Multidisciplinary approach to assess potential risk of mortality of benthic ecosystems facing climate change in the NW Mediterranean Sea

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***Abstract*— Climate change by the end of the 21st century is expected to induce great changes of coastal benthic ecosystems at the sub-regional scale in the North Western Mediterranean Sea. In order to assess the impact of the expected warming, we developed a strategy for the definition of warming scenarios in coastal habitats and their potential sub-lethal to lethal impacts on key benthic species. This was achieved by combining numerical simulations under IPCC-A2 scenario with field observations and thermo-tolerance experiments. First, a model validation was conducted for the period 2001-2008 in contrasted coastal areas. Then, scenarios forecast run temperature outputs were analyzed in order to explore the expected changes in the stratification by the end of the 21st century. These simulations were used together with species spatial distribution and thermo-tolerance functions to explore the potential risk of temperature induced mortality for the red gorgonian *Paramuricea clavata*, considered a key-species in coastal Mediterranean ecosystems, by the end of the century.**

Keywords*— numerical model; Mediterranean Sea; risk assessment ; mortality; climate change ; benthic ecosystems

I. INTRODUCTION

The Mediterranean Sea is highly responsive to climate change. Dramatic impacts are expected to occur in benthic coastal ecosystems which are among the most exposed to the warming trend and to the increase in magnitude and frequency of extreme events [1]. In this semi enclosed microtidal sea with seasonal stratification up to 15°C, the influence of (sub)meso scale dynamics (eg. upwelling, downwelling) is crucial in modulating local thermal regimes and potential impacts of climate change at local scale [2,3]. Developing more precise/realistic scenarios of coastal habitats warming and potential impact on ecosystems is crucial for setting up sound management and conservation plans of the rich Mediterranean biodiversity. It is recognized as a priority theme of international programs (eg. CIESM, MEDPAN, MERMEX). In the present work, we specifically addressed the potential risk of mass mortality outbreaks driven by thermal stress in rocky benthic ecosystems of the NW Mediterranean [4,5] by the end of the 21st century. Our approach is based on the use of scenario A2 temperature from the NEMOMED8 model [6], observations of temperature and information of current

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organisms geographic and depth range distribution and response to temperature changes [5]. We focused on the risk of temperature induced mortality of the red gorgonian *Paramuricea clavata* considered as a key-species in coastal Mediterranean ecosystems.

The paper is organized as follows. The materials and methodology used for risk assessment of mass mortality events of benthic ecosystems by the end of the 21st century are described in section II. Results for the potential warming and impact on benthic mortality under IPCC scenario A2 are given in section III. Conclusions are drawn in section IV.

II. MATERIALS AND METHODS

We conducted a multidisciplinary approach combining hydrodynamic simulations, physical and biological coastal observations, and thermo-tolerance experiments. The vulnerability scenarios were obtained by combining adjusted warming scenarios, biological responses to warming and upper distribution limits, adapting the method described in [3].

A. The T-MedNet network for observation of temperature changes

High resolution temperature series (5-40m) have been obtained over the past 10 years in different coastal areas of Spain, France and Corsica (T-mednet initiative, http://www.t-mednet.org). Observations from 10 stations (Fig. 1) were used for model validation and correction of thermal stress in coastal habitats based on different statistical descriptors (Bias, RMSD, correlation) and distribution functions (percentiles).

Fig. 1. Coastal stations from the T-MedNet temperature observation network in the NW Mediterranean sea. The inset shows a diver attaching a temperature sensor along a rocky wall.

B. The NEMOMED8 model

In order to get the expected warming by the end of the 21st century, a forecast simulation was run under IPCC scenario A2 [7]. The warming was considered as the difference between temperature for the current period (2000-2010) and those for the period 2090-2099. In order to better take into account bias from the observations and the spatio-temporal variability, the warming was projected on the temperature of NEMOMED8 hindcasts for the period 2001-2008, after it was corrected from bias from observations.

We used a regional Mediterranean configuration of the NEMO ocean model of circulation called NEMOMED8 (NM8) that can be seen as an improved version of the OPAMED8 model [6] used in previous studies [8].

