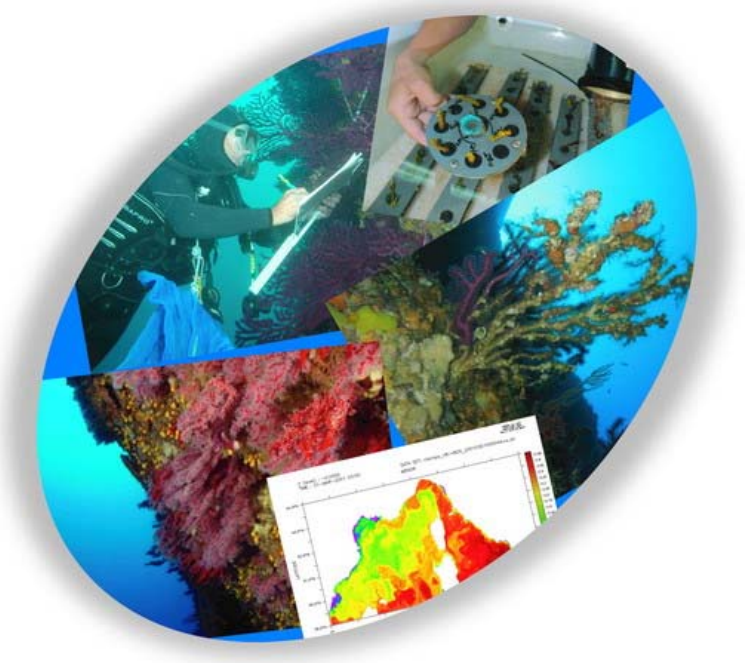
FONDATION TOTAL

Final report June 2013

CLIMCARES

CLimate Impacts on Mediterranean Coastal AREaS



Assessing climate change impacts on marine biodiversity conservation:

The case study of mass mortality events in the NW Mediterranean basin

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Final report on ClimCares project

Executive summary

The Mediterranean is considered a biodiversity hot-spot. The Mediterranean represents less than 1% of global ocean surface, but it hosts about 20% of marine biodiversity with a high level of endemic species. The Mediterranean is also considered a hot-spot for climate change with expected warming over the average along with a very likely increase in the occurrence of heat waves in climate change. In fact Mediterranean waters have been already significantly warming up during the last decades, and this trend is expected to increase during the rest of the 21st century.
Mediterranean marine ecosystems are already displaying clear responses to warming such as pelagic productivity, shifts in species' geographical distributions, modifications of migratory patterns and mass mortality outbreaks.
The MedRecover group (Spanish Research Council –CSIC- and University of Barcelona), IFREMER and IPSO-Facto with the funding of the TOTAL Foundation are working to produce sound information to help the conservation of the rich Mediterranean biodiversity. The expertise of the consortium allowed adopting a pluridisciplinary approach combining numerical simulations, field observations and experimental settings lead by specialists in the fields of physical oceanography modelisation, analysis of temperature regimes, benthic ecology, citizen science initiatives and conservation biology.
The aim of the ClimCares project was to assess the climate change impacts in the NW Mediterranean. We used ocean models to obtain information on the expected warming conditions by the end of 21st century which were coupled with the expected biological responses to the new temperature conditions. The final output of the project were mass mortality risks maps for key benthic communities to inform managers of coastal habitats about the potential effects of climate change.

Main conclusions

1. The availability of temperature records (T-MEDNet network www.t-mednet.org) was key to characterize temperature regimes and establish temperature conditions linked to mass mortalities reported during the last decades.

2. The comparison of *in situ* temperature records with outputs of the ocean models (MENOR and NEMOMED8) provided reliable estimates on temperature conditions in the NW Mediterranean coastal areas and they can be used to explore warming conditions by the end of the 21st century.

3. Thermotolerance experiments carried out in 12 key species (gorgonians, corals and sponges) depicted that exposure to temperature of 25 ºC for periods between several days or weeks result in negative impacts on the of the tested species. Exposure to temperatures beyond 26 ºC for most of species resulted in the development of severe tissue necrosis of the specimens. Overall, the high-diverse coralligenous communities suffer major impacts when exposed to temperature beyond 25 º C for periods between some days to several weeks.

4. The expected warming for the coastal areas of NW Mediterranean by the end of the 21st century will be characterized by:

-Average warming of about 2°C. Surface warming would be 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 would be on average 3°C warmer than under present conditions.

-Stratification will be enhanced. The warmest conditions met in the upper 20-30 m depth layer under present conditions are expected to be met down to 40 to 60 m depth by the end of the century depending on the areas considered.

-Overall in the depth range 5 to 60 m the exposure to temperatures above 25ºC will be significantly increased.

5. The risk of mass mortality on coralligenous benthic communities will be dramatically increased by the end of the 21st century in the NW Mediterranean coastal areas. The increase of the mortality risk concern areas for which the level at the beginning of the century was low or null are expected to suffer severe mass mortality events by the end of the 21st century.

6. ClimCares has examined only one of the potential effects of climate change showing severe impacts. Bearing in mind that other effects related with climate change and those associated to global change (e.g. overfishing, invasive species) are already underway, we could expect deep consequences for the conservation of the rich marine biodiversity of the Mediterranean.

7. The dissemination of the ClimCares results was supported trough the participation in several international meetings, publication of results in scientific journals, co-organization of 2 workshops devoted to the effects of climate change in the Mediterranean, development of a citizen science platform (seawatchers.org) and interviews in the media.

For more information please visit the ClimCares' project website: climcares.medrecover.org

ClimCares background

Recent climatic trends have resulted in significant responses in marine ecosystems, such as pelagic productivity, shifts in species' geographical distributions, community composition changes and modifications of migratory patterns (Rosenzweig *et al*. 2007). The increase in mass mortality outbreaks in coastal ecosystems during the past few decades has also been linked to modifications in environmental conditions caused by global change (Harvell *et al.* 1999*;* Harley *et al.* 2006). All these responses have occurred in the context of significant warming of the global average surface (+0.76°C for the 20th century; IPCC 2007) and upper global ocean (+0.3°C from 1950 to 2000; Levitus *et al.* 2000). Projections for the 21st century depict an increase in warming (+1.8 or +3.5°C depending on the emission scenario; IPCC 2007) along with a very likely increase in the occurrence of heat waves in climate change Hot-Spots such as the Mediterranean (Déqué 2007; Diffenbaugh *et al.* 2007). This scenario, jointly with other impacts on marine ecosystems, could cause a marine biodiversity loss crisis. Analyzing the impact of these modifications at appropriate scales (spatial and temporal) and biological organization levels (species, populations, communities) is crucial to accurately anticipate future changes in marine ecosystems and propose adapted management and conservation plans.

In the Mediterranean the shifts in the geographic distribution of thermophilic species and the mass mortality events are the first and the most cited signals of the effects of climate change (CIESM 2008). In the ClimCARES project we focused our efforts in analyzing the mass mortality risks associated to warming. During the last decades unprecedented mass mortality events have been observed in the Mediterranean. More than 30 species of macroinvertebrates belonging to 5 different phyla have been affected over broad spatial scales. Although some of the most affected communities may be living under the seasonal thermocline level (in "cold" water), intermittent and transitory processes (upwellings, downwellings, vertical mixing, horizontal advection, heat waves) can affect these habitats. However, mortalities also affected species dwelling in shallower coastal habitats. The NW Mediterranean has been one of the most affected regions by these events which were especially severe in 1999 and 2003 affecting large spatial scales (>1000 km) along the coasts of Spain, France and Italy down to 50 m depth. Other events have been reported from the same and other Mediterranean areas but in these cases the geographic range concerned were less extended and the number of species affected were usually lower and restricted to species of single phyla (e.g. bald sea-urchin disease *Paracentrotus lividus*) (Coma et al. 2009, Calvo et al. 2011). The impacts of mortality events in the populations have been severe especially in gorgonians and sponges species (Garrabou et al. 2009, Cebrian et al. 2011, Stabili et al. 2012). For instance, in some affected areas the populations of the red gorgonian *Paramuricea clavata* incidence of mortality rates could affect up to 90% of the colonies suffering different degree of damages (partial and total mortality) while in others damages were lower with moderate incidence of mortality (Garrabou et al. 2009).

These mass mortality events have occured in a context of regional coastal waters warming of nearly 1°C over the past 3 decades (Vargas-Yanez *et al.* 2008; Bensoussan *et al.* 2009, Calvo et al. 2011). During this period, most of mass mortalities were concomitant with high temperature anomalies (Bensoussan et al. 2010, Crisci et al. 2011). Under the actual climate projections, the NWM sea surface temperature may

experience an average warming of 2 to 4°C by the end of the century (Somot et al. 2008). Under these conditions, incidence of mortality events may spread over larger geographic areas and a wider spectrum of organisms.

However, the spatial resolution (50 to 10 km) of global to regional models used so far for the development of warming scenarii remains inapropriate for the coastal areas which support high ecosystem biodiversity and socioeconomic values. Only through the use of realistic models adressing mesoscale process and fine coastal differences, such as Menor/Mars3D, we will be able to anticipate changes in stratification at regional scale, within sub regions, and their potential impacts.

In the ClimCARES project we focused in the mass mortality events that occurred in the NW Mediterranean benthic communities dominated by emblematic and engineer gorgonian species. These communities belong to the coralligenous assemblages which are considered to be one of the most diverse in the Mediterranean (Ballesteros 2006). This assemblage has also a high socio-economical interest since its diversity harbor potential valuable natural products and the beauty of their seascapes sustain most of the recreational diving activities. Bearing in mind that the Mediterranean harbours a significant part of the marine biodiversity (Coll *et al.* 2010), efforts devoted to promote the conservation of Mediterranean under the current expansion and intensification of global change effects may result in a significant step towards to counterbalance the expected biodiversity loss worldwide during the 21st century.

ClimCares goals

The main aim of ClimCares was to investigate the potential impacts of climate change on Mediterranean marine biodiversity by developing warming scenarios by the end of 21st century which were coupled with the expected biological responses to temperature warming. More particularly the project was focused in the analysis of the occurrence of the mass mortality events under the expected warming. ClimCares developed an original strategy to assess the present and future risk of mortality outbreaks on the NW Mediterranean coastal areas (Figure A). We used a pluridisciplinary approach conducted at large geographic scale (the NW Mediterranean Sea) combining numerical simulations, field observations, experimental settings and bibliographic study lead by specialists in the fields of physical oceanography modelisation, analysis of temperature regimes, benthic ecology, citizen science initiatives and conservation biology. The development of ClimCares project was possible thanks to the successful synergy with past and current research efforts (projects) lead by the members of the ClimCares consortium. For instance, the availability of high resolution temperature series (in some cases more than 10 years of hourly temperature records) allowed the validation of modelisation of present oceanographic conditions. This validation (including correction strategies for some areas) allowed furnishing the most realistic set of warming scenarios for the 21st century available for the Mediterranean. The final output of the ClimCares project is to communicate the obtained to the scientific community, coastal managers and public. A special attention has been devoted to inform Marine Protected Areas (MPAs)

managers. In fact since in MPAs where most of other human activities are regulated, they can act as a sentinel sites to unambiguously detect the effects of climate change.

