there in particular some biological rarities, like the sponges *Asbestopluma hypogea* and *Oopsacas minuta*, which are strict stenotherms. Although the environmental gradients are very marked in this habitat, there is room to fear that even a “buffered” warming will cause irreversible harm for species the sightings of which can sometimes be counted on the fingers of one hand.

All the changes presented above basically concern the western Mediterranean, and usually the northern part of this basin. These floristic and faunistic changes cannot be explained by changes in sampling techniques or by local ecological mechanisms (inter- and intra-species competition, recruitment variations, epizootics); in fact, such hypotheses are incompatible with the long-term trend of northward advance.

One may suppose that the Adriatic Sea, which presents a very marked temperature gradient from the south (warm) to the north (cold), is experiencing the same kind of change as the north-western Mediterranean. Over the past fifteen years, a certain number of fishes have been newly sighted in the Adriatic (Lipej and Dulcic, 2001). The new sightings are mostly of thermophilous species, also mostly sighted in the north-western Mediterranean. Among the 417 species of fish listed by Lipej and Dulcic there are also some Lessepsian species.

In Bianchi and Morri’s (1993) list of species considered to be indicators of Mediterranean warming, Grubelic *et al.* (2004) took a particular interest in the status of the coral *Astroides calycularis* (Fig. 13) in the Adriatic. This emblem species of the south-western Mediterranean, the Sea of Alboran and the Strait of Gibraltar is recognized as being fairly thermophilous, but with a relatively narrow range of thermotolerance. Despite this status of thermophilous species, Bianchi and Morri (1994) considered with caution the pertinence of this long-living coral as an indicator, since it is not possible to date the species’s arrival in a new area solely by observing one colony. Nevertheless, after the sighting of three new colonies between 1990 and 2001, plus some old observations, Grubelic *et al.* noticed that the occurrence of *A. calycularis* in the Adriatic was correlated with rises in temperature of the surface water, even advancing a hypothetical relationship with the NAO index. It is true that by positioning the various sightings of this species over a record of air temperatures in the Adriatic from 1840 to 2000, one can see that all the sightings of the “orange coral” coincide with the hottest periods (Fig. 13).

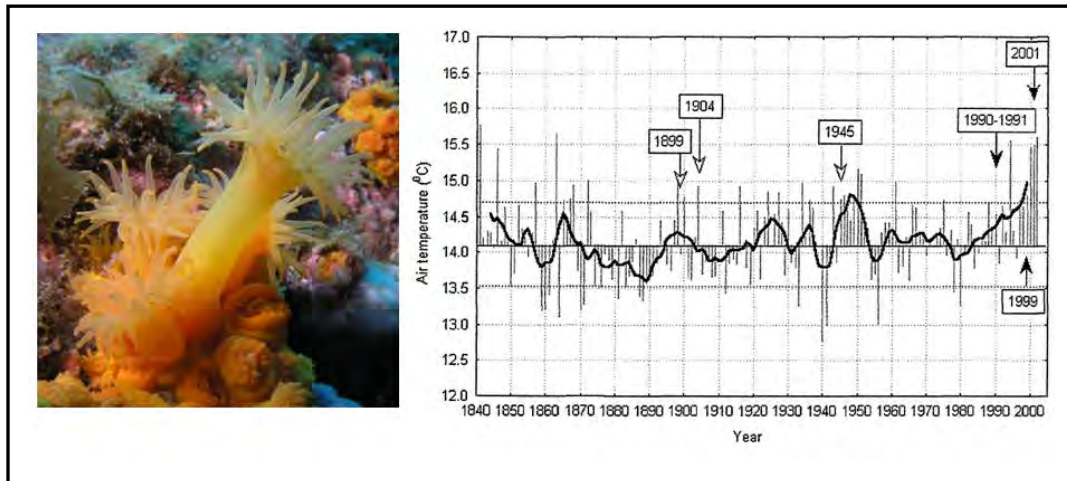


Figure 13 : The orange coral *Astroides calycularis*, basically distributed around the south of the western Mediterranean basin and known to be a thermophilous species. Various sightings of the coral are marked on a curve representing annual averages of air temperatures in the Adriatic region (Trieste) (Grubelic *et al.*, 2004). Photo by T. Pérez.

A mere coincidence or an established relationship? Grubelic's conclusions were certainly made rather quickly, but for Ocaña (2005), *A. calycularis*'s response to warming should not be surprising, given the species's history in classical Tethys and its relationship with the Indo-Pacific genus *Tubastrea*. In 2007, this same author reports the entrance into the Mediterranean through the Strait of Gibraltar of an antipatharia *Antipathella wollastoni*, a species typical of the fauna of the Macronesian islands with clearly established tropical affinities, and again discusses the potential influence of climate fluctuations.

We do not have such precise information in the case of the eastern Mediterranean basin, though we readily accept that its flora and fauna are being "tropicalized" with the permanent introduction of species from the Indian Ocean through the Suez Canal, either actively or passively on hulls of ships or carried in ballast water. The westward and northward advance of Lessepsian migrants cannot be denied.

Warming of the Mediterranean and biological invasions

Biological invasions are often thought to be an element of global change (cf. the definition by the French Institute of Biodiversity) since they affect biodiversity and are often linked to climate change and other environmental disturbance (Bianchi, 1997; Occhipinti-Ambrogi and Savini, 2003). The eastern Mediterranean is open to many biological invasions by exotic species because of its position between the Atlantic and the Red Sea, intense maritime traffic, and the lagoons and bays that contain quantities of fish farms. And yet most of the invasions have resulted from the opening of the Suez Canal in 1869, which enabled species from the Red Sea and the Indo-Pacific (Galil and Zenetos, 2002) to enter the Mediterranean. Thus macrophytes, invertebrates and exotic fishes have today become common in the habitats of the eastern Mediterranean. Even if the trend to increased cases of introduction into the Mediterranean seems unlikely to be linked to climate warming

(Verlaque and Boudouresque, 2004), it is highly probable that the advance of Lessepsian species (like those from the subtropical Atlantic) is encouraged by the rise in the temperature of the marine water (Occhipinti-Ambrogi, 2007). For example, Galil (2007) explains that the sudden growth of *Saurida undosquamis* Brushtooth lizardfish populations and of the Indo-Pacific Goldband goatfish *Upeneus moluccensis* is the result of a rise in temperature of 1-1.5°C during the months of the winter of 1955. According to Galil and Zenetos (2002), the process of colonization of the eastern Mediterranean by Lessepsian species, and their expansion westward, has considerably speeded up over the past 15 years, due to the warming effect. This being so, in the absence of systematic monitoring and of sets of temperature records in this basin, these accounts can be considered as too subjective.

There are cases of introduction, more discreet but no less worrying for Mediterranean biodiversity and the human actions it underpins. The modification of the phytoplankton communities in the Atlantic is fairly well documented, with, for example, at least 16 exotic species that have become common over the past century, among which are the particularly thermophilous species installed up to the North Sea (Elbrächter, 1999; Nehring, 1998). This being so, very little is known about the changes that affect phytoplankton in the Mediterranean. Planktonic dinophyta have been paid particular attention in that many species produce biotoxins likely to cause paralytic syndromes or PSP*. Gómez gives two concrete examples of the advance of exotic dinophyta in the northern Mediterranean. In 1999, Gómez recorded the advance in the Mediterranean of the exotic dinophyta *Gymnodinium catenatum*. This toxic species, until then confined to the Sea of Alboran, was seen for the first time in Algeria in September, then, carried by the current along the southern shore of the Mediterranean, it ended up by reaching the northern basin via the Italian coast (Gómez, 2003). This exotic species, used to eutrophic water but with a great capacity of trophic adaptation, even appears to be dominant in the subsurface in some sectors with low salinity. Its geographical expansion is not only worrying because of its toxicity but because its presence has been associated with recent changes in the structure of the Mediterranean pelagic trophic chains. If there does exist a link with climate change, it is certainly indirect, and, according to the author, its advance is more certainly due to the modifications in nutrient content than to the warming of the surface water. With another case of dinophyta introduction, the same author is far less hesitant regarding the link with warming in the Mediterranean (Gómez and Claustre, 2003). In this case again, there are two thermophilous species originally from the Indian Ocean, *Asterodinium* (*A. gracile* and *A. libanum*), sighted for the first time in the Ligurian Sea and in the Tyrrhenian Sea during the 1999 temperature anomaly, and that the authors even propose as bioindicators of the warming of the north-western Mediterranean (Gómez and Claustre, 2003).

* Paralytic Shellfish Poisoning.

Among the ecological phenomena that are increasingly frequently mentioned we should also mention the case of the proliferation of mucilaginous aggregates regularly reported in the Tyrrhenian Sea and the Adriatic over the last twenty years. The origin of these phenomena differs according to the basin considered. In the eutrophic water of the Adriatic, these mucilages are produced by phytoplanktonic bloom, mainly of diatoms and dinophyta caused by sudden variations in the flow of the Po and nutriment content (for a review see, for example, Degobbis *et al.*, 2000). In the more oligotrophic Tyrrhenian Sea it is the proliferation of a contingent of filamentary algae (mainly *Nematochryopsis marina*, *Chrysonephos lewisii* and *Acinetospora crinita*), able to develop at depth (under the thermocline) that is reported in most cases, the trigger usually remaining a mystery. Whatever the origin, by accumulating on the seabed these mucilages have harmful effects on the benthic populations (Fig. 14).

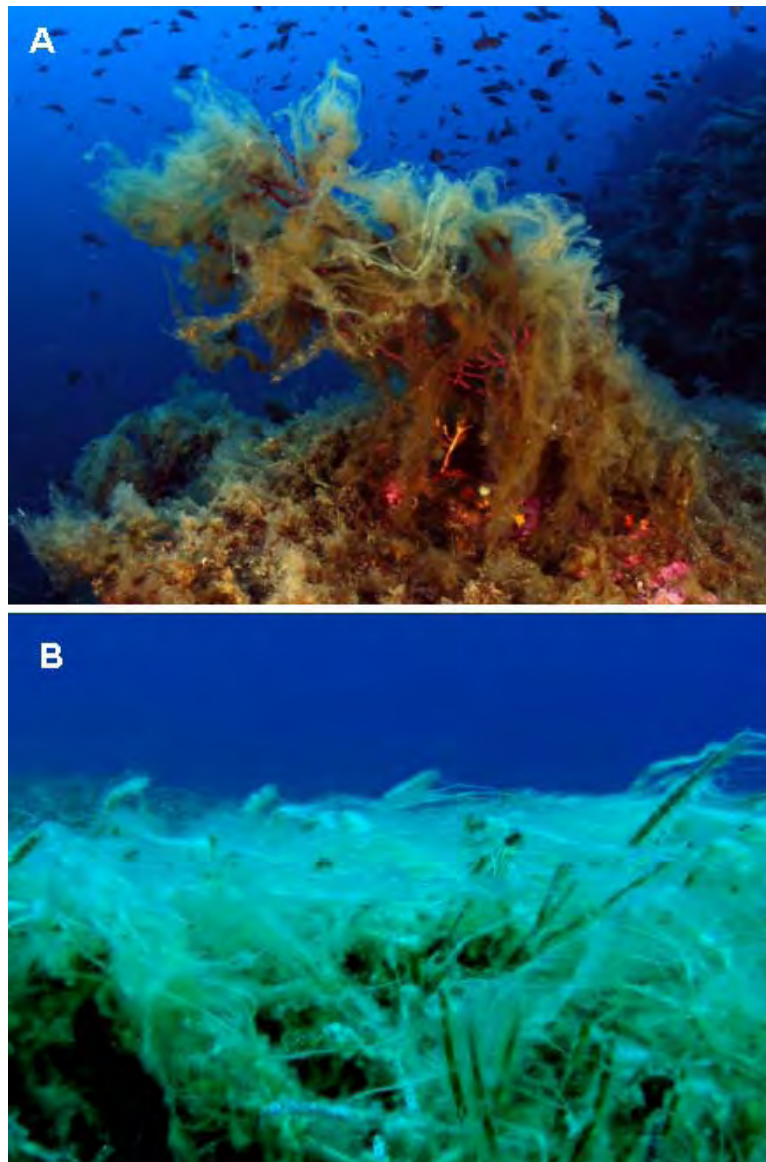


Figure 14: Proliferation of filamentary algae on the seabed in the north-western Mediterranean. Here, two events observed in the water of Port-Cros National Park in 2003 (A) and in 2007 (B). The mucilages covered the epigaeal fauna in the coralligenous droops (A) and the Posidonia meadows (B). Photo by R. Graille (A) and T. Pérez (B).

In the communities of the loose substrata, these phenomena can cause anoxia, and thus the suffocation of the epigaeal fauna (see, for example, Rinaldi *et al.*, 1995), and in the communities of the hard substrata, the accumulation of mucilages can be responsible for the whitening, necrosis or even mass mortality of sessile organisms such as sponges, scleractinian and gorgonians (see, for example, Giuliani *et al.*, 2005). Recently, Schiaparelli *et al.* (2007) have for the first time advanced the hypothesis of a correlation between these proliferations and climate anomaly. In this study, the authors present a bloom of exceptional magnitude during the 2003 summer heatwave, widely agreed to be the hottest event in the last 500 years (Luterbacher *et al.*, 2004). The maximum development of mucilages described by Schiaparelli *et al.* (2007) and the first signs of the effects on benthic organisms were recorded during the heatwave, at a time when even the temperature of the water in the first fifteen metres was clearly higher than the seasonal average (about 27°C). However, it should be noticed that at the start of the event, the temperature in the water column was only a little higher than the seasonal average, which does not allow us to definitively decide which factor triggered the proliferation of filamentary algae. Moreover, we also know that a temperature anomaly can “apparently by itself” have catastrophic effects on the benthic organisms.

EXTREME CLIMATE EVENTS AND MARINE EPIZOOTICS

Necrosis and mass mortality

Extreme climate events can be experienced as acute stress that disturbs the normal functioning of a biological system. Each species presents a “natural” interval of heat tolerance and responds to variations in temperature by physiological, biochemical and molecular behavioural adjustments. Physiological stresses leading to mass mortality and diseases appear when the tolerance thresholds are exceeded and when flight to more tolerable living conditions is impossible. Sessile species are thus particularly affected by these phenomena, which, of course, have repercussions on biodiversity, and when the victims are epigeal, can modify the appearance of the underwater landscape.

Heat stress is today widely recognised as the main factor in triggering diseases at sea, with the frequency of these events having a visible tendency to increase (Peters, 1993; Harvell *et al.*, 1999, 2002). In the Mediterranean, 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 (Fig. 15)

The groups affected are mostly sponges and cnidaria, then bryozoa, molluscs and tunicates (Table I). Among the most often affected species are a high proportion of Mediterranean endemics, some species of great commercial value (*Corallium rubrum*, *Spongia* spp., and *Hippospongia communis*), and the basic elements of the ecosystems that can in some cases structure the landscapes (gorgonians) (Fig. 16).