It predicts the sea temperature based on the following drivers: heat and water air-sea fluxes, river discharges and heat and water exchanges with the surrounding seas [9]. This model covers the whole Mediterranean Sea plus a buffer zone including a part of the near Atlantic Ocean. The horizontal resolution of NEMOMED8 is 1/8° in longitude, resulting in square grid cells of 9–12 km depending on the latitude. The model provides daily outputs of temperature on 43 vertical Z levels which thickness varies from 6m at the surface to 200m at the bottom with 25 levels in the first 1000 m. The computation time step is of 20 minutes.

Various forcings can be applied to NEMOMED8. In this work, we used the NEMOMED8 hindcasts and the A2 scenario outputs.

1) hindcast over the period 2001-2008

The atmospheric forcing comes from a dynamical downscaling of the ECMWF reanalysis filtered at the ERA40 resolution by the regional climate model ARPEGE-Climate named ARPERA with a resolution of 50 km [8,10,11,12]. The complete time series is available over the period 1961-2008.

2) A2 scenario over the period 2000-2010 and 2070-2099

Climate change scenario A2 is defined by the SRES (Special Report on Emissions Scenarios) as an emission scenario that is conservative for future prediction of global warming (IPCC, 2007). It assumes a very heterogeneous world that preserves local identities, and which results from a continuously growing human population and an atmospheric CO_2 concentration of 815 p.p.m. by 2099 [7]. The A2 scenario is a standard for regional climate studies. The atmospheric model follows the observed greenhouse gas and aerosol concentrations up to the year 2000 and the SRES-A2 scenario between 2001 and 2099. The forcing is the same as in [6]. This scenario is homogeneous in time throughout the time period from 1960 to 2099. This atmospheric model provided daily temperature data at a horizontal resolution of 50 km. Details on the implementation can be found in [9] and in Annex 2 of [13]. Using the NEMOMED8 projected temperatures for the 21st century under scenario A2, [13] assessed the potential effects of climate change on the species richness and mean body size of coastal Mediterranean fish assemblages. In the current study, the impact of the climate change during the 21st century is measured as the difference in temperature between a future period (2090–2099) and a reference period for the present climate (2000-2010). Information about potential bias and missing variability in the scenario can be assessed using the hindcast outputs over the reference period. In this study, we focused on the NW Mediterranean, north of 39°N (Fig. 2).

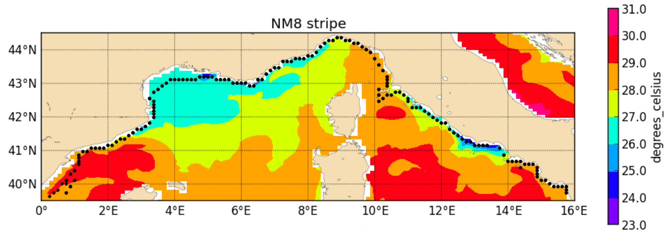

Fig. 2. Fig. 2. SST of August 2099 from NM8 under IPCC-A2 scenario and position of the 175 points extracted along the continental coastline (isobath 60m) in the NW-Mediterranean Sea

C. Thermo-tolerance functions for Paramuricea clavata

Thermo-tolerance response functions of the red gorgonian *Paramuricea clavata* were compiled from in situ temperature records obtained during 1999, 2003 and 2006 mass mortality events affecting this species [4,5] and from thermo-tolerance experiments. These experiments applied different treatments at constant temperature (23 to 28°C) to determine the exposure duration (number of days) until first sign of necrosis of colonies. The experiments were carried out with several populations of the red gorgonian dwelling in different areas in the NW Mediterranean, allowing to obtain a fair estimate on the response of this species to temperature stress.

Temperature impacts were classified in four risk levels: sub-lethal, moderate, high, and extreme. The last three were defined as the minimum, mean and maximum number of days of exposure at each temperature to when the first signs of necrosis were observed (see Tab. 1, adapted from [3]). The sub-lethal level was defined as half the duration of exposure of the high lethal level (or, if less, the duration of the moderate lethal level).