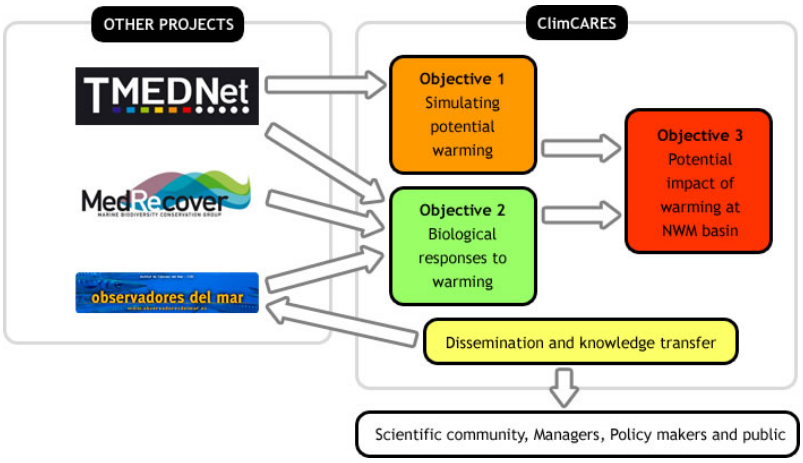

Figure A. *Schematic representation of ClimCares objectives*.

Description of ClimCares main tasks and results

Objective 1. Simulating potential warming of NWM coastal areas by the end of the century

Main tasks	Main activities
1.1.Development of T-MEDNet web platform for data management	• www.t-mednet.org web platform to visualize and manage temperature data series
1.2. High resolution temperature database and data acquisition	• Database with T hourly records from 1999-2013, 30 sites East. & West. Med. > 5.10^6 records
1.3. Definition of a strategy for modeling realistic warming scenario by the end of the 21st century along NW Mediterranean coastal areas	• Local correction of NM8* regional modeling under IPCC-A2 scenario • High resolution downscaling with MENOR**
1.4. Models validation for their use in the NW Mediterranean coastal areas	• Comparison T-MedNet series with NM8 hindcasts 2001-2008 • Comparison T-MedNet series with MENOR hindcasts 2000-2010
1.5. Warming scenarios along NW Mediterranean coastal areas	• Analysis of IPCC A2 scenario NM8 2090-2099 vs. 2000-2010 • Run and analysis of IPCC A2 scenario MENOR 2099
1.6. Obtaining thermal stress conditions for benthic communities by the end of the 21st century along NW Mediterranean coastal areas	• Development of model's correction approach to provide the best estimate on thermal stress conditions for benthic communities by the end of the 21st century

*NM8 = Nemo-MED8 model, 1/8 deg horizontal grid cell resolution

**MENOR = MARS3D-MENOR model, 1.2 km horizontal grid cell resolution

Task 1.1. Development of the T-MEDNet web platform for data management

ClimCares supported the development of new functionalities of the T-MEDNet (www.t-mednet.org) web platform published in July 2012. Two main components are available. The public one allows the visitors to explore the temperature records results through a graphical interface with different display options (Figure 1a). The second component provides access to different tools and information related with the T-database management to the partners of T-MEDnet (e.g. uploading the T records). This component is a key step forward the coherence of the T database since it is allowing the development of semi-automatic data treatment procedures (Figure 1b).

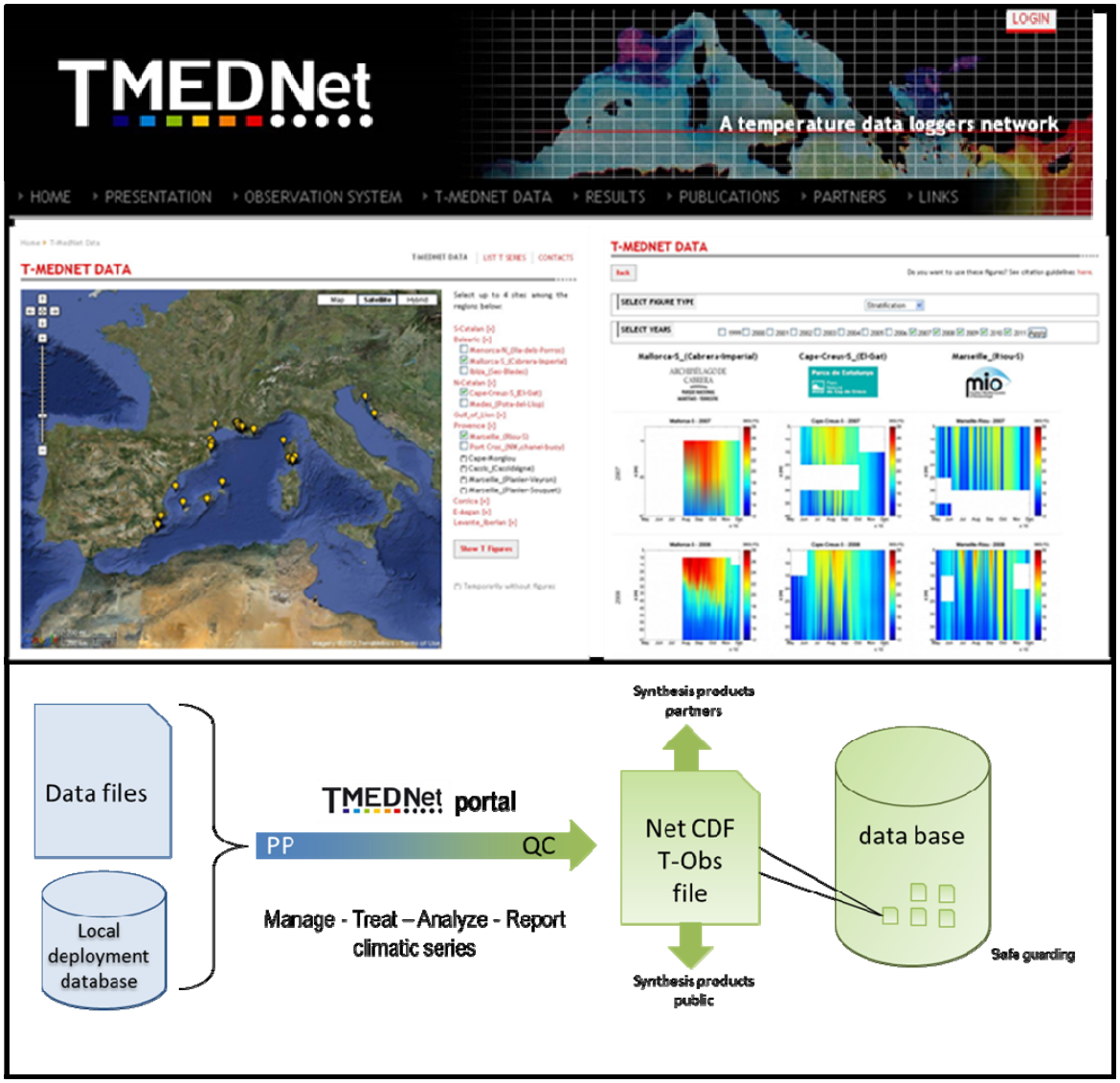

***Figure 1**. a) T-MEDNet graphical interface to explore the results of high resolution temperature records. b) Schematic representation of new functionalities for data series management and analysis through semi-automated procedures*.

Task 1.2. High resolution temperature database and data acquisition

We continued the acquisition of temperature records in the Catalan coast, Balearic Island and W Corsica. New teams are joining the T-MEDNet initiative providing records for new areas such as the Adriatic Sea, the Agean Sea and SE Spanish Coast. More than 30 sites are now active in acquiring high resolution temperature records. Some of these data are being compiled in the database developed within the ClimCares project. At this point more than $5x10^6$ temperature records are available. The t-MEDNet protocols on temperature surveys have been adopted by other international programs such as Tropical Signals (CIESM) and MERMEX (http://mermex.pytheas.univ-amu.fr). The network of T survey sites is expected to be enlarged during the next years.
In the framework of the CLIMCARES project, 12 coastal stations were considered for models validation (see Task 1.4). Their position and temporal coverage is shown in Figure 2.

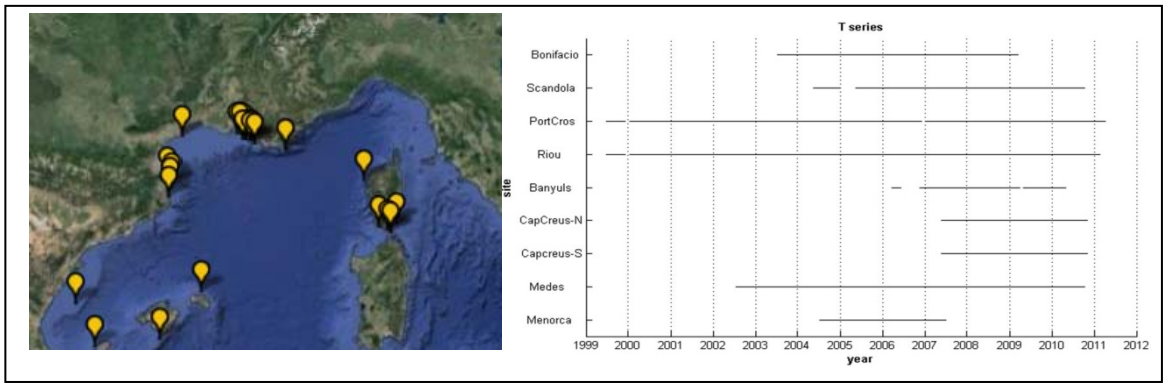

Figure 2. *Position of the T-MEDNet stations in the NW-Mediterranean and temporal distribution of some of the data series considered and analyzed in the project (all excepted Bonifacio).*

Task 1.3. Define strategy for modeling "realistic" warming scenario by the end of the 21st century along NW Mediterranean coastal areas

In order to get the expected warming by the end of the 21st century forecast simulations were run under the IPCC scenario A2. To obtain the forecast two ocean models NEMOMED8 (see Box 1) and MENOR (see Box 2) were used. One of the main differences of these models is the spatial horizontal resolution 10 vs 1.2 km for NEMOMED6 and MENOR respectively. The use of both models was retained because they provide complementary results (see Tasks 1.4). Finally, working with numerical scenarios of climate change requires the availability of realistic boundary conditions and atmospheric forcing. Within ClimCares we used the boundary provided by Meteo-France thanks to collaboration with Dr. Samuel Somot (French Met-Office), who

managed coupled ocean-atmosphere system at Mediterranean scale in the framework of IPCC scenarios (Somot et al. 2006, 2008).

A schematic representation of the approach conducted for the definition of temperature conditions along the coastline by the end of the 21st century is shown in Figure 3.