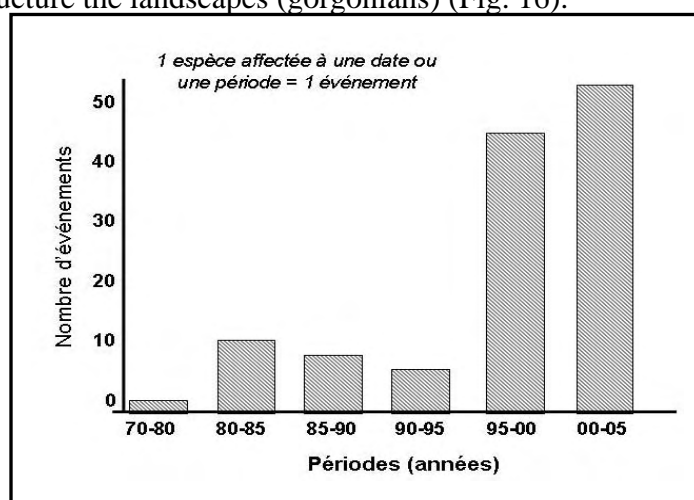


Figure 15: Rising trend of frequency of cases of mass disease and mortality. With a few rare exceptions, these events all coincided with a period of abnormal warming of the water masses (Boury-Esnault *et al.*, 2006).

Over thirty years ago Weinberg (1975) attributed the mortality of the white gorgonia *Eunicella singularis*, in Banyuls-sur-mer, to an extremely high temperature (over 24°C above the thermocline in the summer of 1973). Later, the 1980s saw the first epizootic on a Mediterranean scale, devastating stocks of commercial sponges for several years (Vacelet, 1990, 1991, 1994; Ben Mustapha and Vacelet, 1991; Gaino *et al.*, 1992). According to fishermen, the first signs of this disease happened in 1986 during a particularly hot dry summer, but the epizootic lasted for several years. The incidence and virulence of this disease appeared to be linked to warming, in that sponges in the coldest parts of the Mediterranean and below 40 metres down were much less affected (Vacelet, 1990;

Vacelet, 1994). This explanation was also invoked, among other possible causes, to explain a major mortality episode (between 33 and 41% of the colonies, according to the site prospected) of the big gorgonia *Paramuricea clavata* that had happened before summer 1992 in Port-Cros National Park (Harmelin and Marinopoulos, 1994). These writers have from then on advanced the hypothesis that this gorgonian becomes more vulnerable with temperature, as well as other natural or human-induced causes. These various cases of mortality prefigured the other events, of greater extent, that were to happen in the late 1990s and then be repeated in the 2000s.

Table I: Fixed invertebrates whose mass disease and mortality have been the subject of scientific reports over the past 30 years (“<” events before 1999 and “>” events after 2003).

	<	1999	2003	>
Sponge				
<i>Agelas oroides</i>			X	x
<i>Aplysina cavernicola</i>		x		
<i>Cacospongia mollior</i>		X	x	
<i>Cacospongia scalaris</i>	X	X	x	
<i>Clathrina clathrus</i>		x		
<i>Crambe crambe</i>			x	
<i>Hippospongia communis</i>	X	X	x	
<i>Ircinia dendroides</i>	x	X	x	
<i>Ircinia oros</i>	x	X	X	
<i>Ircinia variabilis</i>	x	X	X	x
<i>Petrosia ficiformis</i>			x	x
<i>Sarcotragus muscarum</i>	x	X		
<i>Spongia officinalis</i>	X	X	X	x
Cnidaria				
<i>Balanophyllia italica</i>			x	
<i>Cladocora caespitosa</i>		X	x	x
<i>Corallium rubrum</i>	X	X	X	x
<i>Eunicella cavolinii</i>	x	X	X	x
<i>Eunicella singularis</i>	X	X	X	x
<i>Eunicella verrucosa</i>		x	x	
<i>Leptogorgia sarmentosa</i>		x	x	
<i>Oculina patagonica</i>	x	x		
<i>Paramuricea clavata</i>	X	X	X	x
<i>Parazoanthus axinellae</i>			x	x
Bryozoa				
<i>Adeonella calvati</i>		x		
<i>Myriapora truncata</i>		X	x	
<i>Pentapora fascialis</i>		X	x	
<i>Reteporella</i> spp.			x	
<i>Turbicellepora avicularis</i>		x		
Bivalve molluscs				
<i>Arca</i> spp.		X	x	
<i>Lima lima</i>		X	x	
<i>Lithophaga lithophaga</i>			x	
<i>Neopycnodonte cochlear</i>		X		
<i>Ostrea edulis</i>			x	
<i>Spondylus gaederopus</i>	X		x	
Tunicates				
<i>Halocynthia papillosa</i>		x		
<i>Microcosmus</i> sp.		X		
<i>Pyura dura</i>		X		



Figure 16 : Benthic invertebrates affected by repeated climate anomalies in the Mediterranean. A) The gorgonians *Eunicella singularis* (left) and *Paramuricea clavata* (right); B) the red coral *Corallium rubrum*; C) the zoantharian *Parazoanthus axinellae*; D) the scleractinia *Cladocora caespitosa*; E) the bryozoa *Pentapora fascialis*; F and G) the commercial sponges *Spongia officinalis* and *S. agaricina*; H) *Agelas oroides*. Photos by T. Pérez.

The best documented mortality events were those of summer 1999 and 2003. These two events affected at least thirty invertebrate species of the hard substratum over several hundred kilometres of coastline between France and Italy, and some places in Spain (Cerrano *et al.*, 2000; Pérez *et al.*, 2000; Rodolfo-Metalpa *et al.*, 2000; Garrabou *et al.*, 2001; Coma *et al.*, 2004; Cerrano *et al.*, 2005; Linares *et al.*, 2005; Cerrano *et al.*, 2006; Coma *et al.*, 2006; and unpublished data) after positive temperature anomalies. The organisms mainly affected were the same in 1999 and in 2003. The sponges, including bath sponges, and the gorgonians, including the red coral, were the taxonomical groups most impacted. The scleractinia were also victims of repeated whitening (Rodolfo-Metalpa *et al.*, 2000, 2005). The zoantharian *Parazoanthus axinellae*, and several species of bryozoa, molluscs and ascidians were also among the victims (Fig. 17).

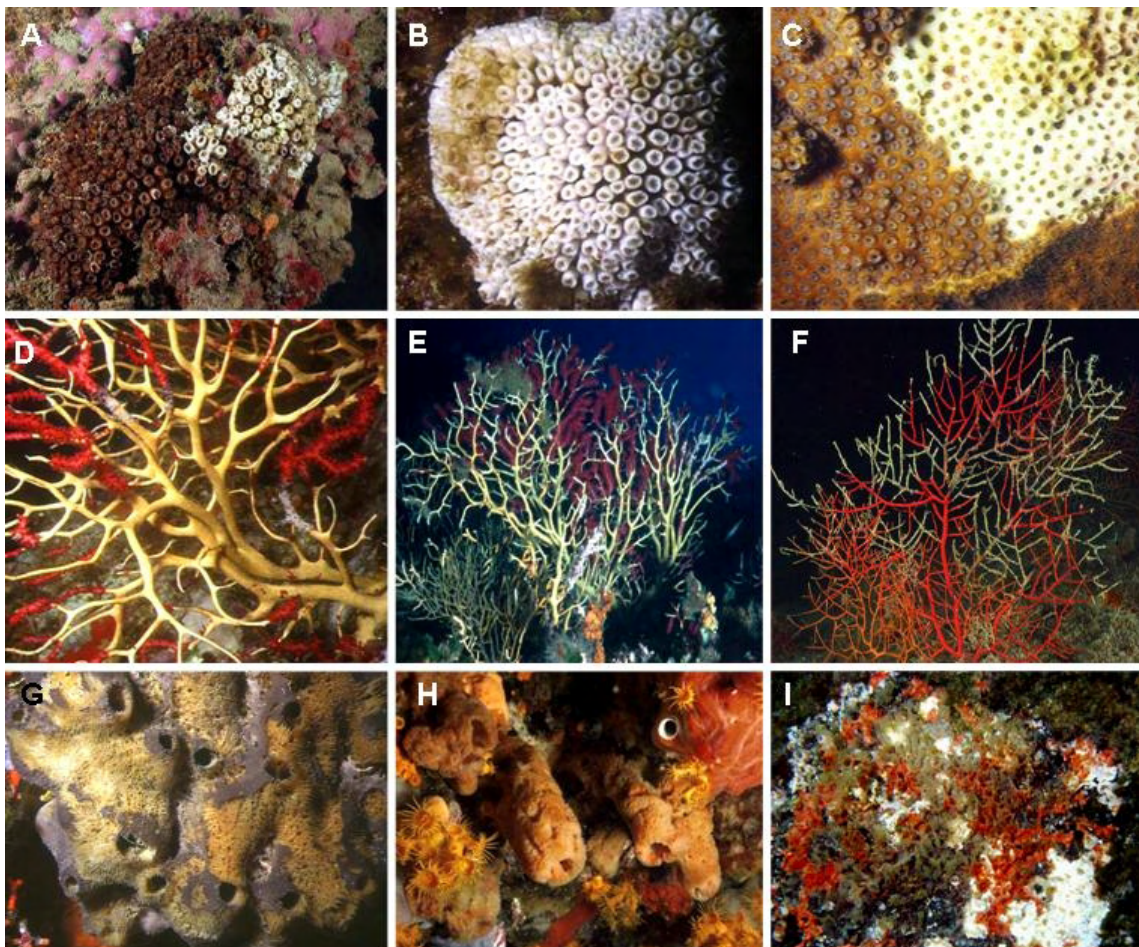


Figure 17: Signs of disease and mortality. Partial (A, C) and total (B) whitening of the scleractinian *Cladocora caespitosa* (A, B) and *Oculina patagonica*; necrosis of *Paramuricea clavata* gorgonians in the first hours (D) and some weeks after the start of the disease (E), *Leptogorgia sarmentosa* (F); necrosis of the bathing sponge *Spongia officinalis* (G), skeletons of the sponges *Agelas oroides* (H) and *Crambe crambe* (I). Photos by R. Graille (A,F). J. Harmelin (B. D. E. G. I). and T. Pérez (C. H).

Examination of the various hypotheses offered to explain these catastrophic mortalities over such a very extensive area quickly enabled the theory of accidental pollution or a single pathogenic agent to be eliminated. Indeed, no proof of a series of synchronous epizootics affecting thirty or so species belonging to different branches had been found until then. However, analysis of the meteorological data and sea water temperature recordings done in Provence enabled in both cases exceptional temperature anomalies to be noticed (Fig. 5; Pérez *et al.*, 2000; Romano *et al.*, 2000; Boury-Esnault *et al.*, 2006). However, great variability of the incidence and virulence of the phenomenon was observed according to site, geographical area and depth. In both cases a good correlation was shown between death rate and duration of exposure to the heat stress (Pérez, 2001; Bonhomme *et al.*, 2003; Boury-Esnault *et al.*, 2006; Bianchimani, 2006). The temperature thus acts by the combination of its high value and the duration of the organisms' exposure. Both characteristics must be taken into account. If one compares the two last mortality events in the north-western Mediterranean, it is especially worrying that the last one hit several new species and extended to new geographical areas (Corsica and Spain). Furthermore, the 1999 event already followed a mortality of gorgonians and some sponges observed in 1997 in the Provençal region (unpublished observations).

Fairly little information has been published outside the north-western basin. On the Tunisian coast, Ben Mustapha and El Abed (2000) have reported cases of mass mortality of gorgonians of the *Eunicella* genus and sponges in summer 1999, linked here again to a temperature anomaly and the plunging of the thermocline to over 60 metres down, as factors triggering this event. The white gorgonian *E. singularis* appears to be the most severely affected species in the Cap Bon and Tabarka regions, with sponges seeming to be less affected. Nevertheless, as in the northern Mediterranean, this impact was seen to be extremely variable, with dense gorgonian populations left totally untouched, sometimes very near to the affected stations (Ben Mustapha and El Abed, 2000). In 2003, only the mortality of sponges (essentially Dictyoceratidae) was noted in southern Tunisia, a phenomenon that in fact persisted until 2006 but more moderately (Ben Mustapha, personal comm.). In the Aegean Sea, no scientific information has been published despite many accounts by local scientists and sponge fishermen (Castritsi-Catharios, personal comm.), and some lines in a work by Warn (2000) on sponge fishing in Kalymnos, which however do seem to indicate a very virulent event.

Since these two large-scale events, some often very localized “replicas” have been observed every year, except in 2004, in the north-western Mediterranean. Each time the organisms affected are the same. The repeated nature of these events has given rise to major landscape changes (Fig. 18) and could thus bring about important changes in biodiversity as we know it today, which will not be without its effect on the economic activities that depend on it (fishing and tourism especially). The eastern basin of the Mediterranean where the heat regime is much higher gives a picture of what in the long term the seabed of the north-western coast could become. Indeed, in the warmest parts of the Mediterranean, species those are sensitive to warming are usually absent or distributed in cooler water at depth. These mass mortality events should thus help on the process of

southernizing the Mediterranean, with the migration of thermophilous species and the advance of Lessepsians.