Table 1 shows that for the red gorgonian *Paramuricea clavata*, necrosis arose after sustained “moderate” increase in temperature (24-25°C) during several weeks or stronger short (duration of the order of the day) overheating (26-28°C). One should note that the highest the exposure temperature, the less variability in the biological response (e.g. all populations showed signs of necrosis after 2 days at 28°C).

TABLE I. SUMMARY OF THE THERMO-TOLERANCE FUNCTIONS AND ASSOCIATED LEVEL OF MORTALITY RISK.

Temperature threshold	**Number of days before 1st sign of necrosis**		
	Min	***Average***	***Max***
23°C	37	49	83
24°C	21	22	22
25°C	1	9	21
26°C	3	4	5
27°C	2	3	4
28°C	2	2	2
Risk level	moderate	high	extreme

D. Geographic and depth range distribution of key benthic species

From inquiry to Marine Protected Areas managers and researchers from Spain, France and Italy, inputs from citizen science initiatives and literature survey, we gathered information on the geographic and depth range distribution of the main gorgonian Mediterranean species over the NW Mediterranean basin. For the survey, the coastline was first divided in "coherent" sub-regions of 50 to 150 km width delimited by main geomorphological traits, expert knowledge and also Spain-France-Italy state frontiers. Each sub-region was then divided in two to three sub areas. Presence and upper distribution limit (UDL, in meters) data concerning each gorgonian species were pooled inside these sub-areas. For each sub-area, UDL of the red gorgonian *Paramuricea clavata* was calculated as the average of observations or integrative expert knowledge.

E. Risk assessment and impact maping

Maps on *P.clavata* potential risk of mortality induced by thermal stress by the end of the 21st century in the NW Mediterranean were built following a refined scheme of the methodology developed for the current period [3].

The method consisted of five steps:

1- NEMOMED8 hindcast temperature time series were extracted along the coastline within the 60-100 m isobath for the years 2001-2008 from Spain to Italy (Fig.2). Corrections were applied to the simulated temperatures using the bias computed by comparison with observations, or transfer functions between percentile distribution depending on the area.

2- the average warming expected at each location along the coastline during the period 2090-2099 was calculated by comparison of NEMOMED8 temperature scenario over 2090-2099 with those of 2000-2010 which was thus considered as the "control" run.

3- this warming was added to the NEMOMED8 2001-2008 hindcast temperatures, corrected of bias from observations, along the coastal stripe, in order to get a composite temperature pattern adjusted to the coastal habitats, representative of the end of the century.

4- for each year, we calculated the number of days when the temperature hindcast was above given thresholds, from 23 °C to 28 °C. These data were crossed with the thermo-tolerance response function of the red gorgonian *P. clavata* to evaluate the risk of mortality for each area and each depth range considered. Temperature impacts were classified in four risk levels obtained from thermotolerance functions: sub-lethal, moderate, high, and extreme lethal impact. The maximum stress level over the 8 year composite period was calculated, thus taking into account the hindcast pluri-annual variability.

5- the temperature stress level was crossed with information on the spatial (geographical and depth) distribution of *P.clavata* to evaluate the risk of mass mortality for the NW Mediterranean populations.

From this approach, we built maps of potential risk of *P. clavata* mortality outbreak for the beginning and the end of the 21st century.

III. RESULTS AND DISCUSSION

A. *Comparison between modeled and observed temperatures for the current period (2001-2008)*

Models comparison with coastal temperature series for 2001-2008 showed good performances for the NEMOMED8 hindcasts for monthly to annual time scales, even if extremes were underestimated, especially in subsurface layers (Fig. 3). Thus the approach of local correction of the regional model predicted temperature was used to explore the long term changes in stratification and extreme events by the end of the century.