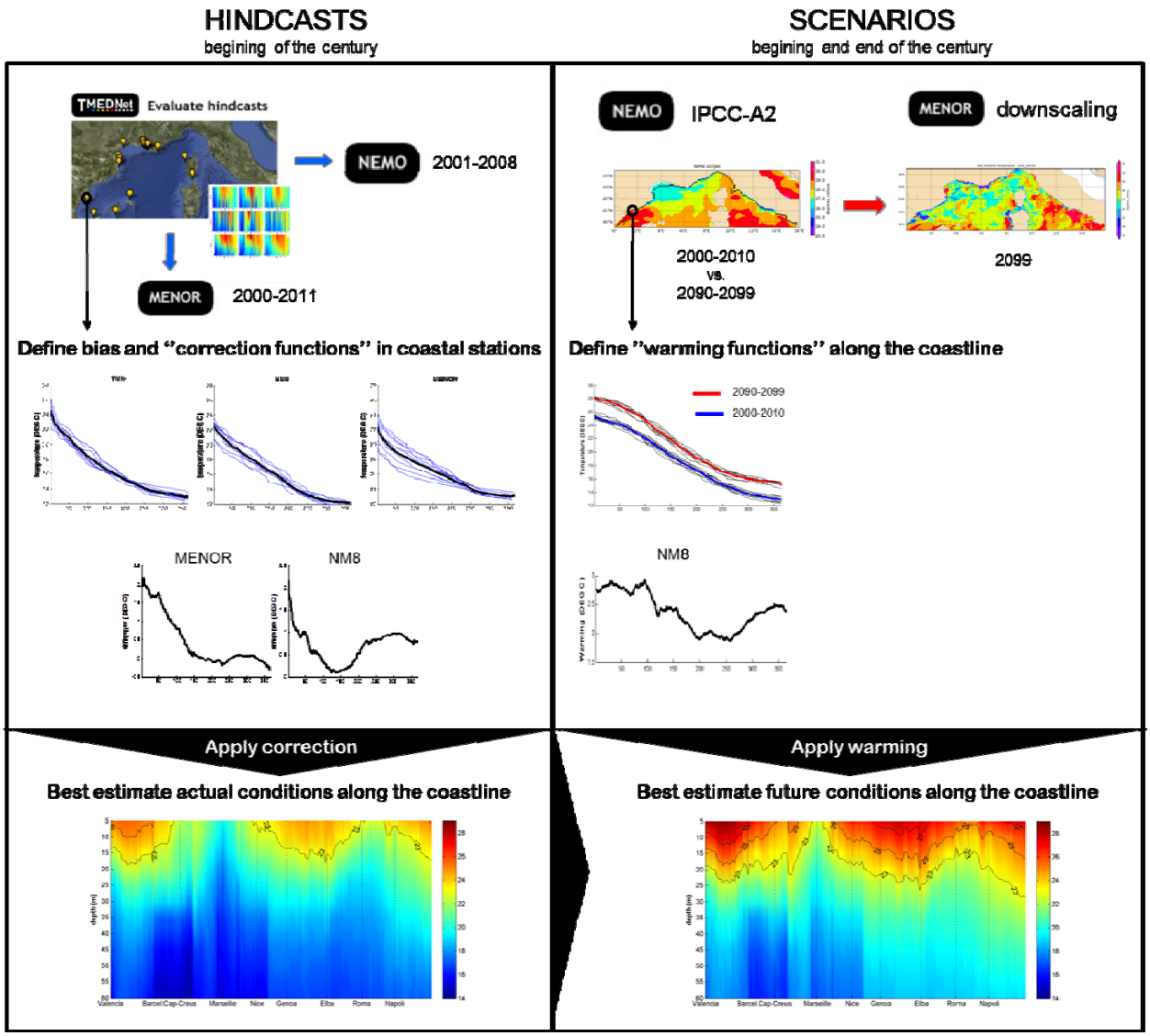

Figure 3. *Schematic representation of the successive steps for the definition of refined coastal temperature scenarios along the NW Mediterranean coastline by the end of the century. Bottom figures shown for final step correspond to average summer temperature profiles along the coastline north of 39°N.*

The approach consists in the following steps:

1- Evaluation of the ocean models on coastal areas. Using hindcasts runs for the beginning of the 21st century vs. high resolution temperature time series (T-MEDnet), it was possible to conduct thorough evaluation of NM8 and MENOR models performances at different time scales (day, season, pluri-annual) in contrasted coastal stations.
2- Definition of model corrections. From these comparisons, average bias and local transfer functions were defined for local correction in the coastal stations.
3- Simulation of temperature conditions by the end of 21st century. Using the NEMOMED8 run under IPCC-A2 scenario, it was then possible to obtain temperature conditions by the end of 21st century along the coastal stripes (within the 60-100 m isobaths, north of 39°N, Figure 4).
4- Definition of warming by the end of 21st century. Warming functions for each location/depth along the coastline were calculated from comparison of scenarios between the first and last decade of the 21st century.
5- Warming conditions by the end of 21st century in the NW Mediterranean coastal areas. These warming functions were then projected on the corrected hindcast coastal stripe (step 3) to obtain refined potential temperature stress by the end of the century.

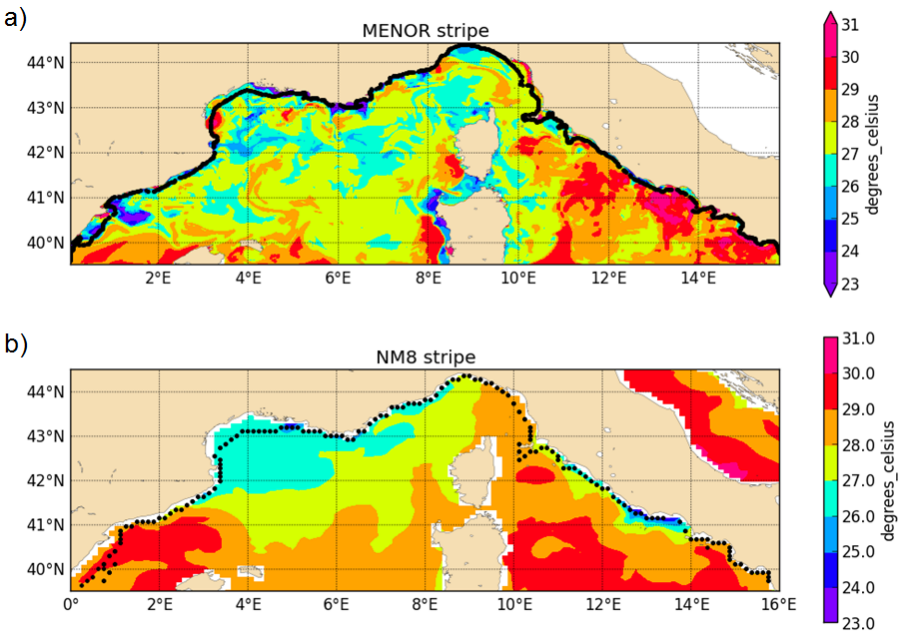

Figure 4. *(a) High resolution Sea Surface Temperature simulated by MENOR and position of the 925 vertical profiles (black) extracted along the continental coastal stripe (isobath 60 m). (b) Position of the 167 vertical profiles (black) extracted from NEMO-MED8 (NM8, 1/8 degree) along the continental coastal stripe (isobath 60 m).*

Box 1 - Description of the NEMO-MED8 model

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 (Somot et al., 2006) used in Coll et al. (2010).
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 (Beuvier et al., 2010). This model covers the whole Mediterranean Sea plus a buffer zone including a part of the near Atlantic Ocean. The horizontal resolution of NM8 is 1/8° in longitude, resulting in square grid cells of 9–12 km depending on the latitude (around 9-10km in our area). 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.
In this work, we used the NM8 hindcasts and the A2 scenario outputs, which are described hereafter.

- NM8 hindcast over the period 2001-2008:
The atmospheric forcing comes from a dynamical downscaling of the ERA40 reanalysis from the ECMWF by the regional climate model ARPEGE-Climate named ARPERA with a resolution of 50 km (Herrmann and Somot, 2008; Somot and Colin, 2008; Tsimplis et al., 2008; Beuvier et al., 2010). The complete time series is available over the period 1961-2008.

- NM8 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 CO2 concentration of 815 p.p.m. by 2099 (IPCC, 2007). 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 Somot et al. (2006). 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 is described by Beuvier et al. (2010) and in Annex 2 of Albouy et al. (2013). Using the projected temperatures for the 21st century under scenario A2, Albouy et al. (2013) 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 (2070–2099) 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.

Box 2 - Description of the MENOR model

The 3D numerical ocean model MARS3D (Model for Application at Regional Scale; Lazure and Dumas, 2008) was used to simulate temperature variations in the NW Mediterranean coastal areas over the period 2001-2010. It is a free surface primitive equation model under Boussinesq and hydrostatic assumptions, with an Arakawa-C grid.
The model configuration used for this study was the MENOR configuration which covers the region between 39°30' N and 44°30' N in the western basin. It was designed to reproduce mesoscale variability, with a horizontal resolution of 1.2 km and 30 sigma-coordinate vertical levels refined near the surface and the bottom. The initial and open boundary conditions were provided by an ocean global model in the framework of Mediterranean Operational Oceanography Network (http://www.moon-oceanforecasting.eu). The results were exploited after a 5-month spin-up. The atmospheric forcing for 2005-2010 was derived from the non-hydrostatic MM5 model (Mesoscale Model 5) developed by the National Center for Atmospheric Research (3 to 9 km horizontal resolution). Between 2001 and 2004, the results of the French Met-Office model ALADIN (10 km resolution) were used as an alternative. For the years 2001 to 2008, we used the 3-hourly MENOR outputs from the work on small-scale pelagic recruitment by Nicolle et al. (2009).
Similar configurations of MARS3D in the NW Mediterranean Sea have already been performed and evaluated for operational purposes (PREVIMER; http://www.previmer.org/en) or used to investigate surface ocean circulation (Andre et al. 2005; Andre et al. 2009), associated cross- shelf exchanges (Rubio et al., 2009), sediment dynamics (Dufois et al. 2008) or the effect of high resolution atmospheric forcing on the dynamics (Schaeffer et al. 2011).
In a previous work dealing with the validation of a coastal model of the eastern Gulf of Lions for the years 2007-2008, Pairaud et al. (2011) showed that the MENOR model satisfactorily reproduces the alternating increase and decrease of temperature that can be observed in summer in the eastern gulf of Lions under upwelling influence. Even if temperature extremes were underestimated, the spatial extent and duration of summer upwelling events were well reproduced in comparison with satellite SST imagery.
In collaboration with Dr. Samuel Somot (French Met-Office), a downscaling of the MENOR model in the NM8 scenario for a given year, 2099, was performed. In this case, the NM8 scenario atmospheric fluxes were used.

Task 1.4. Models validation for their use in the NW Mediterranean coastal areas

Models validation

Hindcasts run of NEMOMEM8 and MENOR were compared to temperature profile measurements of T-MEDNet in 12 stations (Figure 2) in order to evaluate statistically bias and errors and then apply local corrections to refine the climate change scenario proposed by Somot et al. (2008). Different time scales were examined (day-season-pluri-annual), focusing on the evaluation of the spatial (vertical, inter-site) and temporal coherence of information. Complementary descriptors such as RMS, correlation and Bias were employed (Pairaud et al 2011).

Since hindcasts runs were forced by realistic atmospheric models (see Box 1 & 2) we show here results for selected sites characterized by intense air-sea interactions: the downwelling area of north Catalonia (W Gulf of Lions) and the upwelling area near Cassis (E Gulf of Lions) (Figure 5).