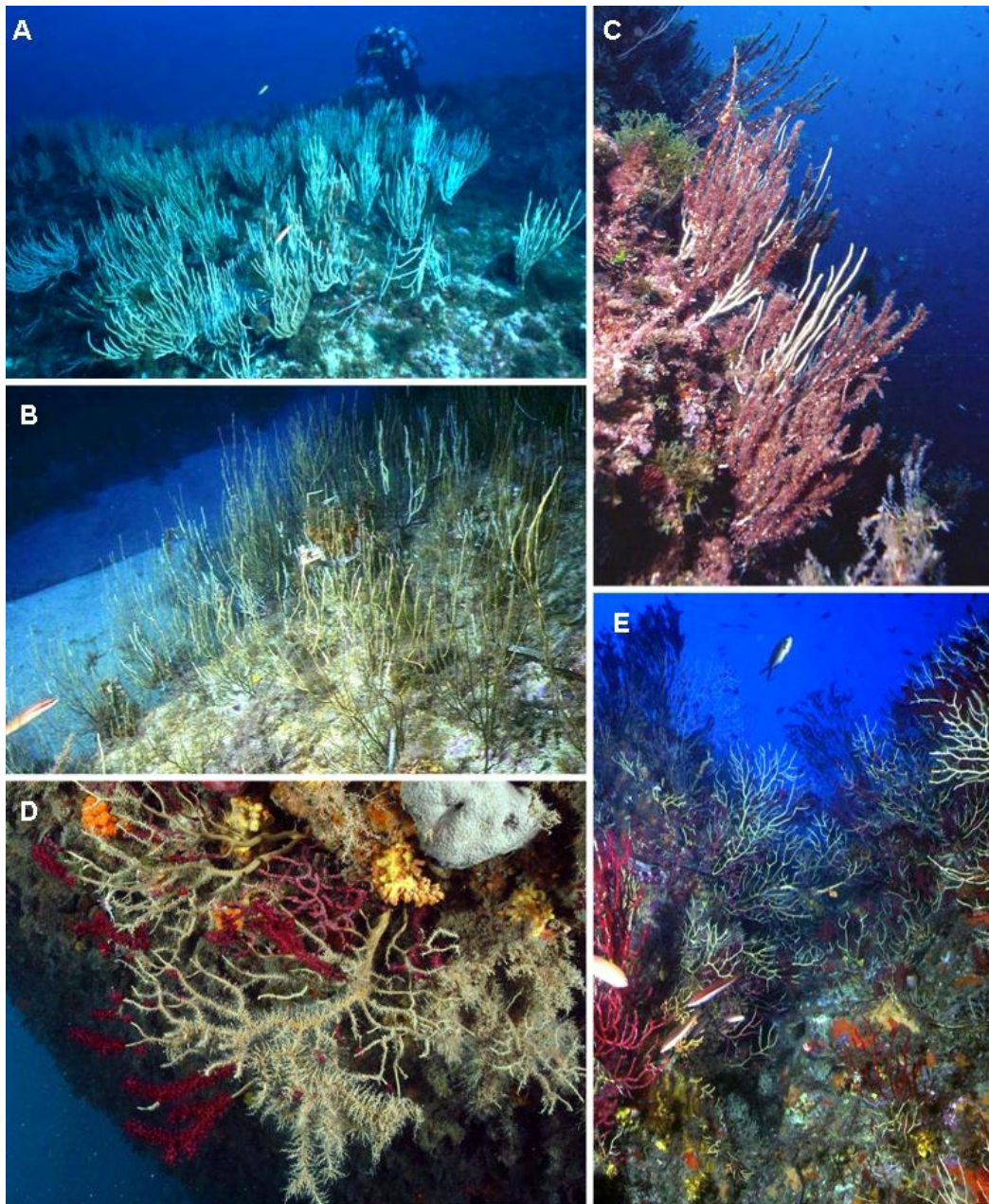


Figure 18: The impact of mass mortality of gorgonians on landscapes. A) Population of *Eunicella singularis* before (A) and immediately after (B) the mass mortality of 1999. Several months later, the gorgonians' naked skeletons are colonized by opportunistic species of algae, hydrozoa and bryozoa (C). The coralligenous community can be dominated by the big gorgonia *Paramuricea clavata*. The impact of the mortalities on the appearance of this community on a face (D) or a plateau (E). Photos by J.G. Harmelin (A, B, C, E) and R. Graille (D).

Emergence of pathogens

Despite the growing number of mass diseases and mortalities reported out at sea, very little is known about the infectious agents that can act in temperate ecosystems. The main problem lies in the effort needed to check Koch's* premise and decide with certainty on the infectious agent responsible. It is thus that diseases affecting exploited species are often given particular attention that have enabled the agents that caused them to be identified in 70% of cases (Harvell *et al.*, 1999). For non-exploited marine species, scarcely 30% of the diseases observed have been given sufficient research effort to lead to the pathogens being identified. Even in very much studied tropical ecosystems, where we are also witnessing an upsurge in cases of coral disease, we are far from having identified most of the agents responsible. But we do know the impact of a certain number of bacteria, fungi on the scleractinian and gorgonia of the Indo-Pacific and the Caribbean (for a review see Nagelkerken *et al.*, 1997; Harvell *et al.*, 2002; Rosenberg and Bein-Haim, 2002).

In the Mediterranean, after the sponge disease of the 1980s, an inquiry mandated by the FAO was carried out to assess the incidence and virulence of the phenomenon, and to identify its possible causes (Vacelet, 1994). Beyond the context of warming signalled all around the Mediterranean, several studies that tally showed that this disease was very probably infectious in origin. The pathogenous agent responsible, identified by electronical microscoping studies, was a bacterium that attacked the spongin skeleton of commercial sponges, making them crumbly and thus useless for marketing (Gaino and Pronzato, 1989; Vacelet *et al.*, 1994). After this work, Vacelet *et al.* (1994) argued that the virulence of this pathogen could be triggered by a temperature shock. In the case of the mortality of sponges observed in 1999, no bacterial attack on the skeleton was observed (Vacelet and Pérez, unpublished observations).

This explanation was also advanced and then proved by applying Koch's premise in the case of the whitening of the coral *Oculina patagonica* in the eastern Mediterranean (Kushmaro *et al.*, 1996; Kushmaro *et al.*, 1998). In fact, after identifying the infective agent, *Vibrio shiloi*, responsible for the whitening of *O. patagonica*, Kushmaro *et al.* showed experimentally that warming would significantly increase the pathogen's virulence. The bearded fireworm *Hermodice carunculata* is said to be the reservoir and vector of the pathogenous agent (Sussman *et al.*, 2003). In cases of whitening of other Mediterranean scleractinians occurring later (Rodolpho-Metalpa *et al.*, 2000, 2005), it has not been possible to check the hypothesis of the Israeli school.

In the case of the 1999 mortality of gorgonians, the potential role of pathogenous micro-organisms has often been advanced (Cerrano *et al.*, 2000; Martin *et al.*, 2002; Sidri, personal comm.). Cerrano *et al.* (2000) have observed a proliferation of ciliated protozoa around gorgonians' polyps (*P. clavata* and *L. sarmentosa*), but they were very probably

* Isolate the sick organism, cultivate it, use it to infect healthy organisms, trigger the disease in these and isolate the pathogen of the newly affected organism.

saprophytic micro-organisms rather than true pathogenous agents that had caused the necrosis of the colonies. Martin *et al.* (2002) focused on looking for *Vibrio* in two gorgonian species. They isolated 11 bacterial strains, among which five *Vibrio* seem to provoke necrosis in the tissues from 23°C on. And yet since the isolated strains do not belong to pathogenic taxa, the authors have advanced the theory that these are opportunistic strains, responding like many other *Vibrio* to variations in the environmental conditions, and able to speed up the necrosis of gorgonians in the case of warming (Martin *et al.*, 2002).

Between 2000 and 2003, signs of disease in *Parazoanthus axinellae* were regularly observed in the summer period (Cerrano *et al.*, 2006). After three years of monitoring, the authors showed successions of micro-organisms proliferating on the polyps of the infected zoantharians: first of all, the polyps are covered by a dense population of cyanobacteria in the early summer. The polyps are then contracted. Then fungal development appears in the middle of August, while the infected polyps degenerate rapidly (Cerrano *et al.*, 2006). Most of the fungi observed again belong to opportunistic saprophytic genera, some of which are known to also act in immunodeficient human or plant diseases.

After the summer 2003 mass mortality, several bacterial strains were isolated in infected *Paramuricea clavata* colonies and then grown to assess their role as potential pathogenous agents using a series of experiments done in aquariums (Fig. 19; Bally and Garrabou, 2007).

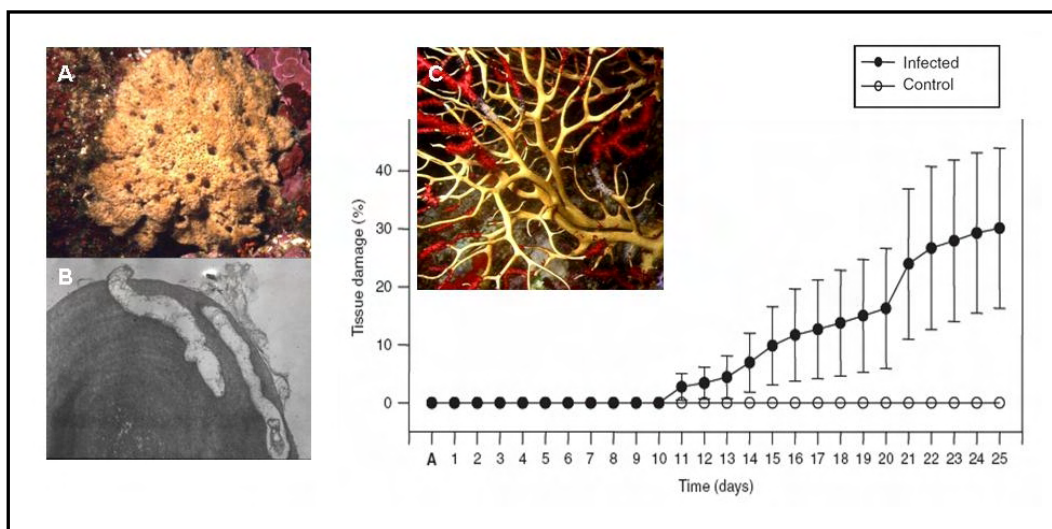


Figure 19: Infectious diseases caused by warming episodes. A) Skeleton of *Spongia officinalis* spongin made crumbly by the bacterial attack. B) Bacteria “boring” a spongin fibre (from Vacelet *et al.*, 1994). C) Experiment in an aquarium of contaminating *Paramuricea clavata* with *Vibrio coralliilyticus*. The graph shows the changing percentage (average and standard error) of necroses for colonies in the aquarium at 24°C containing *Vibro* compared to the control, kept at 16°C. Even when *Vibrio* is present, gorgonians kept at 16°C suffer from no necrosis (data not shown) (Bally and Garrabou, 2007). Photo by T, Pérez (A), J. Vacelet (B) and J.G. Harmelin (C).

Among the strains isolated, four cause necrosis in gorgonians at high temperatures. At 16°C, the bacteria provoke no lesions, but already at 22°C a large number of colonies are affected by the bacteria. However, the higher the temperature, the less the difference between death rates in the control and the contaminated aquariums. Among these four strains, Bally and Garrabou identified *Vibrio coralliilyticus*, the dominant strain in the diseased colony isolates on which they had checked Koch's premise. This species was already known as a thermo-dependent pathogen of the tropical corals of the Indo-Pacific. It was a priori the first time it was demonstrated that a tropical scleractinian pathogen could affect an Octocorallia of the temperate water (Bally and Garrabou, 2007). This species is also known to infect fishes, crustaceans and mollusc larva, demonstrating the possibility of a wide action spectrum. These authors advance the hypothesis that its introduction and advance into the Mediterranean may be encouraged by climate warming. The other isolated strains also belong to bacterial genera that contain sea organism pathogens.

This mechanism, implying the possible role of a thermo-dependent pathogen, encouraged by the warming of the Mediterranean, has again been evoked to explain the rising death rates for the starfish *Astropecten jonstoni* along the Sardinian coast (Stahli *et al.*, 2008). Here again the authors reveal the presence of bacteria of the *Vibrio* genus in individuals whose disease was probably provoked by a rise in temperature of up to 25°C.

Marine invertebrates, particularly sponges, gorgonians and corals, are known to produce secondary metabolites, substances with anti-microbial activities, which act as chemical defences for these organisms. An attack on a secondary metabolism after a temperature stress can thus encourage the action of pathogenic agents. For example, the anti-fungal activity of the Caribbean gorgonian *Gorgonia ventalina*, a species regularly affected by infectious diseases, is known to be significantly reduced when there is temperature stress, rises in temperature on the contrary encouraging the development of the pathogen *Aspergillus sydowii* (Kim *et al.*, 2000; Alker *et al.*, 2001).

Effects on the secondary metabolism

After the events of 1999 and 2003, research was done to study the effects of temperature anomalies on various indicators of resistance to stress (work by Pérez, ongoing). So far, this work has been done on the sponge *Spongia officinalis* for which an over expression of heat shock proteins (HSP) had been detected in the 1999 event (Pérez, 2001). These accessory proteins have a major role in the cell's response to a great variety of stresses and are particularly important for the organisms' recuperation and survival.

During the 2003 temperature anomaly, these biomarkers were studied at the same time as the production of chemical defences was being monitored (Sarrazin and Pérez, 2006; Thomas *et al.*, 2007 and unpublished data). In fact we could suppose that the stress caused by the heat shock, requiring an expenditure of energy to retain the homeostasis, and the over expression of HSP, would have consequences for the more "accessory" (or "secondary") metabolisms at the origin of the chemical defences. This kind of relationship

had been shown with another sponge species after contamination by heavy metals (Agell *et al.*, 2001). Comparative analysis of the expression of the two markers in the context of the 2003 temperature anomaly confirmed this theory, showing a drop in the production of chemical defences at the same time as over expression of the HSP 70 accessory proteins in the sponge *S. officinalis* (Sarrazin and Pérez, 2006). When these defences are low, the “door” is wide open to every kind of pathogen. Afterwards, chemical techniques for natural marine products were applied to determine the secondary metabolites whose expression had been inhibited. Five majoritary molecules were detected, two of which saw their production inhibited under stress. These were terpenoids known for their anti-proliferative and anti-bacterial action (Cimino *et al.*, 1971; Gonzalez *et al.*, 1982; Garrido *et al.*, 1997). This kind of approach is now envisaged for other species affected by the 1999 and 2003 events (ANR ECIMAR Programme, ongoing), to check whether this kind of effect could encourage the development of infectious diseases.

Short- and medium-term responses by populations

While some species affected by the mass mortality events are considered as essential parts of the Mediterranean natural heritage, knowledge about their dynamics and thus their capacity for recuperation is paradoxically very recent. The affected species are often considered to be long-living, with relatively slow dynamics (low growth rate, limited reproduction effort), and in the fairly usual absence of population genetics data, their capacity of dispersion is supposed to be limited. Such data is vital for assessing the populations’ resilience in the face of great disturbance, and thus indispensable for setting up measures to manage and conserve biodiversity, thus enabling ecosystems that are sensitive to climate warming to be protected (Palumbi, 2001).

After the sponge disease of the 1980s, nearly fifteen years were needed for the fishing activity in the Greek islands to start to recover, before once again undergoing the effects of the 1999 mortality (Warn, 2000). In the water of Port-Cros National Park, certain populations of *S. officinalis* experienced a major recruitment after the 1999 mortality, while other commercial species (*S. agaricina* and *Hippospongia communis*) seem to have completely disappeared (Pérez *et al.*, 2004). In Port-Cros, the 2003 mortality mostly affected the young sponges born after 1999, but this event was also followed by a major recruitment enabling the population density at certain sites to be maintained (Pérez *et al.*, 2004, and unpublished data). This is not surprising in that this species seems to reproduce throughout the year, with two reproduction peaks per year and a reproduction effort that can reach 20% of the biomass of mother sponges (Pérez *et al.*, 2006a).