Overall, a negative bias in the modeled temperatures was found during the period of seasonal stratification and a mean correction of 1°C was applied over the domain. Two areas benefited of refined correction based on comparison with up to 7 years of observation: N-Catalonia (Spain) and Provence (France) (Fig. 1). For these later, the applied correction was based on the shift in distribution of temperature percentile between observed and modelled temperatures as shown for a station near Marseille (Fig. 4).

B. *Warming expected by the end of the century*

1) *IPCC-A2 scenario*

The IPCC-A2 scenario showed a regular temperature increase with time, with a yearly and spatially averaged warming of about 2°C by the end of the century over the depth range examined (5-60 m) (Fig.5). Surface warming by the end of the XXIst century presented a strong seasonal component leading to an increased seasonal cycle (Fig. 6) [6]. Warming was about 2°C in winter and spring and higher in summer (2.9°C on average, up to maximum 3.4°C) and fall (2.3°C). The maximum temperature was on average 3°C warmer than under present conditions (26.4°C on August 21 vs. 23.4°C on August 23). In terms of thermal stress, besides the risk of reaching extreme supra thermoclinal temperatures, the exposure duration to warm temperatures increased tremendously. On average, the temperature of the warmest day under present radiative fluxes is expected to be outrun during

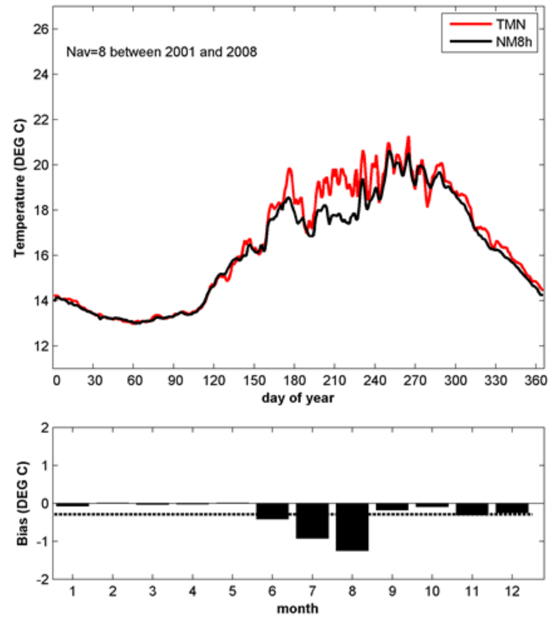

Fig. 3. Fig. 3. (Top) Average annual cycle at 10m depth from t-mednet observations (TMN) and NM8 hindcast for a coastal station near Marseille (France). (Bottom) Average and monthly bias (DEG C).

100 days by the end of the century (Fig.6, 1st July to 9th October).

All sub-areas are expected to experience large (> 2°C) surface warming from July to the end of October (Fig. 7). Maximums of up to 28°C are expected in August in the southwest of the domain (southern Catalonia). The maximum warming is expected in the Eastern Gulf of Lions and along Provence coasts (up to 5°C in Marseille area in September) possibly due to reduced wind stress over the domain, which is another trend of the climate change scenario that may severely affect coastal thermal regimes (modification of upwelling and downwelling regimes).

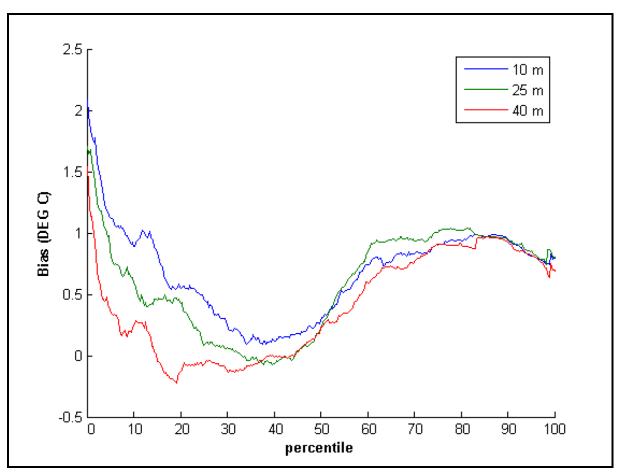

Fig. 4. Coastal transfer function at 3 depth level for a coastal station near Marseille. The 1st percentile corresponds to the maximum temperature and the 100th to the minimum temperature.