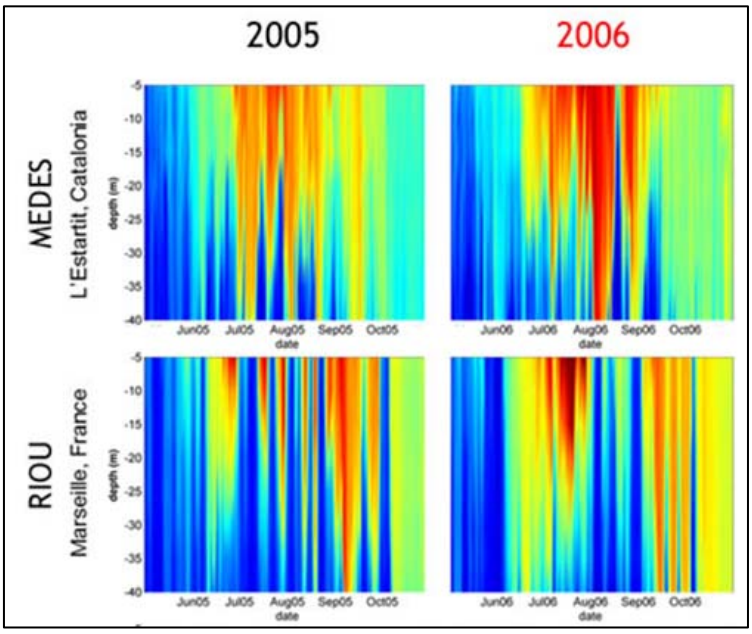

Figure 5. *Example of temperature records from May to October of years 2005 and 2006 (heat wave, warmest July over France for the past century) in N Catalonia (Medes, l'Estartit) and near Cassis upwelling source point (Riou, Marseille). Data source: t-MEDNet.*

Short to annual time-scale

Comparison of measured and modeled wind driven dynamics and seasonal cycle at Riou 10 m depth and Medes 35 m depth for year 2006 are shown in Figure 6. Overall, the annual cycle is fairly well represented by both models even if they tend to reduce the temporal variability. For instance, the strong subsurface warming of July at Riou and the thermocline deepening at Medes in August (Figure 5) are well represented but extrema are underestimated by 1 to 4 °C (Figure 6). In addition, the short term variability is smoothed or sometimes missed by models. This is particularily true for NM8 whose spatial resolution is 10-12 km. For instance, cooling induced by upwelled waters may be well represented but subsequent warming is too slow, leading to

overall large underestimate of thermal stress in upwelling area for NM8. Contrarily, the successive upwelling episodes are well captured in MENOR (spatial resolution 1.2 km), with however reduced amplitude in both cooling and relaxation. Validating the use of NM8 and MENOR models for coastal stations, these results also show the need for appropriate correction for fine estimate of thermal stress (e.g. the 1°C negative bias in NM8 for Medes 35 m or underestimate of extrema in all sites/depths).

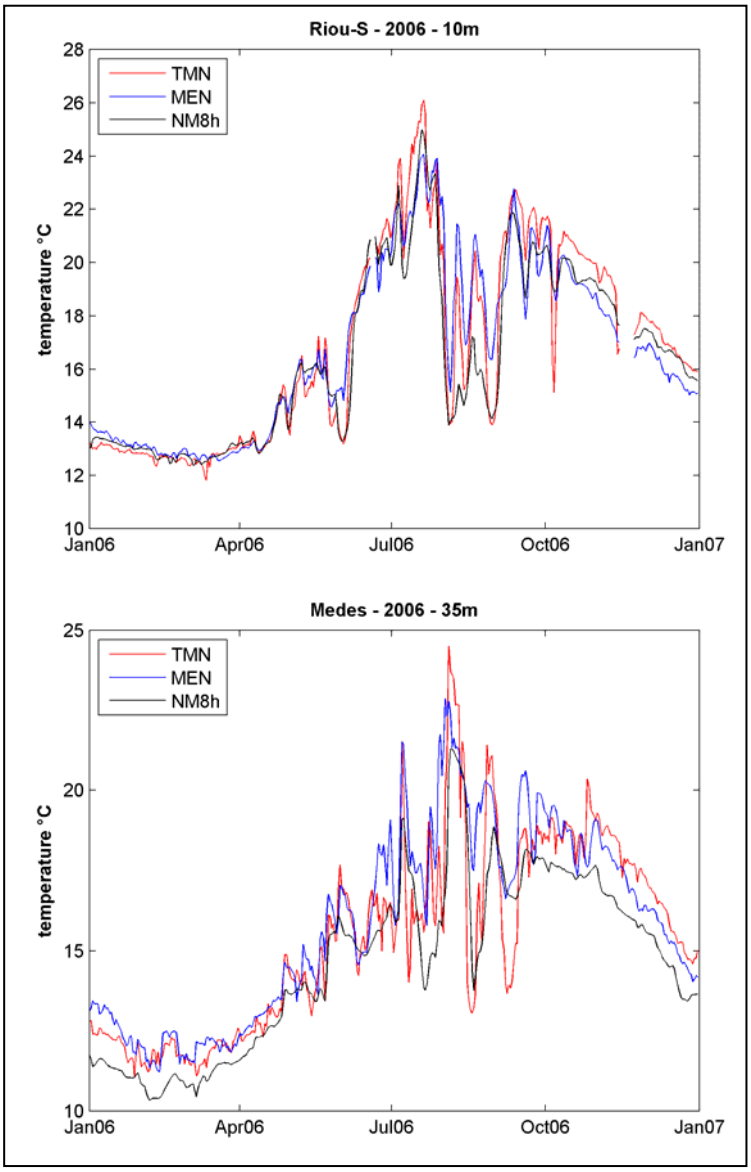

Figure 6. *Comparison of T-MEDNet observations (TMN), high resolution MENOR (MEN) simulations and coarse grid simulations of NEMOMED8 hindcasts (NM8h) for year 2006 at Riou 10 m and Medes 35 m depth.*

Pluri-annual time scale

MENOR and NEMMED8 yielded satisfying results in reproducing the average annual cycle calculated from pluri-annual observations, as shown at 10 m depth for selected sites (Figure 7). Fair agreement was observed for Catalonia (Medes), while negative bias was observed for both models during the stratified period in Marseille area, up to 2°C for MENOR in August.

The statistics (bias, correlation and Round Mean Square difference–RMS) were calculated for each depth level (Figure 7c), allowing evaluation of models performances over the 5-40 m depth water column. In Medes, both models yielded close results and logically much better scoring than scenario NEMOMED8 (NM8f; Figure 7) for the same period.

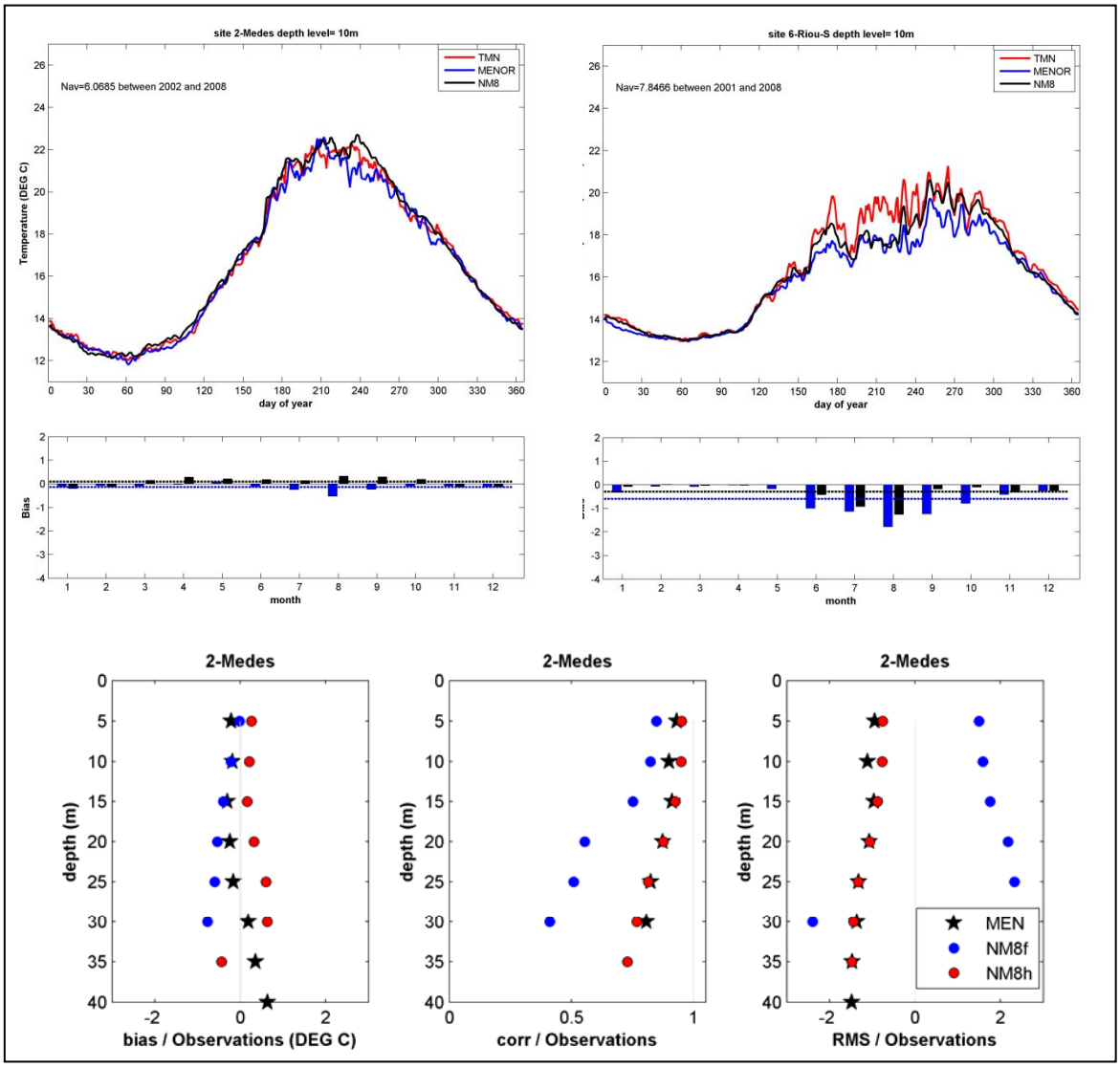

***Figure 7**. (Top and middle) Average annual cycle at 10 m depth at Medes and Riou coastal stations over the periods 2001-2008 and 2002-2008 respectively. T-MEDNet observations (TMN), MENOR (MEN) and NEMOMED8 (NM8) hindcasts are shown. The calculated average bias (lines) and monthly average bias (bars) are shown in bottom panels. (bottom) Exemple of statistic descriptors calculated along the depth gradient over the stratified period (May to October) for Medes. As previously, MENOR (MEN), NEMOMED8 hindcasts (NM8h) are shown but with different colors. The scenario for the beginning of the century provided by NEMOMED8 (NM8f) is also shown for information.*

However, spatial patterns on bias were observed showing negative bias in both models, i.e. the models tend to avoid extreme temperatures (Figure 8). Globally MENOR exhibited better scoring than NEMOMED8 for N Catalonia and contrarily NEMOMED8 better scoring along Provence, Corsica and Menorca (warmer waters). Schematically, MENOR performed better than NM8 in "cold and dynamical" areas and NM8 better than MENOR in "warm" areas.