The gorgonia *Paramuricea clavata* is another example of a species that is very sensitive to warming, the acquisition of knowledge on whose dynamics was to a great extent caused by the recent mass mortalities. This species was the subject of “post-1999 mortality” population dynamics studies in France, Italy and Spain. In Spain, C. Linares’s theory including work on reproduction, and mortality, survival and growth rates, allows us today

to envisage for the first time population dynamics modelling (Linares, 2006; Linares *et al.*, 2008). Only this kind of work, completely finished, will in time enable predictions to be made concerning the populations of this gorgonian according to different scenarios of climate warming and combinations of effects with other factors of disturbance.

While we are awaiting this, the sets of observations launched in the north-western Mediterranean after 1999 (or sometimes just before this) enable some indications to be given concerning the recuperative capacity of this species. According to the parameters followed by the different authors, the medium-term consequences of the mortality events are assessed in various ways. Overall, several years after the mass mortality of 1999, the average size of *Paramuricea clavata* colonies fell significantly in the studied populations, whatever the region considered (Bonhomme *et al.*, 2003; Cerrano *et al.*, 2005; Linares *et al.*, 2005; Bianchimani, 2006; Boury-Esnault *et al.*, 2006). In Provence, these mortalities also caused a significant drop in population density (Bonhomme *et al.*, 2003; Linares *et al.*, 2005; Bianchimani, 2006) which in Italy was probably compensated for by a major recruitment of new colonies (Cerrano *et al.*, 2005). With time, a recovery has been visible in the affected populations thanks to the gradual decline in the colonies' rate of necrosis. This recovery is probably the result of a certain regenerative capacity in the affected colonies (Cerrano *et al.*, 2005), and especially of the breaking of necrosed branches under the weight of colonization by fouling species (Pérez *et al.*, 2000; Bianchimani, 2006). This last, "delayed-action" (Linares *et al.*, 2005) effect, and the disappearance of the dead colonies, explain the very great reduction in the biomass within the gorgonian populations (Bonhomme *et al.*, 2003; 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 their original state (Bianchimani, 2006). In Port-Cros, for example, the succession of mortality events caused a 45% dwindling of the biomass between 1992 and 2004 (Harmelin and Garrabou, 2005). Worse still, among the least deep Ligurian populations, some were totally devastated after the mortality event of 2003, only leaving a few rare unharmed colonies where before there had been dense *P. clavata* populations. Perception of the medium-term effects of these mortalities is thus extremely variable, ranging from a very pessimistic assessment that envisages the extinction of this species over the next thirty years (Linares, 2006) to an apparent recovery of the original condition through major recruitment in other populations (Cerrano *et al.*, 2005). This last observation is all the more surprising in that the 1999 mortality seems to have altered the reproductive system of the female colonies more severely than that of the male, thus leading to a major change in the sex ratio within the populations (Cerrano *et al.*, 2005; Linares *et al.*, 2008).

Generally speaking, we need much more information before we can precisely assess the resilience of invertebrate populations affected by extreme climate events: (i) good knowledge of life-cycles, reproductive efforts, successful reproduction and recruitment of larvae, the contribution made by asexual reproduction and regeneration in maintaining populations; (ii) good characterization of the genetic structuring of populations, enabling

the flow of genes between them and the dispersion capacities of propagules to be assessed; (iii) tools enabling an assessment of the possibilities of adapting to stress generated by overall change in the Mediterranean, whether physiological (phenotype plasticity) adjustments or microevolutive processes. These various questions are currently at the heart of different research programmes.

EXAMPLES OF EFFECTS ON THE FUNCTIONING OF THE MARINE ECOSYSTEMS

The anticipated consequences of changes in biodiversity caused by the displacement or disappearance of certain species are modifications in the way the marine ecosystems function. Again in this case, long-term observations that enable us to assess the natural variations in the composition of communities and the links with climate fluctuations on various scales are essential to predict the effects of climate change on natural resources.

Plankton communities, particularly copepod assemblages, play a major part in the flows of matter and energy within the pelagic ecosystems, offering a biological carbon pump downwards, and exercising a strong influence over the recruitment of fishes. These same plankton communities can be subjected to the powerful control of “gelatinous” species (jellyfish in the wider sense, Siphonophora and Ctenophora), among which are major predators on copepods and fish eggs and larvae. It is vital to assess the influence of climate on the life-cycle of this kind of very short-lived organism whose stocks are renewed every year, and changes in which can give rise to consequences that are important for how the ecosystems function. Molinero’s team (2005a and b) thus identified a set of chain reactions linked to the North Atlantic Oscillations (NAOs). Firstly, a phenological study done over 27 years showed that the period when peaks of abundance of two copepod species, *Centropages typicus* and *Temora stylifera*, appeared was well correlated with the NAO index (Fig. 20; Molinero *et al.*, 2005a).

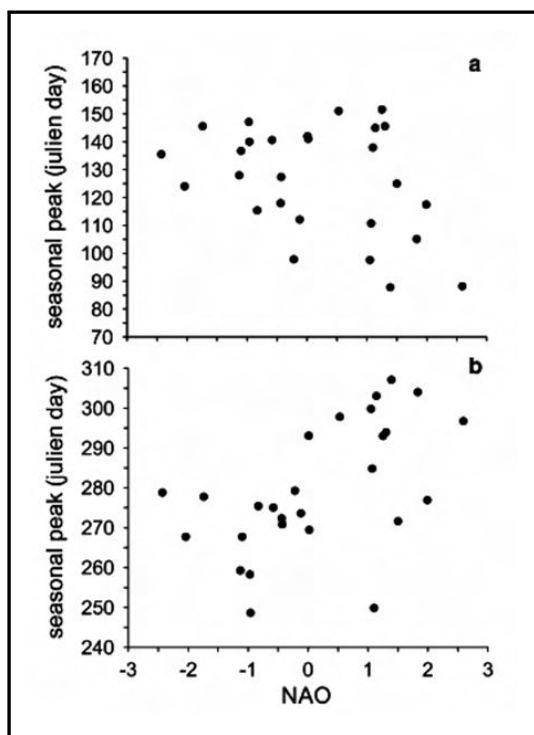


Figure 20 :

Relationship between the interannual variability of the seasonal peaks of abundance of two copepod species and the NAOs. The trends for the two species are opposite:

- a) *Centropages typicus* ($r = -0.58$; $p < 0.01$)
- b) *Temora stylifera* ($r = 0.53$; $p < 0.01$)

From Molinero *et al.*, 2005a.

The two species studied have opposite responses. Positive NAOs favour *C. typicus* and disfavour *T. stylifera*, whose peak of abundance is delayed and diminished by a factor of 2. Exactly opposite effects are observed in the years of lower NAOs. According to the

authors, these differences in reaction to climate fluctuations are explained by many factors. In the present context of comprehensive change in the Mediterranean (warming, changes in nutriment content), for two decades we have been witnessing major changes within the phytoplanktonic communities, with a dwindling representation of “siliceous” species (diatoms) to the advantage of the “non-siliceous” species, including dinophyta (Béthoux *et al.*, 2002; Goffart *et al.*, 2002). Thus, both species of copepod studied have a diet that changes during the life-cycle, but different overall preferences. In this instance, the rise in the representation of dinophyta in the phytoplankton in periods of positive NAO are good for *C. typicus*. For this species, positive temperature anomalies could also act at the level of reproduction, shortening the period of embryonic development and thus enabling earlier development in the water column than that of its congener *T. stylifera* (Molinero *et al.*, 2005a). The same authors also showed an important change in the dynamics of the relations between copepods and gelatinous plankton in the 1980s in the Ligurian Sea (Molinero *et al.*, 2005b). The repeated temperature anomalies, dry conditions and thus relative stability of the water masses that happened in the mid-1980s probably greatly encouraged blooms of jellyfish and thus increased predation on copepods. This ensemble of results shows the complexity of the effects of climate forcing on interactions between two different trophic groups. Even if these studies were extended to other functional groups to obtain a better knowledge of the mechanisms that lead to the modification of the functioning of pelagic ecosystems, they have for the first time enabled attention to be drawn to biological compartments that are the main sources of little pelagic fishes (anchovies, sardines etc.) whose stocks have also been modified over the past decades (cf. above sections). Correct assessment of the medium- and long-term consequences of global warming on Mediterranean natural resources thus requires a greater number of studies on the effects of the climate on interspecific interactions and comparative studies on the trophic networks of the various geographical areas.

The great productivity of the coastal marine ecosystems is due partly to the entry of nutriments and terrestrial-origin organic matter brought down by the rivers. In Europe, the rate of flow of the rivers is strongly linked to NAO variations, a lowering of the index giving rise to increased rainfall over the countries of the south, and an increase in the flow of the great rivers like the Rhône, for example. With the succession of positive NAOs in the 1980s, the Rhône’s rate of flow gradually increased, and one of the consequences observed was a rise in landings of common sole in the Golfe du Lion (Salen-Picard *et al.*, 2002). During the past 30 years, catch has fluctuated in parallel to the flow of the Rhône, with a 5-year time-lag (Fig. 21). This phenomenon has been explained by the rise after spates of the polychaete populations that are the main prey of the soles (Salen-Picard *et al.*, 2002). Long-term monitoring of the benthic populations has indeed shown that the density of the polychaete population and biomass rises and falls in parallel with the flow of the river. These fluctuations are expressed with different time-lags (a few months to 3 years) according to the life-cycle and the feeding of the species. Short-lived opportunistic species present short peaks of density and biomass only a few months after the spate, whereas the density of longer-living species increases over several years and is maximal 2 to 3 years

after the spates (Salen-Picard *et al.*, 2002). The hundred-year 1994 spate, which the authors had the chance to study, saw an over threefold rise in the quantities of polychaetes off the Rhône. This rise kept up for nearly 4 years, thanks to the succession of peaks of different species. Climate-linked fluctuations in river flow thus have repercussions on the marine environment for several years. Later, this long-term monitoring was supplemented by a study on the feeding of the main flat-fish species in the sector, analysing their stable carbon isotope ($^{13}\text{C}/^{12}\text{C}$) composition. This work permitted an understanding of how terrestrial-origin organic matter is integrated into the coastal trophic networks and in particular encourages the sole's life-cycle when massive entries are brought down in times of spate (Darnaude *et al.*, 2004).

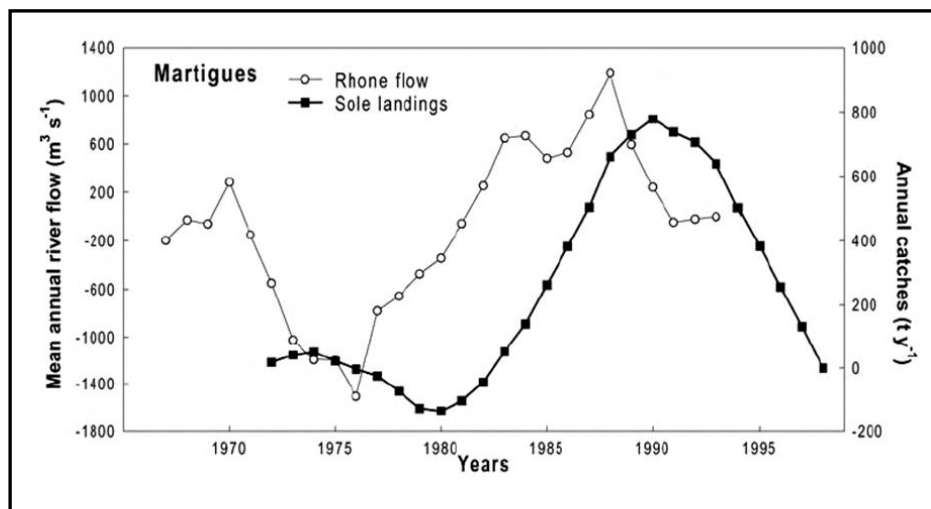


Figure 21: Fluctuations of the Rhône's annual mean flow and annual landings of common sole in Martigues (Golfe du Lion). The maximal correlation is seen with a 5-year time-lag (Salen *et al.*, 2002).

The consequences for the deep environment are much less often studied. Danovaro *et al.* (2001) have reviewed the effects of the recent modifications in the physicochemical features of the deep water of the eastern Mediterranean caused by climate change. These modifications, called by Béthoux *et al.* (1999) a “transitory event”, caused organic matter to build up on the deep sediment, altering the carbon and nitrogen cycles, and having negative effects on the deep-sea bacterial communities and the benthic fauna (Fig. 22). Again, originally we find the modification of phytoplanktonic assemblages (measured by the diatom/dinophyta ratio) and an overall increase in primary production encouraging the vertical flow of phytodetritus and organic carbon down to the deep sediment. These phenomena observed in the eastern Mediterranean are the opposite of those described after the El Niño episodes when exports of matter from the euphotic area are small (Danovaro *et al.*, 2001). The benthic fauna most sensitive to these changes is the meiofauna, particularly the nematodes often considered to be good environmental bioindicators (Bongers and Ferris, 1999). This meiofauna ought to profit from the accumulation of organic matter – but this has not been the case; in 10 years, it has, on the contrary, significantly dwindled in density and biomass (Danovaro *et al.*, 2001). Two hypotheses could explain this

phenomenon: (i) the slight cooling of the deep water of the eastern Mediterranean for two years (Lascaratos *et al.*, 1999) which would have affected the nematodes' reproductive potential; (ii) the dwindling of the biomass and bacterial activity resulting in a drop in the appropriate food sources. Overall, the ensemble of these results goes against what could be expected regarding the modification of the physico-chemical features of the deep water in relation to overall change. The eastern Mediterranean could be a special case, which does not prevent Danovaro and colleagues proposing it as a model for appraising the consequences of the growing instability of ocean movements. In any case, a major contribution made by these authors' work is the demonstration that deep ecosystems can also respond very rapidly to variations in climate.