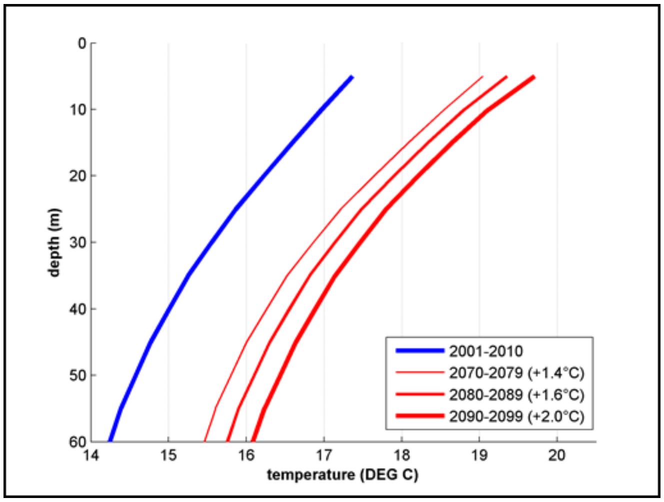

Fig. 5. Annual vertical temperature profiles averaged over the coastal stripe (isobath 60m) for the beginning and the end of the 21st century under IPCC-A2 scenario. Warming for each decade (vertical average) is indicated in the figure legend.

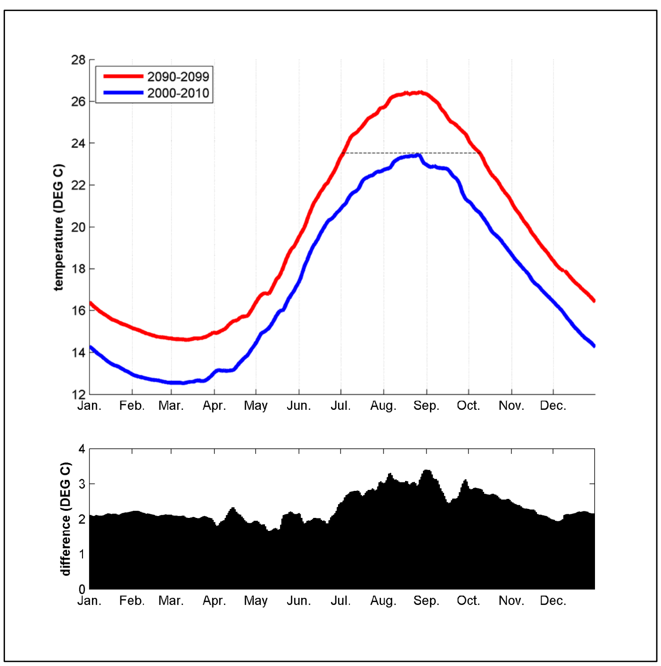

Fig. 6. Annual temperature cycle at 5 m depth averaged over the coastal stripe (isobath 60m) and expected warming (bottom panel) for the beginning and end of the 21lst century under IPCC-A2 scenario.