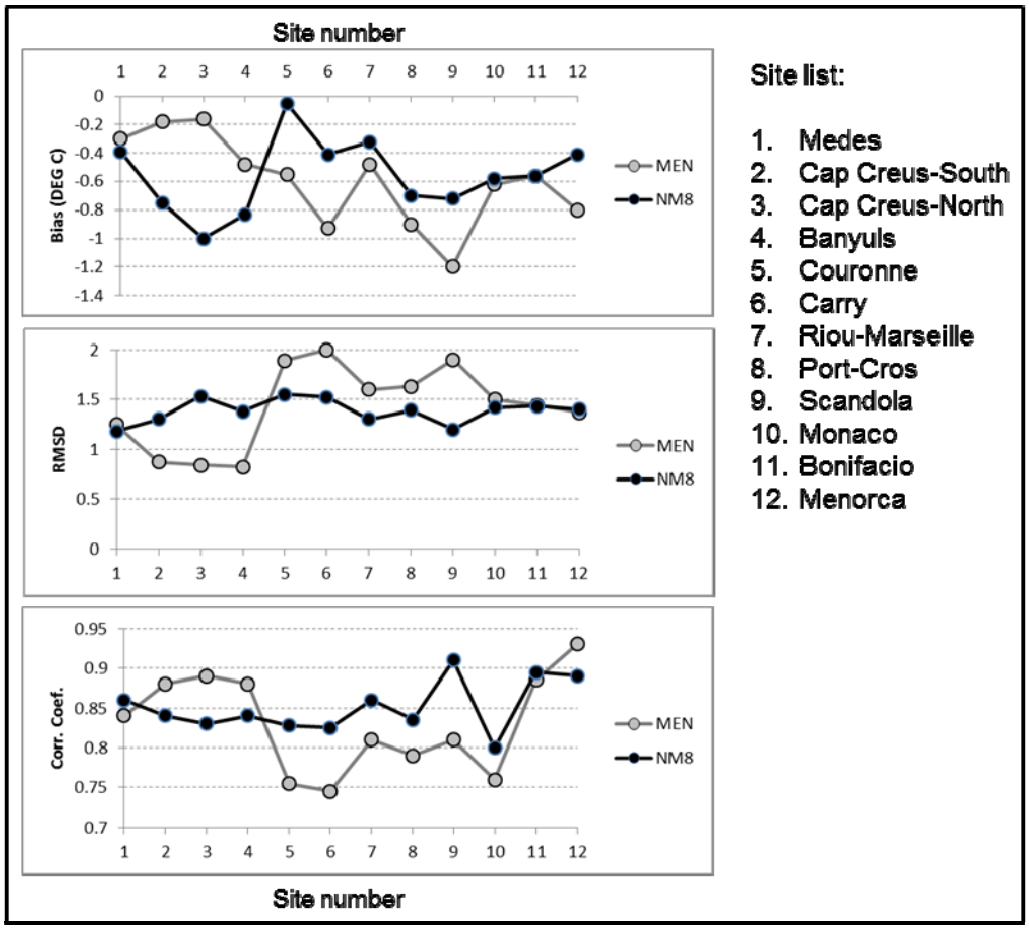

Figure 8. *Pluri-annual and vertically averaged Bias, RMSD and Correlation coefficient over the period from May to October for NEMOMED8 (NM8) and MENOR (MEN) at the 12 stations considered.*

This evaluation of NM8 and MENOR performances showed the interest of both models that appear complementary depending on the time scales and area considered. This first step of model validation permits to have reasonable confidence in long term trends as addressed in this study.

Calculation of transfer functions: a novel correction approach

Shift in distribution functions between simulations and observations was considered as a tentative approach for defining transfer functions for more realistic estimate of temperature stresses in coastal benthic habitats. These transfer functions were then applied to the hindcasts runs for local correction of modeled temperatures.

For each station, year and depth level, observed and simulated daily temperatures were sorted, from the highest to the lowest temperature (Figure 9). The pluri-annual

average distribution functions (percentiles of observed and simulated) were calculated (thick line). Difference between the two was then considered as a coastal transfer function that can be applied to the model outputs for more realistic estimate of temperature conditions.
In the example below, for Riou 10 m depth (Marseille area), the transfer function permits to take into account the strong underestimate of extrema in both models (ca. 2.2°C) while difference for the 50th warmest temperature is around 1°C in NEMOMED8 and 1.7°C in MENOR.

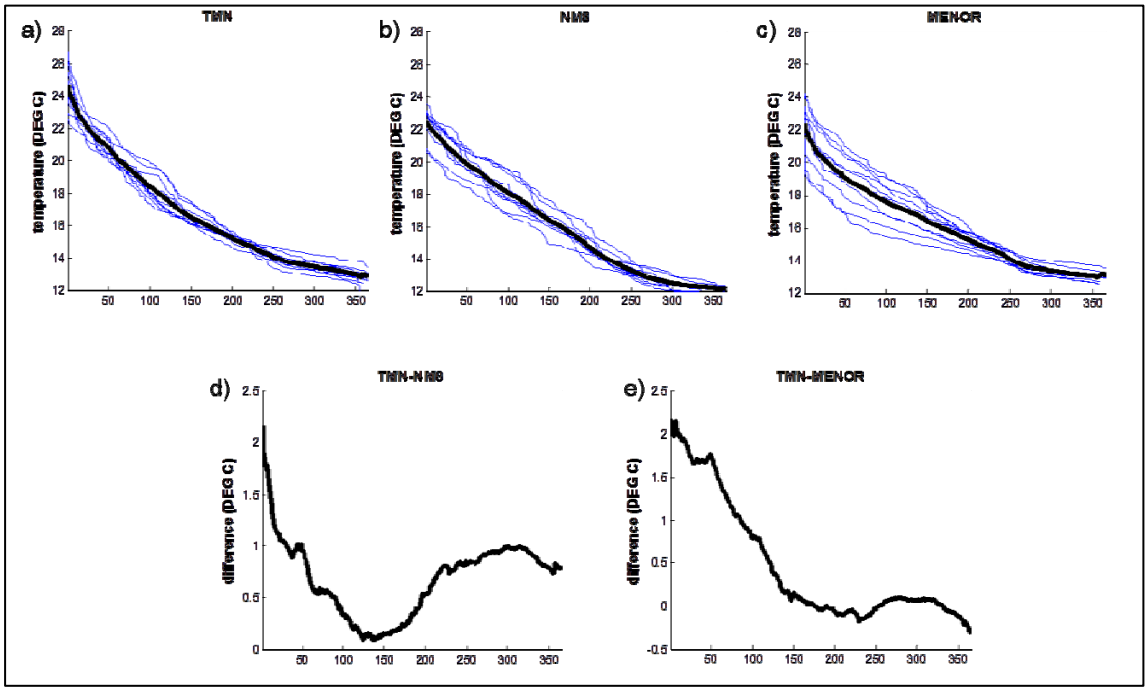

***Figure 9**. (a-c) Daily temperatures sorted from the warmest to the coldest, for each year available and data sets (observations, TMN and simulations: NM8 & MENOR) at Riou 10 m depth. Average values are indicated (black thick line). (d,e) Transfer function calculated as difference between average curves (a-b and a-c respectively).*

Task 1.5. Warming scenarios along NW Mediterranean coastal areas

NEMOMED8 warming scenario

The magnitude of warming by the end of the 21st century, was first evaluated through comparison of NEMOMED8 scenarios along the continental coastal stripe between the beginning and end of the 21st century.
NEMOMED8 scenario showed a regular temperature increase along time with a yearly and spatially averaged warming of about 2°C by the end of the century over the depth range studied (5-60 m) (Figure 10). Surface warming by the end of the 21st century presents a strong seasonal component leading to an increased seasonal cycle (Figure 11). Warming is 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 is on

average 3°C warmer than under present conditions (26.4°C on August 21 vs. 23.4°C on August 23).

Besides the risk of reaching extreme supra thermoclinal temperatures, the exposure duration to warm temperatures increases tremendously. In average, the temperature of the warmest day under present radiative fluxes is expected to be outrun during 100 days by the end of the century (Figure 11, 1st July to 9th October).

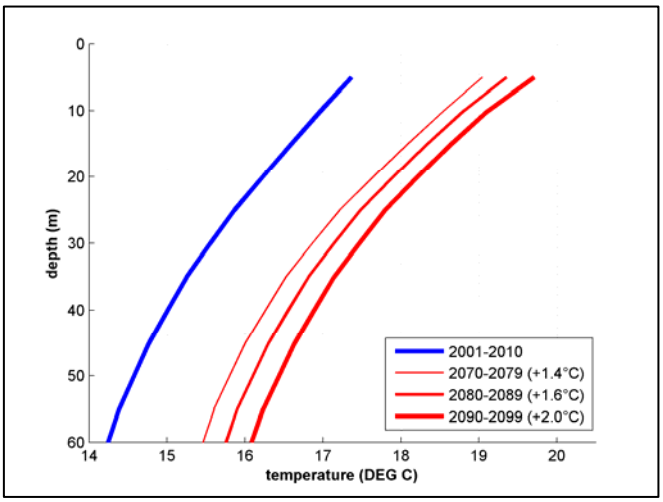

Figure 10. *NM8 IPCC A2 scenario. Annual vertical temperature profiles averaged over the coastal stripe for the beginning and end of the XXIst century. Warming for each decade (vertical average) is indicated in the figure legend.*

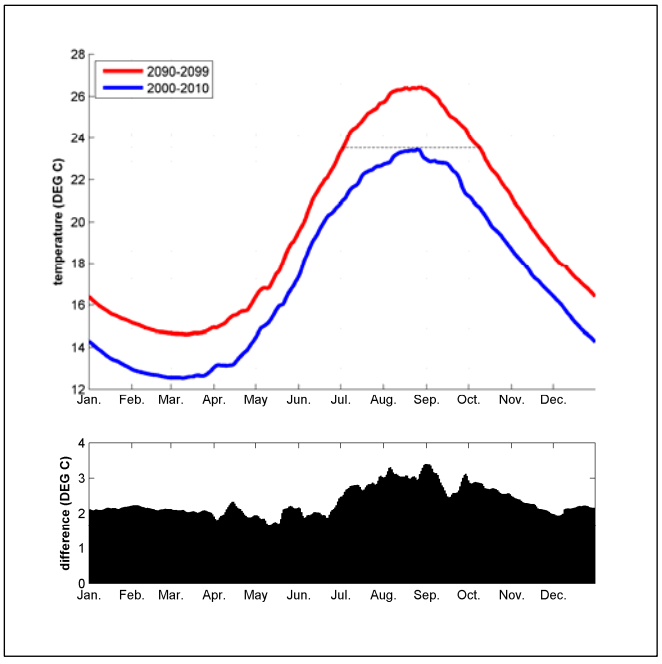

Figure 11*. NM8 IPCC A2 scenario. Annual temperature cycle at 5 m depth averaged over the coastal stripe for the beginning and end of the XXIst centur (Bottom pane)l*

All sub-areas are expected to experience large (> 2°C) surface warming from July to the end of October (Figure 12). Maximums up to 28°C are expected in August in the southwest of the domain (southern Catalonia). 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 ongoing climate change that can severely affect coastal thermal regimes (modification of upwelling and downwelling regimes).