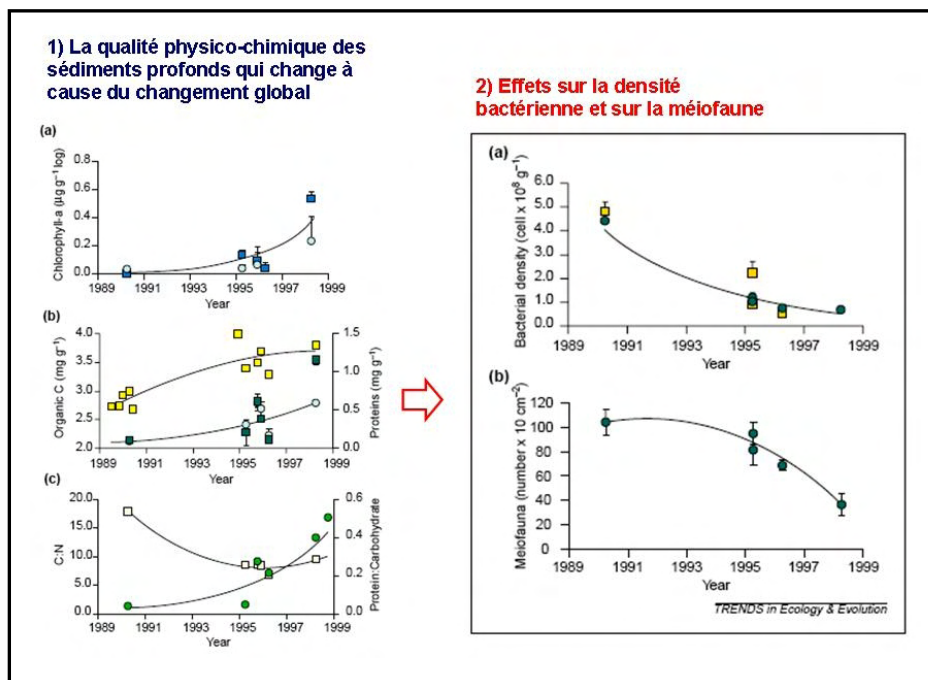


Figure 22: Left, modification between 1989 and 1999 of the factors affecting the quality of the sedimentary organic matter; a) chlorophyll a; b) organic carbon and proteins; c) C/N and proteins/sugars ratios. Right, bacterial density and meiofauna in the sediment of the Cretan Sea. Two stations were monitored at #900 and 1,500 metres (squares and circles) (Danovaro *et al.*, 2001).

CONCLUSION AND PROSPECTS

Climate change and the future of Mediterranean biodiversity

Climate change is at work in the Mediterranean – that's a fact! The recent appearance of a set of long-term temperature records has demonstrated for the north-western Mediterranean a warming trend of about 1°C in 30 years and a rise in the frequency of extreme events. During the past few decades, several large-scale events have given rise to a succession of major ecological events. In the mid-1980s, a succession of periods with positive NAOs coincided with a significant advance northward of a contingent of southern species, with a demographic explosion of gelatinous species that shattered a certain equilibrium within the plankton communities, and with the triggering of a disease that affected sponge populations throughout the Mediterranean. The late 1990s and the early 2000s were also marked by a succession of positive temperature anomalies, which caused mass mortalities with local extinctions of populations, or the proliferation of harmful species (dinophyta and filamentary algae).

So we are witnessing an upheaval in the climate geography in the Mediterranean, affecting the spatial displacements of species that will enable them to survive in environmental conditions that are favourable to their growth and reproduction. Most of the examples of displacement presented in this document may seem like rather pleasant biological effects, stimulating certain fisheries (e.g. *Sardinella*) or leisure activities (e.g. underwater diving). This is the case, for example, of the arrivals of southern species in the northern parts of the Mediterranean, whereas the departures are far more rarely mentioned. But what consequences will these displacements have on the functioning of the ecosystem? What impact will the arrival of new big predators, like Barracudas and Coryphenae, have on the coastal ecosystems of the northern basin? Are the developments of new species really beneficial to the human societies, and do they compensate for the (certainly more discreet) departures of other species? These questions also concern the eastern and southern basins, even though it is already well known that some Red Sea fishes have had an important place in local fisheries since that major modification of ecosystems provoked by the opening of the Suez Canal.

For low-mobility species, the consequences of climate change are much more often presented as ecological catastrophes that could lead to local extinctions of species and thus an erosion of Mediterranean biodiversity. On a world scale, a modelling exercise was done to try to assess how great biodiversity erosion will be by 2050, taking into account the displacement of climate areas, obviously highly critical for species with low dispersion ability, and the dwindling of the surface areas of habitats as a function of the expansion of environments that have been changed by man (Thomas *et al.*, 2004). In this context, climate change would be the first cause of extinction, giving rise to the disappearance of 18-35% of species according to the climate scenarios selected. This study only dealt with a

sample of the regions which covered 20% of the surface of the planet. Although it contains 4-18% of world marine biodiversity according to the taxonomical groups considered, the Mediterranean was not part of the area studied, but the rare models that exist and that take into account the combined effects of climate change and human activity, are equally pessimistic (e.g. Linares, 2006).

One also wonders about the combined effects of climate change and other sources of biodiversity disturbance. The reduction and fragmentation of the areas that can be inhabited by species, given the extension of built-over areas, represents a major constraint for marine biodiversity. Biological invasions, and the advance of exotic species encouraged by the warming, can also be a supplementary stress factor for species that have already been weakened by climate fluctuations. Several cases of infectious diseases, sometimes involving pathogens that are already known in the tropical areas, are now well described in the Mediterranean. In the absence of reference data, it is hard to say whether we are witnessing a real emergence of pathogens, or whether the rising trend of descriptions of marine epizootics results from a growing interest in epidemiological studies. Ward and Lafferty (2004), who have developed an approach that enables a predicted rise in cases of infectious diseases in the marine environment to be assessed by applying it to nine groups of organisms, believe there is no single trend. Over the past thirty years, these authors detect a rising trend in cases of infectious diseases in corals, molluscs, sea-urchins, turtles and marine mammals, while there is no particular trend for macrophytes, decapods and chondrichthyans, and that diseases are rarer for bony fishes. The authors see this as showing that the rise in cases of disease is not solely the result of a greater effort put in by scientists. Furthermore, some aspects of the overall change, such as warming or pollution, that are supposed to increase the sensitivity to infection of potential victims, may also affect the pathogens more than their targets (Ward and Lafferty (2004). To make recommendations about the management of natural resources requires a good knowledge of disease dynamics. The rising trend of epizootics in certain groups makes such research all the more urgent in that there are few operational solutions to mitigate the effects of diseases in the marine environment.

The most “plastic” species will adjust their metabolism to compensate for the stress undergone and/or modify their phenology by advancing or delaying such or such an event in the life-cycle to prevent effects on their fitness. Fairly few ecophysiological studies have been done on the Mediterranean species affected by climate change. The most recent work concerns those species recently affected by the positive temperature anomalies in the late 1990s, such as gorgonians (Gemini, 2006; Torrents *et al.*, 2008), scleractinians (Rodolfo-Metalpa *et al.*, 2006), sponges (Pérez *et al.*, 2006; Sarrazin and Pérez, 2006; Thomas *et al.*, 2007) or crustaceans (Lejeusne *et al.*, 2006). A new approach offering the prospect of better visibility of the adaptation mechanisms in marine ecosystems is emerging through the fusion of ecophysiology and macroecology (Osovitz and Hofmann, 2007). This new,

multidisciplinary, approach, called marine macrophysiology, examines the metabolic functions of marine organisms over big spatial and temporal scales, thus bringing pertinent elements to explain, for instance, biogeographical distributions. Large-scale physiological information would thus permit us to check the value of the principle that species would be more abundant/more efficient at the centre of their distribution area and would decline as they approached the outlying distribution edges (Sagarin *et al.*, 2006). By extension, macrophysiology would improve our knowledge of large-scale complex phenomena such as biological invasions or responses to climate change, and would supply arguments to define the outlines of marine protected areas. Such approaches are in their infancy in the Mediterranean. They aim at describing the life-cycles and reproduction cycles of a certain number of benthic species throughout the Mediterranean (e.g. the EU Phenomed programme) or acquiring the basic levels of expression of the physiological markers involved in resistance to stress caused by climate change (e.g. the ANR Medchange and Ecimar programmes).

Moreover, recent studies have shown that climate change could also lead to genetic modifications of animal populations (for a review see Bradshaw and Holzapfel, 2006). Out at sea, although the effects of stress and adaptation are relatively well known at ecological level, it is by no means the same for adaptation mechanisms at genetic level. But this last aspect is vital, for it is the genetic bases of adaptation that give the greatest adaptative power to a population confronted by environmental stress. Also, distinguishing between the effects of the various evolutive forces (migration, natural selection, and genetic drift) is of vital importance for understanding and possibly predicting the adaptative responses to environmental stress of organisms and populations.

Before addressing the aspect of recommendations and adaptation measures, it should be recalled that certain consequences of climate change will be irreversible, and that in some of these cases there is therefore no possible adaptation. That is an important risk, especially for activities which depend on marine biodiversity (fishing, fish farming, and recreational activities). Some ecosystems have often already been weakened by pollution, the fragmentation of habitats, and biological invasions and can thus present very great sensitivity to climate change, with reduced capacities of adaptation. This is especially true in the coastal areas of the developing countries of the southern and eastern shores of the Mediterranean.

Lines of research to be pursued

The lines of research suggested below follow on directly from the current knowledge of the biological effects of climate change in the Mediterranean. Among these suggestions for action, we shall later set out lines of research that have so far remained unexplored in the Mediterranean.

Acquire sets of temperature records and other physicochemical parameters related to the overall change in the Mediterranean as a whole. Today, only the north-west Mediterranean is well monitored; equivalent strategies should be set up in the Adriatic, and in the southern and eastern Mediterranean

Using the available sets of data, develop modelling to predict the warming of the Mediterranean water and the modifying of the general movement

Create a georeferenced database on the distribution of species that are sensitive to climate change in the Mediterranean. Perfect methods of monitoring the distribution boundaries and models for predicting the risks of extinction in the Mediterranean

Develop research programmes on life-cycles, reproductive cycles and the dynamics and genetics of sensitive populations. Acquire basic data in various geographical areas and assess the effects of a temperature regime change on phenology. Develop a system of phenological information for managing and studying climate change in the Mediterranean. Only this kind of approach will enable the adaptation capacities of the species threatened by climate change to be assessed

Study the different adaptative responses implemented by organisms and populations in the coastal environments that are facing large-scale disturbance such as climate change and the growing pressure of human activity and biological invasion. Assess the combined effects of different sources of disturbance. Study the effects of natural selection at physiological level. Assess the role of genetic diversity in the adaptative response of organisms and how it is maintained in the face of climate change and sources of disturbance. Develop macrophysiological approaches enabling basic levels of expression of physiological markers involved in resistance to stress to be acquired. Perfect biological indicators of early stress effects enabling the mechanisms leading to biodiversity changes to be explained

Do more studies on the effects climate change has on the way ecosystems function. What consequences do movements of species have on specific interactions: the prey/predator relationship? The host/parasite relationship? Rivalry for space, competition for a resource? What consequences do the mass mortality of benthic suspensivorous invertebrates have on the way the communities function, on the benthos/pelagos couple?

Possible adaptation measures and suggested action

The aim of adaptation measures is to restrict the negative aspects of impacts by reducing the ecosystems' vulnerability, and to exploit the positive aspects or opportunities in the best possible way. Adaptation strategies must aim at increasing flexibility by managing vulnerable ecosystems, encouraging the species' and ecosystems' inherent capacities of adaptation, and lastly reducing the environmental and social pressures that could increase vulnerability to climate variability (Hulme, 2005).

Faced by an evolving environment, the possible adaptation options deserve in-depth strategic reflection that takes into account the indirect and long-term consequences of the various possible attitudes. Thus we only suggest here a few paths that could be explored by a broader group of specialists in the field.

Reduce uncertainty by widening the base of knowledge: the first of the recommendations obviously involves doing everything possible to deepen scientific knowledge and explore new paths of research. It is vital that we know the potential impacts of climate change on species or communities before any attempt is made at an adapted management strategy. Although most of the knowledge contained in this document concerns the effects of heat stress, we must remember that temperature is not the only variable to be modified by overall change. According to region, we must also consider the modifications in rainfall regimes that can cause stream and major river spates, a rise in the sea level, solar radiation, modification of currents, changes in biogeochemical equilibria etc.

General use of epidemiological studies is needed to determine the factors that trigger and spread pathogenic agents. It is also vital to assess the relative sensitivities of the various Mediterranean marine communities

Develop predictive modelling: There is still some doubt about the response of species and ecosystems to a given climate scenario. Correlative models could give good indications about the effects of climate change on the abundance and distribution of species. On the other hand, models incorporating aspects of life-history features, intra- and inter-species competition, or the prey/predator relationship would give a much better knowledge of the processes. The models are particularly sensitive to the uncertainties inherent in climate prediction, the complexity of specific interactions and the difficulty of defining dispersion functions. Thus, there is no question of using without precaution modelling resulting from predictive tools that have not been validated by real data found in the field

Improve the visibility of the problems of conserving Mediterranean marine biodiversity in the context of climate change. This requires a gathering of the forces that are present in the Mediterranean to build federal programmes. It is necessary to communicate better and to draft an inventory of specialists in the field and programmes and actions at national or regional level

Develop economic indicators to measure the consequences of the modifications of biodiversity for the human activities that depend on it

Assistance to the developing countries is necessary to enable their vulnerability to be assessed through collecting data on climate change (observation policy) and possibly modelling this

Towards good ecological engineering! While the impacts of climate change can be severe, they are often worsened by “current” ways of managing the marine environment, such as building protective anti-wave sea walls or regulating spates. In most cases, the adaptations to climate variability set up and leading to the maintaining of certain economic interests, run counter to biodiversity conservation options (for a review, see Hulme, 2005). Climate change increases the danger of fish stocks collapsing and can in certain cases affect fisheries. In this case, it is thus necessary to adapt the fishing effort. Climate change can also affect the quality of habitats and thus threaten species with limited dispersion capacities. For this kind of species, well planned transplantation operations could prove to be a better option than management aiming at improving the connectivity between populations. Unfortunately, at sea, there have been very few attempts to transplant species affected by climate change. Linares’s (2006) approach, coupling experimental study and application of a viability model, has enabled the pertinence of gorgonian transplants to be tested, and has shown that this approach could be used as a tool for managing and restoring populations that have been severely affected by the temperature anomalies

General principles: Controlling climate variability is an impossible task. However, eliminating other sources of disturbance could reduce the vulnerability of species and ecosystems. By acting on introductions, we can try to check the arrival of competitors for space and the resource, new pathogens or parasites. By acting on emissions of pollutants, we avoid synergy with heat stress. By limiting the fragmentation of habitats, we are facilitating dispersion while maintaining connectivity between populations. Moreover, it is also possible to increase connectivity by providing corridors of habitats. This approach is a priori very attractive, but its value is often very “species dependent” and cannot always be appropriate. Thus, the management plan must not automatically focus on corridors for “nature in the wild” at the expense of appropriate management of larger marine protected areas

Start integrated action on a Mediterranean scale. To this day, work done on the impact of climate change on coastal biodiversity has been the fruit of national initiatives or the collaboration of a small number of European countries.