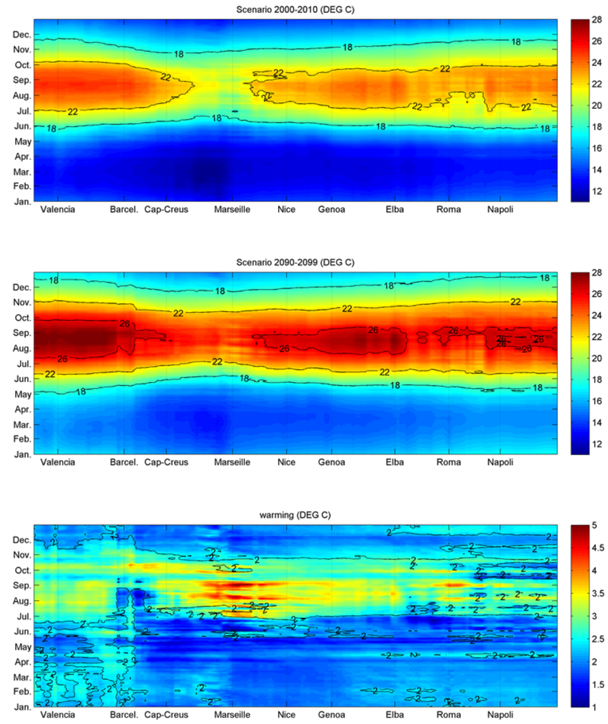

Fig. 7. Average annual temperature cycle over the coastal stripe at 5 m depth under IPCC-A2 scenario for (Top) the 2000-2010 period, (Middle) the 2090-2099 period and (Bottom) warming between the two periods.

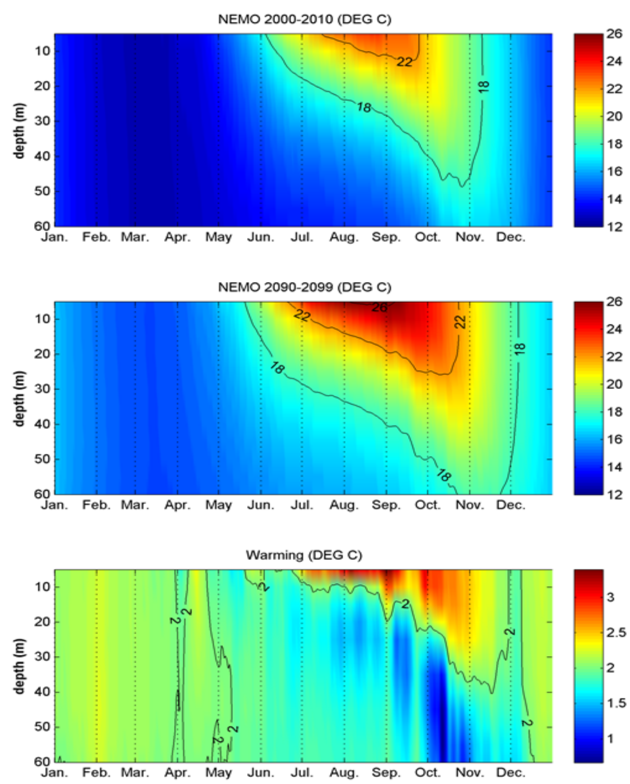

Fig. 8. Annual cycle of vertical temperature profiles averaged over the coastal stripe uner IPCC-A2 scenario for (Top) the 2000-2010 period, (Middle) the 2090-2099 period and (Bottom) warming between the two periods.

Examining the expected changes in the annual cycle of vertical temperature profiles (5-60 m) averaged over the continental coastal stripe showed homogenous warming of ca. 2°C in winter (Fig.8). Maximum warming (up to 3.3°C) is observed in supra-thermoclinal waters from July to November, confined to the upper 10-15m depth till September, then propagated at greater depth in October and November as illustrated by the deepening of isotherms 18 and 22°C.

2) Warming projection on hindcasts

In order to take into account the seasonal component of warming (i.e. highest warming for highest temperatures), warming functions were calculated from scenarios for each location/depth as the shift in distribution of temperature percentile between the beginning and end of the 21st century. These functions were projected on the corrected hindcast coastal stripe, for subsequent calculation of potential stress resulting from 21st century climate change in NW Mediterranean coastal habitats.

C. *Mortality risk assesment and impact maping*

To assess potential impacts of warming on coastal ecosystems by the end of the century, we focused here on the risk of temperature induced mortality. The temperature conditions along the coastal stripe were crossed with information on geographic and depth range distribution and thermotolerance function of the red gorgonian *Paramuricea clavata* considered a key species.

Over the entire coastal area, the UDL of *P. clavata* ranged between 10 and 50m depth. Populations are thus exposed to contrasted thermal environments.