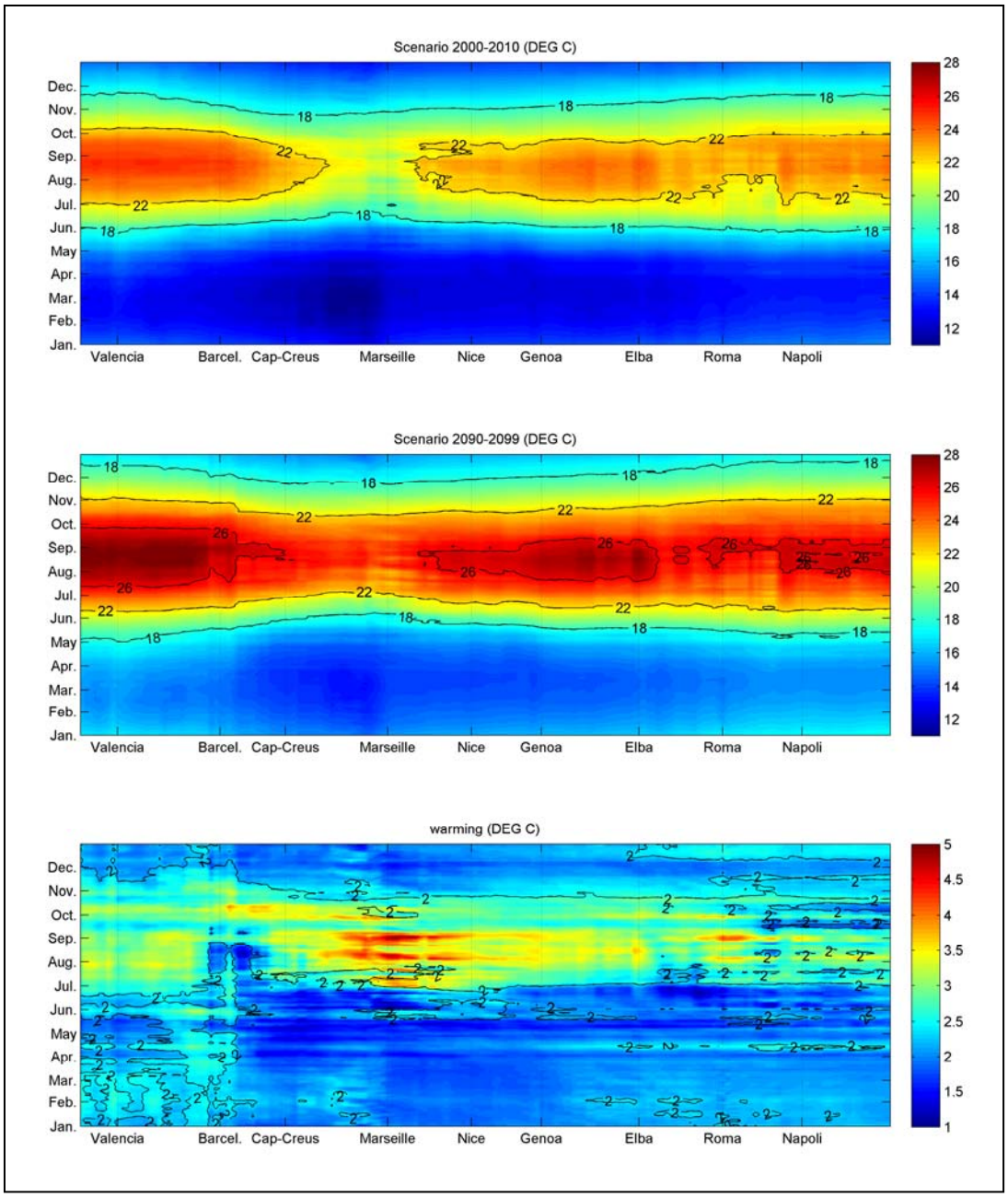

***Figure 12**. Average annual temperature cycle over the coastal stripe at 5 m depth for (top) the 2000-2010 period, (middle) the 2090-2099 period and (bottom) warming between the two periods.*

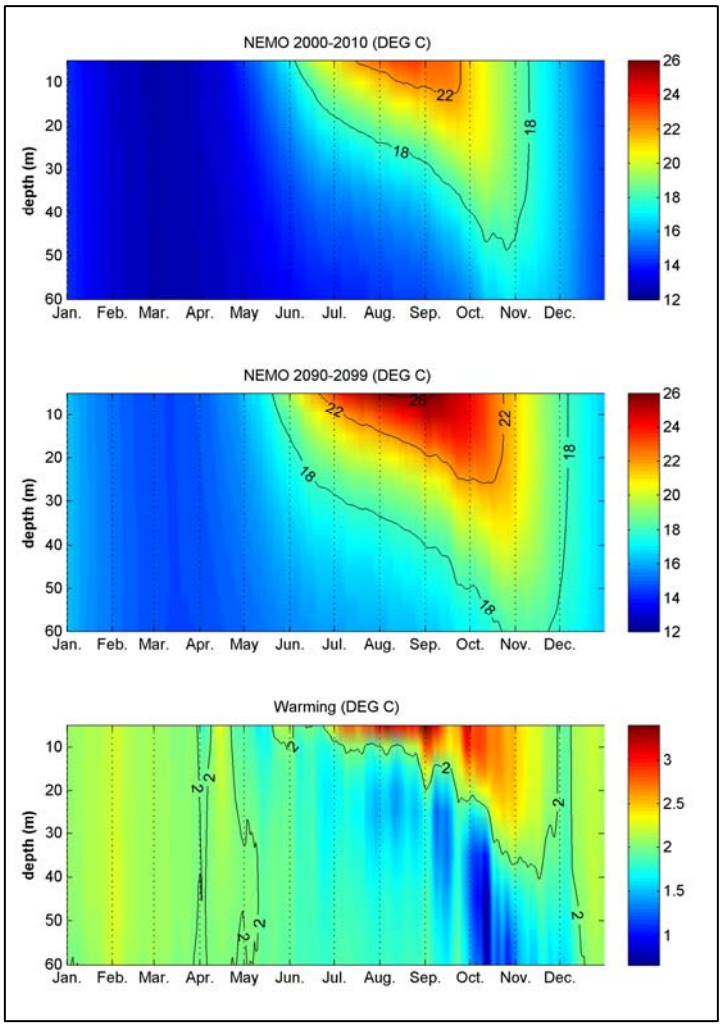

***Figure 13**. NM8 IPCC A2 scenario. Annual cycle of vertical temperature profiles averaged over the coastal stripe for (top) the 2000-2010 period, (middle) the 2090-2099 period and (bottom) warming between the two periods*

Looking at the expected changes in the annual cycle of vertical temperature profiles (5-60 m) averaged over the domain showed homogenous warming of ca. 2°C in winter (Figure 13). Maximum warming is observed in supra-thermoclinal waters from July to November. The 22°C isotherm that hardly reached 15 m depth mid-September at the beginning of the century may reach 25 m depth in mid-October by the end of the 21st century.

Indicators of stratification, such as surface-bottom temperature gradients and depth of the mixed layer calculated from vertical temperature profiles (Gailhard-Rocher et al. 2012) were also examined (Figure 14). Overall, in average over the continental coastal stripe north of 39°N, the mixed layer depth annual cycle exhibits little changes. The increased stratification (vertical gradient) is accompanied by slightly shallower thermocline during the warm period (July-October) by the end of the century. Located around 20 m depth till September.

Examining now the temperatures of the warmest day along the coastal stripe provides interesting and complementary information (Figure 15). Increases of the maximum of up to 4°C are expected to occur locally. The warmest conditions met in the upper 20-

30 m depth layer under present conditions are expected to be met down to 40 to 60 m depth by the end of the century depending on the areas considered. Thus lethal thermal stress may potentially affect deeper benthic communities that under present conditions.

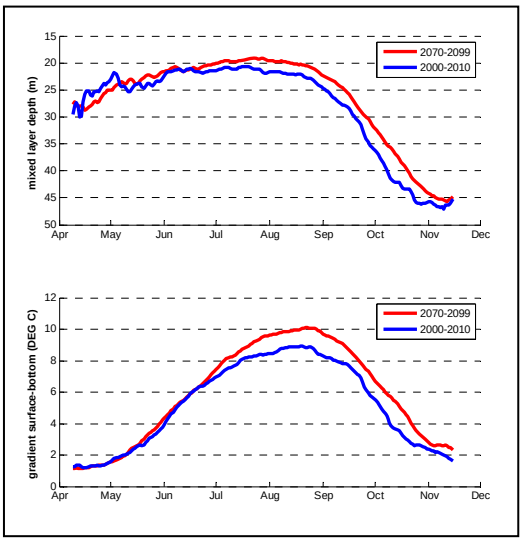

Figure 14. *Average mixed layer depth and surface-bottom T gradients.*

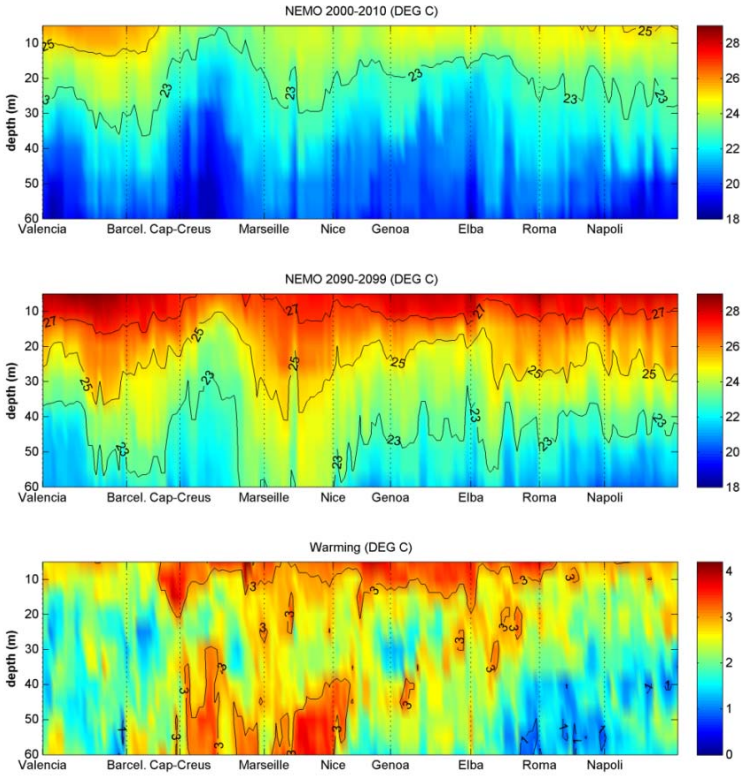

Figure 15. *NEMPMED8 IPCC A2 scenario. Maximum temperature along the coastal stripe for (top) the 2000-2010 period, (middle) the 2090-2099 period and (bottom) difference between the two periods*

MENOR warming scenario

A numerical experiment was conducted to obtain a high resolution forecast simulation of a particular year (2099) using MENOR forced by NEMOMED8 (NM8) fields.

MENOR and NEMOMED8 surface temperatures for 8 August 2099 north of 39°N in the NW Mediterranean are shown in Figure 16 (a-b). Due to its refined bathymetry, topography, and grid size, MENOR allowed high resolution modelling of sub-mesoscale processes, particularly in the coastal zone, inducing finer spatial and temporal variability when NM8 showed large patchy areas.

NEMOMED8 and MENOR surface temperatures for year 2099 along the continental coastal stripe are shown in Figure 16 (c-d). Main differences are found in the South-East of the domain and in the Gulf of Lions (GoL) and Estern provence (between 3 and 7°E) where NM8 was warmer. In the GoL, the higher temporal variability observed in MENOR is more in agreement with actual observations and expected oceanographic processes (eg. episodic coolings from coastal upwellings). Thus, NM8 scenario may tend to over-estimate warming and associated temperature stress level in highly dynamic areas such as the GoL, which is the area where NM8 predicts the highest warming (Figure 17).