Today it is recognized that the effects of climate change will be felt at every level – human health, animal health, water resources, biological resources, quality of the environment and economic activity (agriculture, industry, transport, insurance, etc.) (Parry, 2000). Throughout the Mediterranean, climate change will have a particular effect on the future

demand, supply and quality of water resources and will modify the frequency, spatial distribution and intensity of droughts and floods. As a consequence, these effects of climate change do indeed represent priorities, and thus will be addressed by the first adaptation measures. Nevertheless, the coastal areas of the entire planet, already subject to multiple constraints, today house 60% of all human beings on a 60 km.-wide strip. The marine coastal water is the seat of 14-30% of the oceans' primary production and hosts 90% of the fishing catch. The Mediterranean is no stranger to the general rule, quite the reverse; and the effects of climate change to which the region is particularly sensitive represent new threats to the coastal biodiversity. Thus, integrated management of the coastal zone must be a constant concern if we wish to succeed in simultaneously regulating uses, protecting the coastal environment and ensuring sustainable development of this much coveted territory. At the end of this study it is necessary to remember that climate change and its effects are irremediable processes. In the long term, the major issue will probably be no more than successfully predicting the future of Mediterranean biodiversity, the future composition of the fisheries and the underwater landscapes, and adapting our ways of using them accordingly!

Global change, especially climate warming and the increasing frequency of extreme events, affects both terrestrial and marine ecosystems. Today's climate change is very clearly a result of the exponential development of human activity and goes far beyond the boundaries of natural variability. The potential effects of global change act at different levels of biological organisation, from the physiological disturbance of individuals to modifications of a community and how it functions, through the local extinctions and/or extensions of certain species. All the predictions concerning the consequences of warming for biodiversity as a whole are very worrying. On the basis of a moderate climate change scenario, today we anticipate an extinction of 15-37% of the species occupying this area by 2050. The Mediterranean Sea is one of the regions that is sensitive to climate change, and contains 4-18% of world marine biodiversity according to the taxonomical groups considered. However, so far no modelling has tried to assess the future of Mediterranean biodiversity. From the scientific publications and validated data available, as full an inventory as possible has been drawn up of the impact of climate change on marine biodiversity in the Mediterranean Sea. Starting from this initial assessment, it will be possible to discuss various measures of adaptation in order to restrict the impacts' negative aspects by reducing the ecosystems' vulnerability, and to make the most of any possible positive aspects or opportunities.

The existence of sets of long-term temperature records demonstrated, in the north-west Mediterranean, a warming trend of about 1°C in 30 years and a rise in the frequency of extreme events. Since this kind of data is often lacking in the other parts of the Mediterranean, suitable strategies should be set up to develop prediction models for changes in the environmental conditions (warming, movement, nutrient content).

The (usually westward and northward) migrations of southern species were the first signs of the biological effects of warming in the Mediterranean. The most numerous reports are for the north-west Mediterranean and the Adriatic. It is thought that short-term modifications of the ichthyological populations reflect almost in real time – in any case on the scale of one generation – changes in the hydrological conditions. In the north-western Mediterranean, the most recent list mentions several dozen species whose area of distribution has significantly changed since the 1970s. Among these movements we note the arrival of several species of fish (Sardinella, barracudas, coryphenes) which are gradually taking their place in the regional fisheries. Beyond these positive effects we are also witnessing the collapse of stocks of small pelagics (sprat, anchovy) and/or modifications of the life-cycles of certain favoured catches (tuna, amberjack). Biological invasions are often seen as an element of global change since they affect biodiversity and often appear to be linked to climate change, encouraging, especially in the eastern Mediterranean, the advance of Lessepsian species. Moreover, recent cases of the introduction of exotic dinophyta with biotoxins or the proliferation of species producing mucilages, have also been correlated to the occurrence of climate anomalies.

Extreme climate events are experienced as acute stress that disturbs the normal functioning of a biological system. Today, heat stress is widely recognized as the main factor in triggering diseases at sea, with a visible tendency for these events to become increasingly frequent in the Mediterranean. The species affected by these events are vital elements of the underwater landscapes, mostly sponges and gorgonians. Although mortalities of gorgonians have been known since the 1970s, and those of commercial sponges since the mid-1980s, the two events that stayed in people's minds were those of 1999 and 2003, both happening after exceptionally great temperature anomalies. The primordial role of warming has been well established, but different modes of action have been evoked. It has been shown on several occasions that temperature anomalies could trigger the virulence and/or condition the propagation of pathogenic agents (*Vibrio*) for sponges, cnidaria or echinoderms. Furthermore, the action of pathogenic agents could be facilitated by an inhibition of the defence capacities of organisms subjected to heat stress. It therefore seems necessary to develop epidemiological studies to decide which factors trigger and propagate pathogenic agents. Very generally speaking, it would be interesting to set up a georeferenced database on the distribution of species that are sensitive to climate change in the Mediterranean, and to perfect methods for monitoring their distribution boundaries, and models that will predict the risk of extinction in the Mediterranean. Major information is still lacking before we can assess with precision the resilience of invertebrate populations affected by extreme climate events:

- Good knowledge of life-cycles, reproductive effort, successful reproduction and recruitment of larvae, contribution of asexual reproduction and regeneration in keeping up populations
- Good characterization of the genetic structuring of populations permitting the flow of genes between them, and the dispersion capacities of the propagules, to be assessed
- Tools enabling the possibilities of adaptation to the stress generated by overall change in the Mediterranean to be appraised, whether this means physiological adjustments (phenotype plasticity) or microevolutive processes.

The expected consequences of the changes in biodiversity caused by the displacement or disappearance of certain species are modifications in how the marine ecosystems function. Only long-term observation can enable the natural variations in community composition, and the links with climate fluctuations on various levels to be appraised. They are essential for predicting the effects of climate change on natural resources. For instance, the temperature anomalies of the mid-1980s were what triggered very great modifications in the plankton communities that are at the base of the trophic network of many pelagic species. The productivity of the marine ecosystems can also be influenced by variations in the flow of the major rivers, which itself is influenced by climate variability. This was shown in a series of chain reactions after the Rhône spates that caused major entries of terrigenous organic matter into the coastal environment, encouraging polychaete, and then flat-fish, populations. It was also shown that deep ecosystems can also respond very quickly to climate variability.

Faced with the evolving Mediterranean environment, possible adaptation options deserve in-depth strategic reflection. So at the end of this inventory, a few paths are put forward:

- Widen the base of knowledge, and study the effects that can result from other variables linked to climate change: modifications of rainfall regimes, currents, biogeochemical equilibria, etc.
- Develop predictive models that incorporate aspects of the life-history features of sensitive species, intra- and inter-specific competition, or prey/predator relationships
- Improve the visibility of Mediterranean marine biodiversity conservation issues in the context of climate change
- Develop economic indicators to measure the consequences of modifications of biodiversity for the human activities that it underpins
- Give assistance to the developing countries to assess their vulnerability in the face of climate change
- Develop correct ecological engineering

- Reduce other sources of disturbance to marine biodiversity, minimize the fragmentation of habitats, and facilitate dispersion by maintaining connectivity between populations
- Protect relic systems (not impacted at all, or little impacted) by putting them into reserves.

BIBLIOGRAPHY

- Abboud-Abi Saab M., Romano J.C., Bensoussan N., Fakhri M., 2004 - Suivis temporels comparés de la structure thermique d'eaux côtières libanaises (Batroun) et françaises (Marseille) entre juin 1999 et octobre 2002. *Comptes Rendus Geoscience* 336 : 1379-1390.
- Agell G., Uriz M.J., Cebrian E., Marti R., 2001 - Does stress protein induction by copper modify natural toxicity in sponges? *Environmental Toxicology and Chemistry* 20 : 2588-2593.
- Alker A.P., Smith G.W., Kim K., 2001 - Characterization of *Aspergillus sydowii* (Thom et Church), a fungal pathogen of Caribbean sea fan corals. *Hydrobiologia* 460 : 105-111.
- Astraldi M., Bianchi C.M., Gasparini G.P., Morri C., 1995 - Climatic fluctuations, current variability and marine species distribution : a case study in the Ligurian Sea (north-west Mediterranean). *Oceanologica Acta* 18 (2) : 139-149.
- Bally M., Garrabou J., 2007 - Thermodependant bacterial pathogens and mass mortalities in temperate benthic communities: a new case of emerging disease linked to climate change. *Global Change Biology* 13 : 2078-2088.
- Barry J.P., Baxter C.H., Sagarin R.D., Gilman S.E., 1995 - Climate-related long-term faunal changes in California rocky intertidal community. *Science* 267 : 672-675.
- Ben Mustapha K., El Abed A. 2000. - Données nouvelles sur des éléments du macro benthos de Tunisie. *Rapp. Comm. Int. Mer Médit.*, 36 : 358.
- Ben Mustapha K., Vacelet J., 1991 - Etat actuel des fonds spongifères de Tunisie. In Boudouresque C.F. et al. (ed.), *Les espèces marines à protéger en Méditerranée*. GIS Posidonie, France : 43-46
- Béthoux J.P., Gentili B., 1999 - Functioning of the Mediterranean Sea: past and present changes related to freshwater input and climate change. *Journal of Marine Systems* 20: 33-47.
- Béthoux J.P., Gentili B., Morin P., Nicolas E., Pierre C., Ruiz-Pino D., 1999 - The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. *Progress in Oceanography* 44 : 131-146.
- Béthoux J.P., Gentili B., Raunet J., Tailliez D., 1990 - Warming trend in the western Mediterranean deep water. *Nature* 347 : 660-662.
- Béthoux J.-P., Gentili B., Tailliez D., 1998 - Warming and freshwater budget change in the Mediterranean since the 1940s, their possible relation to the greenhouse effect. *Geophysical-Research-Letters* 25 : 1023-1026.

- Béthoux J.P., Morin P., Ruiz-Pino D. 2002. Temporal trends in nutrient ratios: chemical evidence of Mediterranean ecosystem changes driven by human activity. *Deep-Sea Research II* 49 : 2007-2016.
- Bianchi C.N. 1997. - Climate change and biological response in the marine benthos. *In : Atti 128 Congresso Associaz. Italiana Oceanol. Limnol. (18-21 settembre 1996, Isola di Volcano), Piccazzo M. ed. : 3-20.*
- Bianchi C.N., 2004 - Biodiversity issues for the next coming tropical Mediterranean Sea. *Biologia Marina Mediterranea* 11 : 4.
- Bianchi C.N., 2007 - Biodiversity issues for the forthcoming tropical Mediterranean Sea. *Hydrobiologia* 580 : 7-21.
- Bianchi C.N., Morri C., 1993 - Range extension of warm-water species in the northernMediterranean evidence for climatic fluctuations? *Porcupine Newsletter* 5 : 156-159.
- Bianchi C.N., Morri C., 2000 - Marine biodiversity of the Mediterranean sea: situation, problems and prospects for future research. *Marine Pollution Bulletin* 40 (5): 367-376.
- Bianchimani O., 2006 - Mortalités massives d'invertébrés marins longévives: impact et récupération des populations de gorgones rouges *Paramuricea clavata* en Méditerranée Nord Occidentale. Université de la Méditerranée, Centre d'Océanologie de Marseille, 37 pp.
- Bodilis P., Ganteaume A., Francour P., 2003 - Recruitment of the dusky grouper (*Epinephelus marginatus*) in the north-western Mediterranean Sea. *Cybium* 27 (2) : 123-129.
- Bombace G., 2001 - Influence of climatic changes on stocks, fishes and marine ecosystems in the Mediterranean Sea. *Archo. Oceanogr. Limnol.* 22 : 67-72.
- Bongers T., Ferris H., 1999 - Nematode community structure as a bioindicator in environmental monitoring. *Trends in Ecology and Evolution* 14 : 224-228.
- Bonhomme D., Garrabou J., Pérez T., Sartoretto S., Harmelin J.G., 2003 - Impact and recovery from a mass mortality event of the gorgonian *Paramuricea clavata* on the French Mediterranean coasts. *Geophysical Research Abstracts* 5 : 10676.
- Boury-Esnault N., Aurelle D., Bensoussan N., Chevaldonné P., Garrabou J., HarmelinJG, Laubier L., Ledoux J.B., Lejeusne C., Marschal C., Pérez T., Romano J.C., Torrents O., Vacelet J. 2006. - Evaluation des modifications de la biodiversité marine sous l'influence du changement global en Méditerranée Nord Occidentale. *Institut Français de la Biodiversité, Rapport final*, 39 pp.
- Bradshaw W.E., Holzapfel C.M., 2006 - Evolutionary response to rapid climate change. *Science* 312 : 1477-1478.

- Cerrano C., Arillo A., Azzini F., Calcinai B., Castellano L., Muti C., Valisano L., Zega G., Bavestrello G., 2005 - Gorgonian population recovery after a mass mortality event. *Aquatic Conservation: Marine and Freshwater Ecosystems* 15 : 147-157.
- Cerrano C., Bavestrello G., Bianchi C.N., Cattaneo-Vietti R., Bava S., Morganti C., Morri C., Picco P., Sara G., Schiaparelli S., Siccardi A., Sponga F., 2000 - A catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (NW Mediterranean), summer 1999. *Ecology Letters* 3 : 284-293.
- Cerrano C., Totti C., Sponga F., Bavestrello G., 2006 - Summer disease in *Parazoanthus axinellae* (Schmidt, 1862) (Cnidaria, Zoanthidea). *Italian Journal of Zoology* 73 (4) : 355-361.
- Chevaldonné P., Lejeusne C., 2003 - Regional warming-induced species shift in north-west Mediterranean marine caves. *Ecology Letters* 6 : 371-379.
- Cimino G., De Stefano S., Minale L., Fattorusso E., 1971 - Furospongins-1, a new C-21 furanoterpene from sponges *Spongia officinalis* and *Hippospongia communis*. *Tetrahedron* 27 : 4673-4679.
- Coma R., Linares C., Ribes C., Diaz D., Garrabou J., Ballesteros E., 2006 - Consequences of a mass mortality in populations of *Eunicella singularis* (Cnidaria: Octocorallia) in Menorca (NW Mediterranean). *Marine Ecology Progress Series* 327 : 51-60.
- Coma R., Pola E., Ribes M., Zabala M., 2004 - Long term assessment of the patterns of mortality of a temperate octocoral in protected and unprotected areas: a contribution to conservation and management needs. *Ecological Applications* 14 : 1466-1478.
- Danovaro R., Dell'Anno A., Fabiano M., Pusceddu A., Tselepides A., 2001 - Deep-sea ecosystem response to climate changes: the eastern Mediterranean case study. *Trends in Ecology and Evolution* 16 (9) : 505-510.
- Darnaude A.M., Salen-Picard C., Polunin N.V.C., Harmelin-Vivien M.L., 2004 - Trophodynamic linkage between river runoff and coastal fishery yield elucidated by stable isotope data in the Gulf of Lions (NW Mediterranean). *Oecologia* 138 : 325-332.
- Degobbi D., Precali R., Ivancic I., Smolaka N., Fuks D., Kveder S., 2000 - Long-term changes in the northern Adriatic ecosystem related to anthropogenic eutrophication. *International Journal of Environment and Pollution* 13 : 1-6.
- Elbrächter M., 1999 - Exotic flagellates of coastal North Sea waters. *Helgoländer Meeresuntersuchungen* 5 : 235-242.
- Francour P., Boudouresque C.F., Harmelin-Vivien M., Harmelin J.-G., Quignard J.-P., 1994 - Are the Mediterranean waters becoming warmer ? Information from biological indicators. *Marine Pollution Bulletin* 28 : 523-526.
- Gaino E., Pronzato R., 1989 - Ultrastructural evidence of bacterial damage to *Spongia officinalis* fibres (Porifera, Demospongiae). *Diseases of Aquatic Organisms* 6 : 67-74.