First results were based on the hindcasts corrected from bias to observations for comparison with known/observed biological impacts over the past decade and aimed at identifying areas of high conservation concern under present conditions. In agreement with biological observations, the impact mapping highlighted a risk of mortality for *P. clavata* in N Catalonia and Provence areas (Fig. 9) [4]. For these areas, specific coastal corrections were applied (eg. Fig. 4). However, two areas highly impacted by the 2003 mass mortality event [4], the Gulf of Genoa (9°E) and the Gulf of Napoli (14°E), were not highlighted here, stressing the importance of coastal time series allowing the definition of coastal transfer functions when using regional model.

The methodology was then applied on the adjusted forecasts to explore for the very first time the potential impacts of climate change on NW Mediterranean *P. clavata* populations by the end of the century (Fig. 9). Results showed dramatic increase in the mortality risk level over a large part of the rocky coasts of the domain. Given the extreme risk level observed, shift in upper distribution limit is expected to occur.

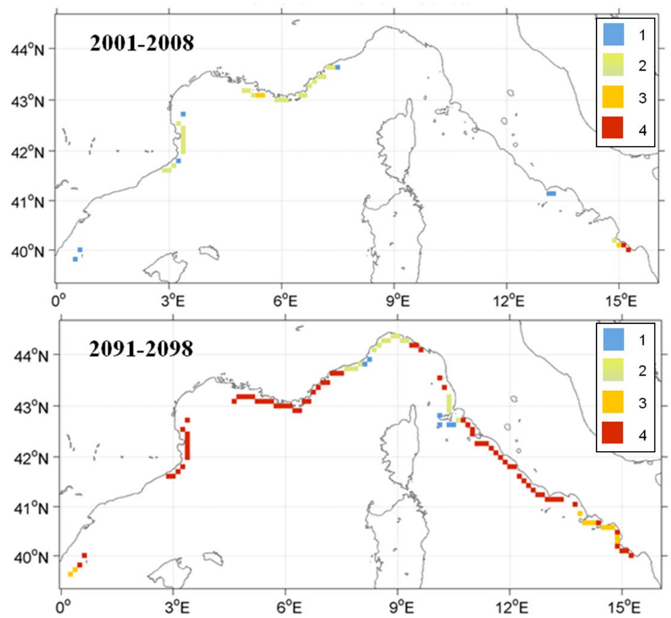

Fig. 9. Impact mapping on the risk of mortality outbreak for *Paramuricea clavata* at the beginning (Top) and end (Bottom) of the 21st century along the continental coastal stripe north of 39°N in the NW-Mediterranean Sea. The color scale, from 1 to 4, corresponds to sub-lethal, moderate, high and extreme lethal impacts respectively.

IV. CONCLUSION

Impact mapping provides information at appropriate spatial scales to stakeholders for sound management and conservation plans to mitigate the impacts of climate change on the rich marine biodiversity in the Mediterranean Sea.

In this paper, a method is proposed to evaluate the potential risk of mass mortality associated with thermal stress in benthic coastal ecosystems by the end of the 21st century at sub-regional scale: the NW Mediterranean.

Current area of mortality concern were identified along Catalonia and Provence from the use of temperature hindcast. They were also observed but not modeled in the Gulf of Genoa (9°E) and the Gulf of Napoli (14°E). Use of the NEMOMED8 scenario A2 to assess potential warming by the end of the century led to a large increase in the risk level over large parts of the rocky coasts of the NW Mediterranean.

In order to refine the previous results, the quality of the model data needs to be better taken into account in the model ratings, especially in areas where the intensity or duration of summer temperature extremes were not well enough reproduced by the hindcast for the current period.

In order to take into account the local variability at (sub)meso-scale, the next step will be to implement a downscaling of the NEMOMED8 scenario using a high-resolution mesoscale model. Overall, biological factors like environmental conditions, genetic factors, acclimatization should be taken into account.

Extension of this work could involve other climate change scenarios, benthic species and integration of other biological processes (e.g. migration of species, shifts in reproductive cycles, jelly fish blooms and the survival of larvae) and other climatic or non-climatic stressors [14].

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