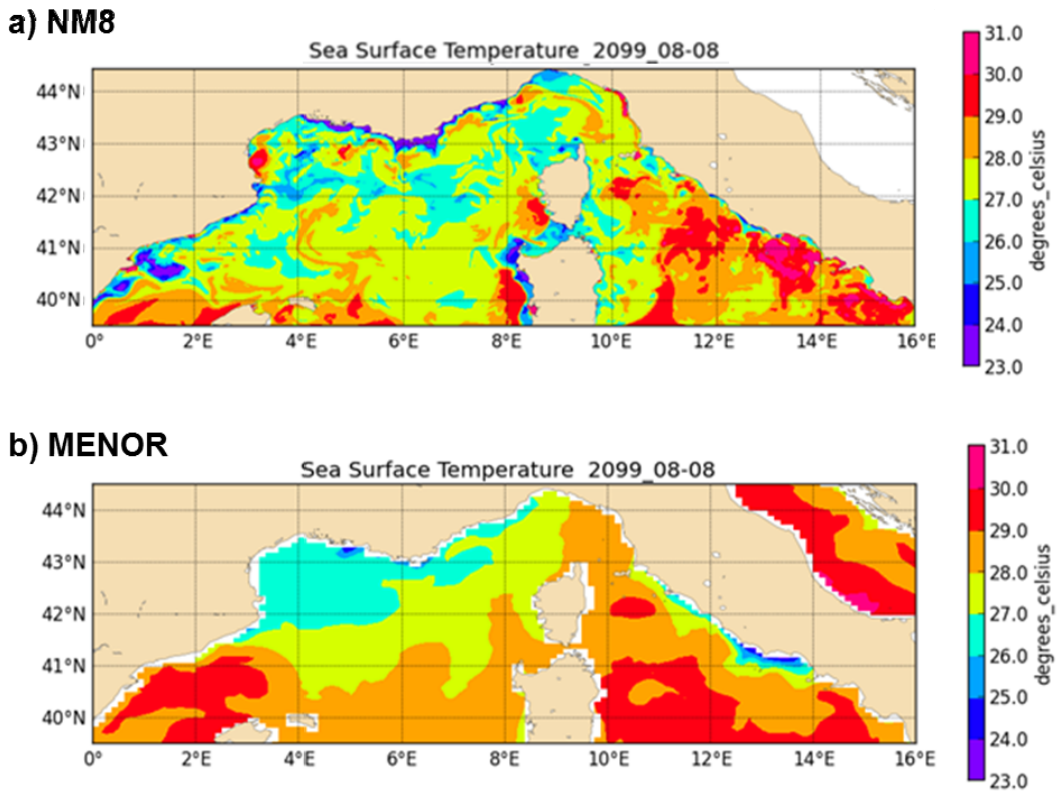

***Figure 16**. Sea surface temperature in the NW Mediterranean, north of 39°N, on 8 August 2099 using NEMO-MED8 (NM8) IPCC-A2 scenario (a) and Menor downscaling (b).*

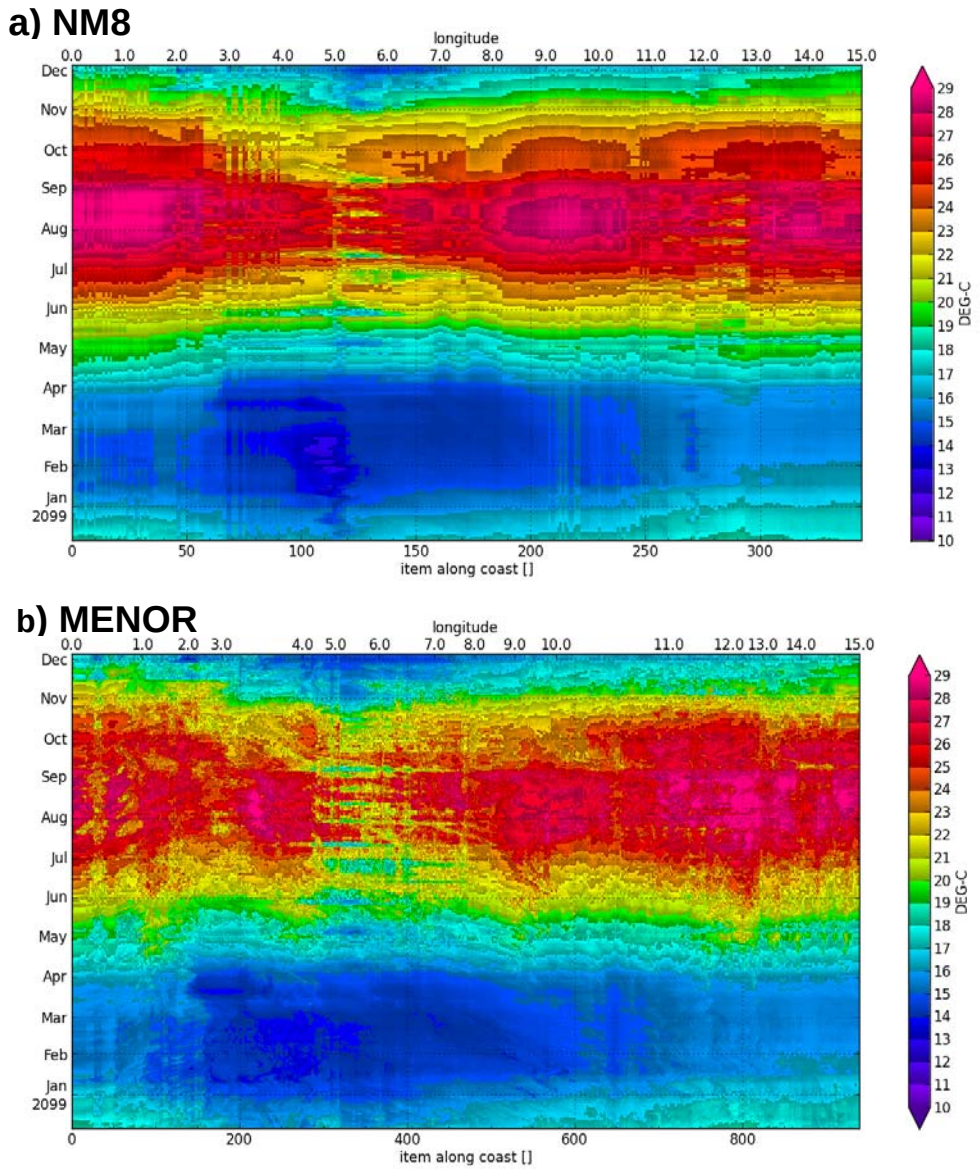

***Figure 17**. Sea surface temperature corresponding to the coastal stripe for year 2099 using NEMOMED8 (NM8) IPCC-A2 scenario (a) and Menor downscaling (b).*

Examining now the vertical distribution of maximum daily temperatures modelled by MENOR at the beginning (2001-2008) and end (2099) of the 21st century (Figure 18) shows increased stratification. This increased stratification corresponds to logically higher surface-bottom temperature gradients (e.g. Figure 14), but also in shallower extension of warm waters by the end of the century (e.g. isotherm 23°C). These results are not in agreement with the vertical pattern obtained from the analysis of NEMOMED8 scenario (Figure 15) and shall be further explored, through comparison of the same downscaling experiment but over a control period (beginning of the 21st century).

From these downscaling simulations, we plan to apply the same methodology as for NEMOMED8 to obtain best estimate of potential temperature conditions by the end of the century (see Task 1.6):

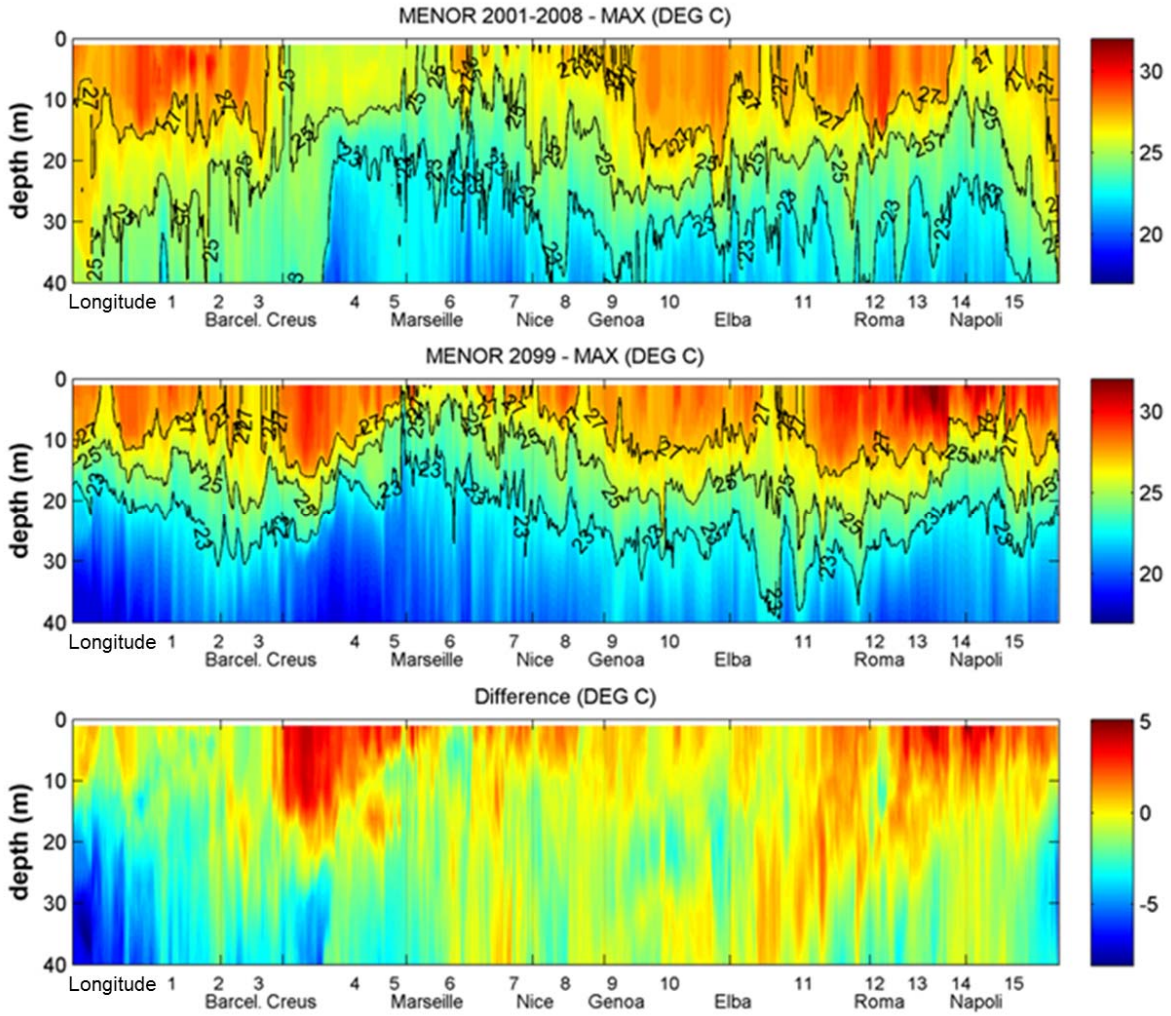

***Figure 18**. Comparison of MENOR modelled maximum T° reached in the upper 40 m along the continental coastal stripe (60 m isobath) between the begining and end of 21st century.*

Task 1.6. Obtaining thermal stress conditions for benthic communities by the end of the 21st century along NW Mediterranean coastal areas

As seen previously (Figures 7, 8), hindcasts run yielded satisfying results and much better fitting than scenario when compared to observations in contrasted coastal stations. Likewise large differences between hindcasts and scenario were observed for the beginning of the century (years 2001-2008, Figure 19). Since coastal ecosystems can be very sensible to high temperatures and prolonged exposures to warm temperatures (both underestimated by the scenarios), we developed a novel approach to cope with the scenarios bias from the observations and the spatio-temporal variability. In order to better take into account these bias, the warming was projected on the temperature of NEMOMED8 hindcasts for the period 2001-2008, after it was corrected from bias from observations We contend that that this procedure will provide a better estimate on the temperature conditions, and thus the temperature stress to which the marine biota will be submitted.