- Gaino E., Pronzato R., Corriero G., Buffa P., 1992 - Mortality of commercial sponges: incidence in two Mediterranean areas. *Bollettino di Zoologia* 59 : 79-85.
- Galil B., 2007 - Loss or gain? Invasive aliens and biodiversity in the Mediterranean Sea. *Marine Pollution Bulletin* 55 : 314-322.
- Galil B., Zenetos A., 2002 - A sea change: exotics in the eastern Mediterranean Sea. *Invasive Aquatic Species of Europe: Distribution, Impacts and Management* : 325-336.
- Garrabou J., Pérez T., Chevaldonné P., Bensoussan N., Torrents O., Lejeusne C., Romano J.C., Vacelet J., Boury-Esnault N., Harmelin-Vivien M., Verlaque M., Boudouresque C.F., Zibrowius H., Harmelin J.G., 2003 - Is the global change a real threat for the conservation of the NW Mediterranean marine biodiversity? *Geophysical Research Abstracts* 5 : 10522.
- Garrabou J., Pérez T., Sartoretto S., Harmelin J.G., 2001 - Mass mortality event in red coral (*Corallium rubrum*, Cnidaria, Anthozoa, Octocorallia) population in the Provence region (France, NW Mediterranean). *Marine Ecology Progress Series* 217 : 263-272.
- Garrido L., Zubia E., Ortega M.J., Salva J., 1997 - New furanoterpenoids from the sponge *Spongia officinalis*. *Journal of Natural Products* 60 : 794-797.
- Gemini M., 2006 - Effets d'une hyperthermie induite sur deux gorgones de Méditerranée: *Eunicella singularis* et *Eunicella cavolinii*. Conséquences de la symbiose dans la résistance au stress thermique. Université de la Méditerranée, Centre d'Océanologie de Marseille, UMR 112 INRA-Université de Nice Sophia Antipolis, 42 pp.
- Giuliani S., Lamberti C.V., Sonni C., Pellegrini D., 2005 - Mucilage impact on gorgonians in the Tyrrhenian sea. *The Science of the Total Environment* 353 : 340-349.
- Goffart A., Hecq J.H., Legendren L., 2002 - Changes in the development of the winter-spring phytoplankton bloom in the Bay of Calvi (Northwestern Mediterranean) over the last two decades: a response to the changing climate. *Marine Ecology Progress Series* 235 : 387-399.
- Gomez F., 2003 - The toxic dinoflagellate *Gymnodinium catenatum*: an invader in the Mediterranean Sea. *Acta Botanica Croatia* 62 : 65-72.
- Gomez F., Claustre H., 2003 - The genus *Asterodinium* (Dinophyceae) as possible biological indicator of warming in the western Mediterranean Sea. *Journal of Marine Biological Association of United Kingdom* 83 : 173-174.
- Gonzalez A.G., Darias V., Estevez E., 1982 - Contribution to the biological study of *Spongia officinalis*. *Il Farmaco* 37 : 179-183.
- Grubelic I., Antolic B., Despalatovic M., Grbec B., Beg Paklar G., 2004 - Effect of climatic fluctuations on the distribution of warm-water coral *Astroides calycularis* in the Adriatic Sea: new records and review. *Journal of the marine biological Association of the United Kingdom* 84 : 599-602.

- Harley C.D.G., Hughes A.R., Hultgren K.M., Miner B.G., Sorte C.J.B., Thornber C.S., Rodriguez L.F., Tomanek L., Williams S.L., 2006 - The impacts of climate change in coastal marine systems. *Ecology Letters* 9 : 228-241.
- Harmelin J.G., 2004 - Environnement thermique du benthos côtier de l'île de Port-Cros (parc national, France, Méditerranée Nord-occidentale) et implications biogéographiques. *Scientific Reports of Port-Cros national Park* 20 : 173-194.
- Harmelin J.G., Garrabou J., 2005 - Suivi d'une population de *Paramuricea clavata* (Risso, 1826) (Cnidaria, Octocorallia, Gorgonacea) dans le parc national de Port-Cros (Méditerranée, France): comparaison des états 1992 et 2004 sur le site de la Galère. *Scientific Reports of Port-Cros national Park* 21 : 175-191.
- Harmelin J.G., Marinopoulos J., 1994 - Population structure and partial mortality of the gorgonian *Paramuricea clavata* (Risso) in the north-western Mediterranean (France, Port-Cros Island). *Marine Life* 4 (1) : 5-13.
- Harmelin J.G., Robert P., 2001 - Evolution récente de la population du mérrou brun (*Epinephelus marginatus*) dans le Parc National de Port-Cros (France, Méditerranée). *Scientific Reports of Port-Cros national Park* 18 : 149-161.
- Harmelin J.G., Vacelet J., 1997 - Clues to deep-sea biodiversity in a nearshore cave. *Vie et Milieu* 47 (4) : 351-354.
- Harvell C.D., Kim K., Burkholder J.M., Colwell R.R., Epstein P.R., Grimes D.J., Hofmann E.E., Lipp E.K., Osterhaus A.D.M.E., Overstreet R.M., Porter J.W., Smith G.W., Vasta G.R., 1999 - Emerging marine diseases - Climate links and anthropogenic factors. *Science* 285 : 1505-1510.
- Harvell C.D., Mitchell C.E., Ward J.R., Altizer S., Dobson A.P., Otsfeld R.S., Samuel M.D., 2002 - Climate warming and disease risks for terrestrial and marine biota. *Science* 296 : 2158-2162.
- Hughes L., 2000 - Biological consequences of global warming : is the signal already apparent? *Trends in Ecology and Evolution* 15 : 56-61.
- Hulme P.E., 2005 - Adapting to climate change: is there scope for ecological management in the face of a global threat? *Journal of Applied Ecology* 42 : 784-794.
- IPCC, 2002. Les changements climatiques et la biodiversité. Intergouvernemental Programme on Climate Change, 75 pp.
- IPCC, 2007. Bilan 2007 des changements climatiques : conséquences, adaptation et vulnérabilité. Intergouvernemental Programme on Climate Change, 24 pp.
- Johnson R.G., 1997 - Ice Age initiation by an ocean-atmospheric circulation change in the Labrador Sea. *Earth and Planetary Science Letters* 148 : 367-379.
- Karl T.R., Trenberth K.E., 2003 - Modern global climate change. *Science* 302 : 1719-1723.

- Kim K., Kim P.D., Alker A.P., Harvell C.D., 2000 - Chemical resistance of gorgonian corals against fungal infections. *Marine Biology* 137 (3) : 393-401.
- Kushmaro A., Loya Y., Fine M., Rosenberg E., 1996 - Bacterial infection and coral bleaching. *Nature* 380 : 396.
- Kushmaro A., Rosenberg E., Fine M., Haim Y.B., Loya Y., 1998 - Effect of temperature on bleaching of the coral *Oculina patagonica* by *Vibrio* AK-1. *Marine Ecology Progress Series* 171 : 131-137.
- Lascaratos A., Roether W., Nittis K., Klein B., 1999 - Recent changes in deep water formation and spreading in the eastern Mediterranean Sea: a review. *Progress in Oceanography* 44 : 5-36.
- Laubier L., 2001 - Climatic changes and trends and marine invertebrates: a need for relevant observing networks and experimental ecophysiology. *Atti Associazione Italiana Oceanologia Limnologia* 14 : 15-24.
- Laubier L., 2003 - Changement et vulnérabilité des peuplements marins côtiers. *Comptes Rendus Geoscience* 335 : 561-568.
- Laubier L., Pérez T., Lejeusne C., Garrabou J., Chevaldonné P., Vacelet J., Boury-Esnault N., Harmelin J.G., 2003 - La Méditerranée se réchauffe-t-elle? Is the Mediterranean warming up? *Marine Life* 13 (1-2) : 71-81.
- Lejeusne C., Pérez T., Sarrazin V., Chevaldonné P., 2006 - Baseline expression of Heat Shock Proteins (HSP) closely related to natural temperature fluctuations in a thermotolerant Mediterranean marine invertebrate. *Canadian Journal of Fisheries and Aquatic Sciences* 63 : 2028-2037.
- Linares C., 2006 - Population ecology and conservation of a long-lived marine species: the red gorgonian *Paramuricea clavata*. Thesis, Universitat de Barcelona, Facultat de Biologia-Department d'Ecologia, 210 pp.
- Linares C., Coma R., Diaz D., Zabala M., Hereu B., Dantart L., 2005 - Immediate and delayed effects of a mass mortality event on gorgonian population dynamics and benthic community structure in the NW Mediterranean Sea. *Marine Ecology Progress Series* 305 : 127-137.
- Linares C., Coma R., Zabala M., 2008 - Effects of a mass mortality event on gorgonian reproduction. *Coral Reefs* 27 : 27-34.
- Lipej L., Dulcic J., 2001 - Factors affecting the diversity of the Adriatic ichthyofauna. *Ann. An. Istrske Mediter. Stud. (Hist. Nat.)* 11 (1) : 18.
- Luterbacher J., Dietrich D., Xoplaki E., Grosjean M., Wanner H., 2004 - European seasonal and annual temperature variability, trends, and extremes since 1500. *Science* 303 : 1499-1503.

- Martin Y., Bonnefont J.L., Chancerelle L., 2002 - Gorgonians mass mortality during the 1999 late summer in French Mediterranean coastal waters: the bacterial hypothesis. *Water Research* 36 : 779-782.
- Marullo S., Guarracino M., 2003 - L'anomalia termica del 2003 nel Mar Mediterraneo osservata da satellite. *Energia, Ambiente et Innovazione* 6 : 48-53.
- Molinero J.C., Ibanez F., Nival P., 2005a - North Atlantic climate and northwestern Mediterranean plankton variability. *Limnology and Oceanography* 50 (4) : 1213-1220.
- Molinero J.C., Ibanez F., Souissi S., Chifflet M., Nival P., 2005b - Phenological changes in the Northwestern Mediterranean copepods *Centropages typicus* and *Temora stylifera* linked to climate forcing. *Oecologia* 145 : 640-649.
- Nagelkerken I., Buchan K., Smith G.W., Bonair K., Bush P., Garzon-Ferreira J., Botero L., Gayle P., Harvell C.D.et-al, 1997 - Widespread disease in Caribbean sea fans: 2. Patterns of infection and tissue loss. *Marine Ecology Progress Series* 160 : 255-263.
- Nehring S., 1998 - Establishment of thermophilic phytoplankton species in the North Sea: biological indicators of climatic changes? *ICES Journal of Marine Science* 55 : 818-823.
- Nicholls R.J., Hoozemans F.M.J., 1996 - The Mediterranean: vulnerability to coastal implications to climate change. *Ocean and Coastal Management* 31 : 105-132.
- Ocana O. 2005. - Biología y divulgación para la conservación y mejor de gestión de la especie *Astroides calycularis* y sus habitats en los litorales de Ceuta y Melilla. *Informe científico realizado para el Ministerio de Medioambiente*, 71 pp.
- Occhipinti-Ambrogi A., 2007 - Global change and marine communities: Alien species and climate change. *Marine Pollution Bulletin* 55 : 342-352.
- Occhipinti-Ambrogi A., Savini D., 2003 - Biological invasions as a component of global change in stressed marine ecosystems. *Marine Pollution Bulletin* 46 : 542-551.
- Osovitz C.J., Hofmann G.E., 2007 - Marine macrophysiology: studying physiological variation across large spatial scales in marine systems. *Comparative Biochemistry and Physiology, A* 147 : 821-827.
- Palumbi S., 2001 - The ecology of marine protected areas. *Marine Community Ecology* : 509-530.
- Parmesan C., Yohe G., 2003 - A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 398 : 421.
- Parry M.L. (ed), 2000 - *Assesment of potential effects and adaptations for climate change in Europe: the Europe ACACIA project*. Jackson Environment Institute, University of East Anglia, Norwich, 320 pp.

- Pérez T., 2001 - Qualité de l'environnement marin littoral : étude des spongiaires pour la bioévaluation des peuplements de substrats durs. Thesis, Université de la Méditerranée, Centre d'Océanologie de Marseille, 229 pp.
- Pérez T., Ereskovsky A., Correia S., Bézac C., Boury-Esnault N., Vacelet J. 2006a. - Life cycle and reproductive effort of the Mediterranean commercial sponge *Spongia officinalis*. 7th international sponge symposium, *Biodiversity Innovation Sustainability*: 86.
- Pérez T., Garrabou J., Sartoretto S., Harmelin J.G., Francour P., Vacelet J., 2000 - Mass mortality of marine invertebrates: an unprecedented event in the Northwestern Mediterranean. *Comptes Rendus de l'Académie des Sciences Série III* 323 : 853-865.
- Pérez T., Graille R., Boury-Esnault N., Vacelet J. 2004. - Suivi des populations de *Spongia officinalis* du Parc National de Port-Cros. *Parc National de Port-Cros*, 25pp.
- Pérez T., Lejeusne C., Aurelle D., Bensoussan N., Boury-Esnault N., Chevaldonné P., Garrabou J., Harmelin J.G., Laubier L., Ledoux J.B., Marschal C., Romano J.C., Torrents O., Vacelet J. 2006b. - Evaluation des modifications de la biodiversité marine sous l'influence du changement global en Méditerranée Nord-occidentale. *Colloque IFB-GICC, Réponses adaptatives au changement global: résultats et prospective*, pp. 58-65.
- Petchey O.L., McPhearson T., Casey T.M., Morin P.J., 1999 - Environmental warming alters food-web structure and ecosystem function. *Nature* 402 : 69-72.
- Peters E.C., 1993 - Disease of other invertebrate phyla: Porifera, Cnidaria, Ctenophora, Annelida, Echinodermata. In Couch J.A., Fournie J.W. (ed.), *Pathobiology of Marine and Estuarine Organisms*. CRC Press, Boca Raton: 393-449
- Rinaldi A., Vollenweider R.A., Montanari G., Ferrari C.R., 1995 - Mucilages in Italian seas: the Adriatic and Tyrrhenian Seas, 1988-1991. *The Science of the Total Environment* 165 : 165-183.
- Rodolfo-Metalpa R., Bianchi C.N., Peirano A., 2000 - Coral mortality in NW Mediterranean. *Coral Reefs* 19 : 24.
- Rodolfo-Metalpa R., Bianchi C.N., Peirano A., Morri C., 2005 - Tissue necrosis and mortality of the temperate coral *Cladocora caespitosa*. *Italian Journal of Zoology* 72 : 271-276.
- Rodolfo-Metalpa R., Richard C., Allemand D., Ferrier-Pages C., 2006 - Growth and photosynthesis of two Mediterranean corals, *Cladocora caespitosa* and *Oculina patagonica*, under normal and elevated temperatures. *The Journal of Experimental Biology* 209: 4546-4556

- Romano J.C. 2003. - Le réchauffement des eaux côtières en Méditerranée Nord Occidentale : une certitude sur les 30 dernières années. The warming trend of the NW Mediterranean coastal waters: an evidence over the last 30 years. International Geosphere Biosphere Programme (IGBP) and World Climate Research Programme (WCRP). *Lettre PIGB-PMRC-France* 15 : 50-55.
- Romano J.C., Bensoussan N., Younes W.A.N., Arlhac D., 2000 - Anomalies thermiques dans les eaux du golfe de Marseille durant l'été 1999. Une explication partielle de la mortalité d'invertébrés fixés. *Comptes-Rendus de l'Académie des Sciences de Paris* 323 : 415-427.
- Romano J.C., Lugrezi M.C., 2007 - Série du marégraphe de Marseille: mesures de températures de surface de la mer de 1885 à 1967. *Comptes Rendus Geoscience* 339 : 57-64.
- Root T.L., Price J.T., Kimberly R.H., Schneider S.H., Rosenzweig C.J., Pounds J.A., 2003 - Fingerprints of global warming on wild animals and plants. *Nature* 421 : 57-60.
- Rosenberg E., Ben-Haim Y., 2002 - Microbial diseases of corals and global warming. *Environmental Microbiology* 4 : 318-326.
- Sabates A., Martin P., Lloret J., Raya V., 2006 - Sea warming and fish distribution: the case of the small pelagic fish, *Sardinella aurita*, in the western Mediterranean. *Global Change Biology* 12 : 2209-2219.
- Sagarin R.D., Gaines S.D., Gaylord B., 2006 - Moving beyond assumptions to understand abundance distributions across the ranges of species. *Trends in Ecology and Evolution* 21 (9) : 524-530.
- Salat J., 1996 - Review of hydrographic environmental factors that may influence anchovy habitats in northwestern Mediterranean. *Scientia marina* 60 (suppl.2) : 21-32.
- Salat J., Pascual J. 2002. - The oceanographic and meteorological station at L'Estartit (NW Mediterranean). *CIESM Workshop: Tracking long-term hydrological change in Mediterranean Sea*, Series n°16 : 31-34.
- Salen-Picard C., Darnaude A., Arlhac D., Harmelin-Vivien M.L., 2002 - Fluctuations of macrobenthic populations: a link between climate-driven run-off and sole fishery yields in the Gulf of Lions. *Oecologia* 133: 380-388.
- Sarrazin V., Pérez T. 2006. - Sponge chemical defenses in stress conditions: the case study of the last disease outbreak observed in the NW Mediterranean. *Congrès "1906-2006: one century of marine research in Europe", European Federation of Marine Science and Technology Societies et Union des Océanographes de France, Institut Océanographique de Paris, 13-15 Septembre 2006.*
- Schiaparelli S., Castellano M., Povero P., Sartoni G., Cattaneo-Vietti R., 2007 - A benthic mucilage event in North-Western Mediterranean Sea and its possible relationships with the summer 2003 European heatwave: short term effects on littoral rocky assemblages. *Marine Ecology* 28 : 341-353.

- Southward A.J., Hawkins S., Burrows M.T., 1995 - Seventy years' observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *Journal of thermic Biology* 20 : 127-155.
- Sparnocchia S., Schiano M.E., Berger J., Del Rio C.M., 2006 - The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean). *Ann. Geophys.* 24 : 443-452.
- Stahli A., Schaerer R., Hoelzle K., Ribi G., 2008 - Temperature induced disease in the starfish *Astropecten jonstoni*. *JMBA2 - Biodiversity Records* : 1-5.
- Stephens J.S., Hose J.H., Love M.S., 1988 - Fish assemblages as indicators of environmental changes in nearshore environments. In Soule D.F., Keppel G.S. (ed.), *Marine Organisms as Indicators*. Springer, New-York : 91-103
- Sussman M., Loya Y., Fine M., Rosenberg E., 2003 - The marine fireworn *Hermodice carunculata* is as winter reservoir and spring-summer vector for the coral-bleaching pathogen *Vibrio shiloi*. *Environmental Microbiology* 5 (4) : 250-255.
- Thomas C.D., Cameron A., Green R.E., Bakkenes M., Beaumont L.J., Collingham Y.C., Erasmus B.F.N., Ferreira de Siqueira M., Grainger A., Hannah L., Hughes L., Huntley B., van Jaarsveld A.S., Midgley G.F., Miles L., Ortega-Huerta M., Peterson A.T., Phillips O.L., Williams S.E., 2004 - Extinction risk from climate change. *Nature* 427 : 145-148.
- Thomas O.P., Sarrazin V., Ivanisevic J., Amade P., Pérez T. 2007. - Sponge chemical defenses in stress conditions: the case of the last disease outbreak observed in the NW Mediterranean. *5th European Conference on Marine Natural Products, Ischia, Italy*.
- Torrents O., Tambutté E., Caminiti N., Garrabou J., 2008 - Upper thermal threshold of shallow vs deep populations of the precious Mediterranean red coral *Corallium rubrum* (L.): assessing the potential effects of warming in the NW Mediterranean. *Journal of Experimental Marine Biology and Ecology* 357 : 7-19.
- Vacelet J. 1990. - Report of a mission in Tunisia, Syria, Cyprus, Greece and Turkey, 26 September-4 October and 25 October-12 November 1989 in the context of the programme Fight against the epidemic decimating sponges in the Mediterranean. *Document FAO* : 14 pp.
- Vacelet J. 1991 - Statut des éponges commerciales en Méditerranée. In Boudouresque C.F. (ed.), *Les espèces marines à protéger en Méditerranée*. GIS Posidonie, France : 35-42
- Vacelet J. 1994. - The struggle against the epidemic which is decimating Mediterranean sponges. *FAO, rapport technique*, 39 pp.
- Vacelet J., Gaino E., Gallissian M.-F., Vacelet E. 1994. Bacterial attack of spongin skeleton during the 1986-1990 Mediterranean sponge disease. in R.W.M.van Soest, T.M.G.van Kempen, J.C. Braekman, eds. *Sponges in time and space; Biology, Chemistry, Paleontology* : 355-362.

- Verlaque M., Boudouresque C.F. 2004. - Invasions biologiques marines et changement global. *Deuxièmes Journées de l'Institut Français de la Biodiversité*, Marseille, 25-28 mai 2004, section 4 : 74-75.
- Walther G.R., Post E., Convey P., Menzel A., Parmesan C., Beebee T.J.C., Fromentin J.M., Hoegh-Guldberg O., Bairlein F., 2002 - Ecological responses to recent climate change. *Nature* 416 : 389-395.
- Ward J.R., Lafferty K.D., 2004 - The elusive baseline of marine disease: are diseases in ocean ecosystems increasing? *PLOS Biology* 2 (4) : 542-547.
- Warn F., 2000 - *Bitter Sea: the real story of greek sponge diving*. Guardian Angel Press, 128 pp.
- Weinberg S., 1975 - Ecologie des octocoralliaires communs du substrat dur dans la région de Banyuls-sur-mer. *Bijdragen tot de Dierkunde* 45 (1) : 50-70.
- Zabala M., Garcia-Rubies A., Louisy P., Sala E., 1997a - Spawning behaviour of the mediterranean dusky grouper *Epinephelus marginatus* (Lowe, 1834) (Pisces, Serranidae) in the Medes Islands Marine Reserve (NW Mediterranean, Spain). *Scientia marina* 61 (1) : 65-77.
- Zabala M., Louisy P., Garcia-Rubies A., Gracia V., 1997b - Socio-behavioural context of reproduction in the Mediterranean dusky grouper *Epinephelus marginatus* (Lowe, 1834) (Pisces, Serranidae) in the Medes Islands Marine Reserve (NW Mediterranean, Spain). *Scientia marina* 61 (1) : 79-98.

EXECUTIVE SUMMARY

Global change, particularly climate warming and the increased frequency of extreme events affects both terrestrial and marine ecosystems. The present climate change is very clearly a result of the exponential development of human activities and goes far beyond the borders of natural variability. The potential effects of global change act at several levels of biological organisation, from the physiological disturbance of individuals to modifications of a community and how it functions, through local extinctions and/or the extinction of certain species. Predictions about the consequences of warming for biodiversity as a whole are very worrying. On the basis of a moderate climate change scenario, a recent estimation anticipates an extinction of 15-37% of the species that today occupy this area by 2050. The Mediterranean is one of the regions most sensitive to climate change and shelters 4-18% of world marine biodiversity according to the taxonomical groups considered. However, none establishment of a model tries to assess Mediterranean biodiversity so far. Inspired by the existing published summaries and the most recent scientific data, a summary on the effects of warming in the Mediterranean was drafted. From this first trial balance, a debate might be possible on adaptation measures to restrict the negative aspects of impacts by reducing the ecosystems' vulnerability, and to exploit the positive aspects or opportunities in the best possible way.

The recent appearance of a set of long-term temperature records has demonstrated for the north-western Mediterranean a warming trend of about 1°C in 30 years and a rise in the frequency of extreme events. Since this kind of data is often lacking in the other parts of the Mediterranean, suitable strategies should be set up to develop prediction models for changes in the environmental conditions (warming, movement, nutriment content).

The migrations of southern species were the first signs of the biological effects of warming in the Mediterranean. The most numerous reports are for the north-west Mediterranean and the Adriatic. It is thought that short-term modifications of the ichthyological populations reflect almost in real time – in any case on the scale of one generation – changes in the hydrological conditions. In the north-western Mediterranean, the most recent list mentions several dozen species whose area of distribution has significantly changed since the 1970s. Among these movements we note the arrival of several species of fish (*Sardinella*, barracudas, coryphenes) which are gradually taking their place in the regional fisheries. Beyond these positive effects we are also witnessing the collapse of stocks of small pelagics (sprat, anchovy) and/or modifications of the life-cycles of certain favoured catches (tuna, amberjack). Biological invasions are often seen as an element of global change since they affect biodiversity and often appear to be linked to climate change, encouraging, especially in the eastern Mediterranean, the advance of Lessepsian species. Moreover, recent cases of the introduction of exotic dinophyta with biotoxins or the proliferation of species producing mucilages, have also been correlated to the occurrence of climate anomalies.

Extreme climate events are experienced as acute stress that disturbs the normal functioning of a biological system. Today, heat stress is widely recognized as the main factor in triggering diseases at sea, with a visible tendency for these events to become increasingly frequent in the Mediterranean. The species affected by these events are vital elements of the underwater landscapes, mostly sponges and gorgonians. Although mortalities of gorgonians have been known since the 1970s, and those of commercial sponges since the mid-1980s, the two events that stayed in people's minds were those of 1999 and 2003, both happening after exceptionally great temperature anomalies. The primordial role of warming has been well established, but different modes of action have been evoked. It has been shown on several occasions that temperature anomalies could trigger the virulence and/or condition the propagation of pathogenic agents (*Vibrio*) for sponges, cnidaria or echinoderms. Furthermore, the action of pathogenic agents could be facilitated by an inhibition of the defence capacities of organisms subjected to heat stress. It therefore seems necessary to develop epidemiological studies to decide which factors trigger and propagate pathogenic agents. Very generally speaking, it would be interesting to set up a georeferenced database on the distribution of species that are sensitive to climate change in the Mediterranean, and to perfect methods for monitoring their distribution boundaries, and models that will predict the risk of extinction in the Mediterranean. Major information is still lacking before we can assess with precision the resilience of invertebrate populations affected by extreme climate events:

- (i) Good knowledge of life-cycles, reproductive effort, successful reproduction and recruitment of larvae, contribution of asexual reproduction and regeneration in keeping up populations
- (ii) Good characterization of the genetic structuring of populations permitting the flow of genes between them, and the dispersion capacities of the propagules, to be assessed
- (iii) Tools enabling the possibilities of adaptation to the stress generated by overall change in the Mediterranean to be appraised, whether this means physiological adjustments (phenotype plasticity) or microevolutive processes.

The expected consequences of the changes in biodiversity caused by the displacement or disappearance of certain species are modifications in how the marine ecosystems function. Only long-term observation can enable the natural variations in community composition, and the links with climate fluctuations on various levels to be appraised. They are essential for predicting the effects of climate change on natural resources. For instance, the temperature anomalies of the mid-1980s were what triggered very great modifications in the plankton communities that are at the base of the trophic network of many pelagic species. The productivity of the marine ecosystems can also be influenced by variations in the flow of the major rivers, which itself is influenced by climate variability. This was shown in a series of chain reactions after the Rhône spates that caused major entries of terrigenous organic matter into the coastal environment, encouraging polychaete, and then

flat-fish, populations. It was also shown that deep ecosystems can also respond very quickly to climate variability.

Faced with the evolving Mediterranean environment, possible adaptation options deserve in-depth strategic reflection. So at the end of this inventory, a few paths are put forward:

- Widen the base of knowledge, and study the effects that can result from other variables linked to climate change: modifications of rainfall regimes, currents, biogeochemical equilibria, etc.
- Develop predictive models that incorporate aspects of the life-history features of sensitive species, intra- and inter-specific competition, or prey/predator relationships
- Improve the visibility of Mediterranean marine biodiversity conservation issues in the context of climate change
- Develop economic indicators to measure the consequences of modifications of biodiversity for the human activities that it underpins
- Give assistance to the developing countries to assess their vulnerability in the face of climate change
- Develop correct ecological engineering
- Reduce other sources of disturbance to marine biodiversity, minimize the fragmentation of habitats, and facilitate dispersion by maintaining connectivity between populations
- Protect relic systems (not impacted at all, or little impacted) by putting them into reserves.