To take into account the spatial variability for each model cell (corresponding to the coastal stripe) warming functions were calculated proceeding as follows (Figure 20):
(a) For each cell, year and depth level, the scenario time series for the beginning and end of the century were sorted, from the highest to the lowest temperature.
(b) The pluri-annual average distribution functions were calculated (blue and red thick lines for the beginning and end of the century respectively).
(c) Difference between these two average curves was then considered as the warming function for this particular site/depth which was applied to the corrected hindcast

As shown in Figure 18 for the South Catalan coast (Spain) at 10 m depth, the warming function permits to take into account the seasonal component of warming, i.e. strongest warming of the 100 warmest days of year.

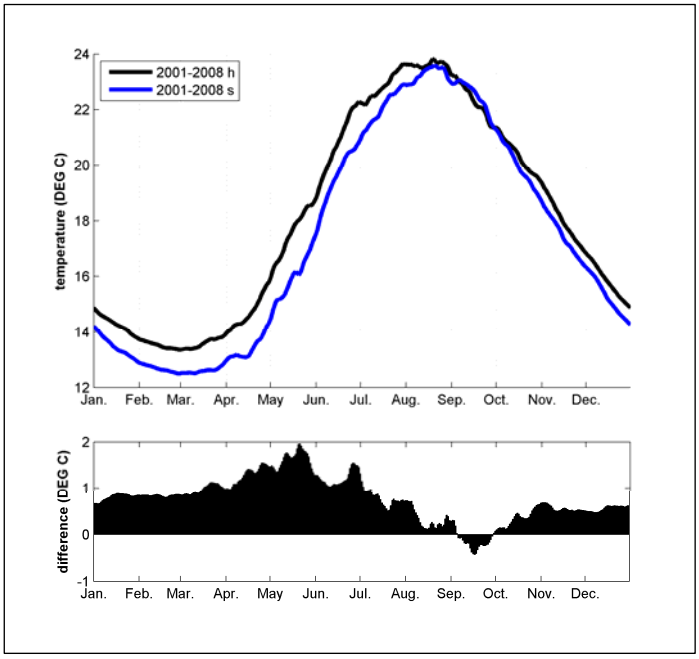

Figure 19. *NM8. Average temperature annual cycle at 5 m depth over the coastal stripe: 2001-2008 hindcast ("h" in black) and scenario ("s" in blue) and difference between them (bottom graph).*

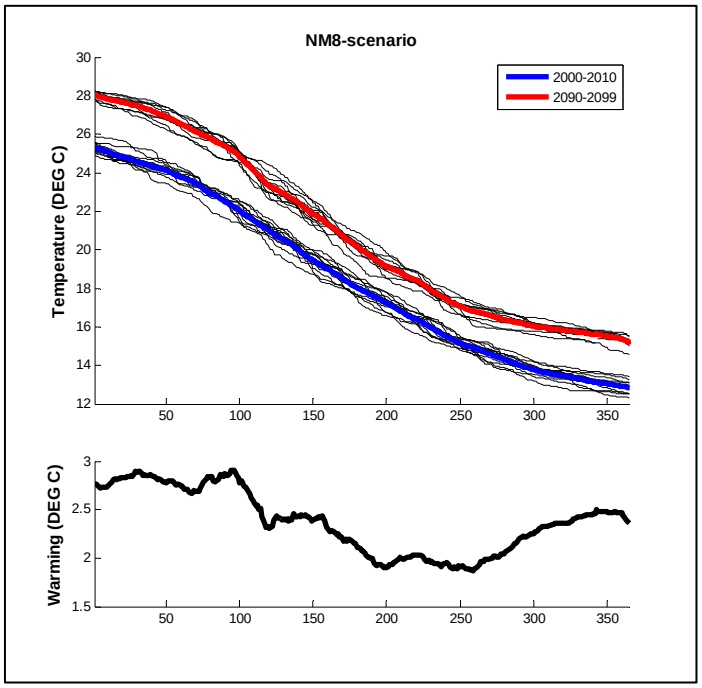

Figure 20. *(top) Daily temperatures sorted from the warmest to the coldest, for each year of the 2000-2010 and 2090-2099 scenario NEMOMED8 (NM8) at 10 m depth along spanish coast. Average values are indicated (black thick line). (bottom) Warming function calculated as difference between the two average curves*

Objective 2. Biological responses to warming: the case study of mass mortality events

Main tasks	Main activities
2.1. Gather quantitative data to assess impacts on populations at NW Mediterranean basin scale	• Conservation status on gorgonian populations surveys
2.2. Development of citizen science tools	• www.observadoresdelmar.es/projecte-1.php
2.3.Thermotolerance of key benthic species	• Thermotolerance experiments on different taxonomic groups • Literature survey
2.4. Definition of mortality risk level associated to temperature conditions	• Define mortality risk levels for the red gorgonian *Paramuricea clavata*

Task 2.1. Gather quantitative data to assess impacts on populations at NWM basin scale.

For the assessment of impacts of mass mortalities linked to warming on rocky benthic ecosystems we are quantifying the conservation status of macrobenthic species populations through field surveys in different areas of the NW Mediterranean. We used rapid assessment methods based on the quantification of an easy descriptors i.e. the percentage of affected colonies using random sampling within populations. We considered as affected colony when the necrosis affected more than 10% of the total colony's surface. We also report whether the colony necrosis is recent (presence of denuded axis or axis colonized by pionnering species such as hydrozoan species), old (axis covered by long-lived species such as bryozoans, calcareous algae) or has both types of necrosis. The presence of recent epibiosis is an indicator of recent mortality events. In each survey we quantified the percentage of affected colonies observing a minimum of 100 colonies following a random transect at constant depth. The gorgonian species concerned by the surveys were the red gorgonian *Paramuricea clavata*, the white gorgonian *Eunicella singularis*, the yellow gorgonian *E. cavolinii* and the red coral *Corallium rubrum*.

Within ClimCares we carried out surveys in different sites in the Catalan coast (NE Spain) and W Corsica (France) during the years 2011, 2012 and 2013. Surveyed populations were located within different degrees of protection in three Marine Protected Areas: Parc Natural del Montgrí, les Illes Medes I el Baix Ter, Parc Natural del Cap de Creus in the Catalan coast and the Réserve Naturelle de Scandola in W Corsica. Thousands of colonies have been observed during the surveys. The main result was that in the ClimCares surveyed areas population did not suffer any significant mass

mortality event as percentages of affected colonies with recent epibiosis were always below 10%, considered normal for gorgonian populations. At our knowledge during this period, only a mass mortality event was observed in a population near Cannes (France) (La Rivière 2013) were more than 70% of colonies displayed signs of recent necrosis.

Task 2.2. Development of citizen science tools

The methods developed by our team have been adapted to be applied by Marine Protected Areas managers and trained recreational divers allowing to expand the assessment of the impact of climate change in other areas of the NW Mediterranean. In this framework, in June 2012 we published the "Endangered gorgonians" project within the citizen science initiative Observadores del mar (www.observadoresdelmar.org). ClimCares contribution was key for the development of the project and to make the English version of web platform.
Through Observadores del Mar (Seawatcher English version) platform we are gathering information on (1) geographic distribution of main gorgonian species, (2) upper limit distribution of gorgonian populations, and (3) degree of affected colonies (at different depths ranges) to quantify present impacts.

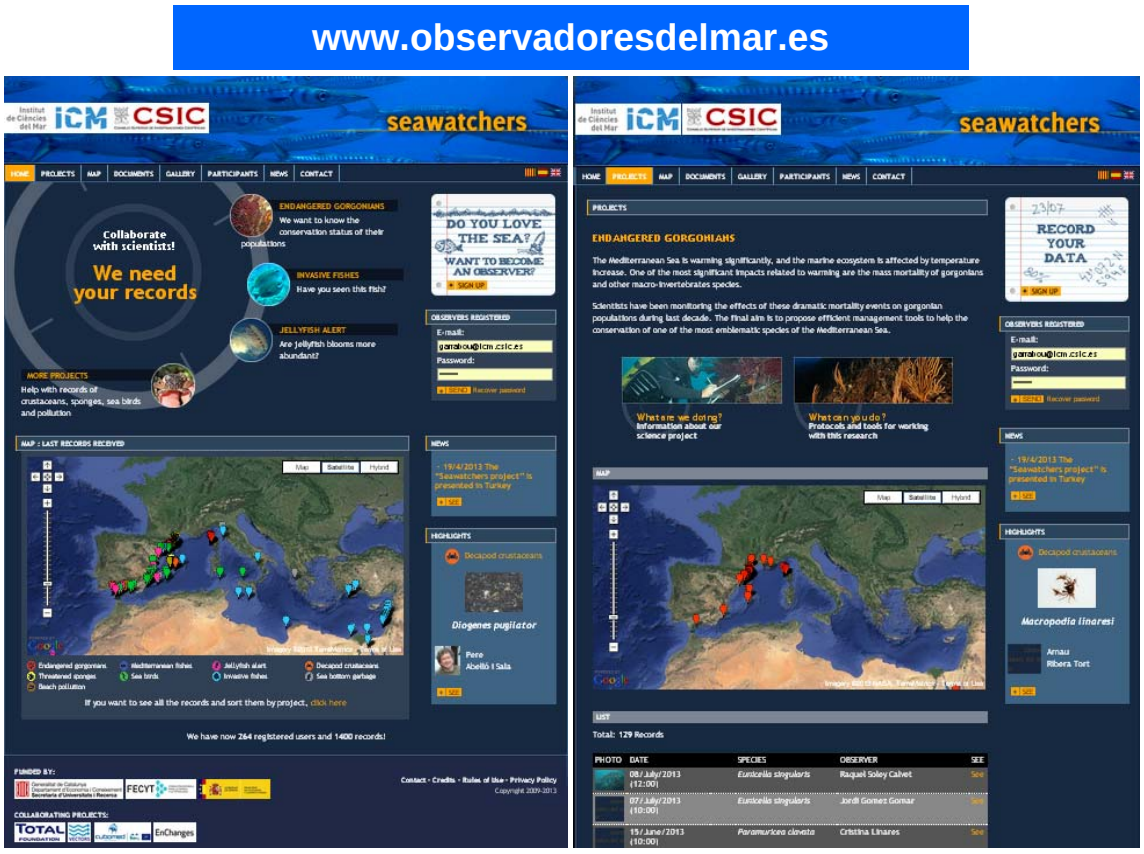

***Figure 21**. Observadores del mar web platform is being used to collect data on the conservation status of gorgonian populations. Home page(left) and Endagered gorgonians project (right)*

To promote the dissemination of the initiative we organized and participated in several meetings to explain the rationale, how to use the different functionalities of the web with emphasis in data integration to the database through the web platform and finally providing guidance for conducting field surveys on gorgonian populations conservation status. Besides informative sessions we co-organized with the MEDPAN (MPAs managers' association) and with the Observadores del Mar initiative two practical workshops. The first one was held in the Réserve Naturelle de Scandola in October 2012. This three days workshop was attended by 20 MPA managers and scientists working in MPAs from 5 countries (France, Spain, Italy, Tunisia and Croatia). The workshop included presentations and field training. The second one was conducted in the Parc Natural del Montgrí, Illes Medes i Baix Ter in May 2013. During this one day training workshop the 15 recreational divers were instructed on how to gather information on the conservation status of gorgonian populations (Figure 22).

***Figure 22**. Participants in the practical workshops. Managers and scientists from 5 different Mediterranean countries working in the MPAs during the training in Galeria (Corsica, France), workshop co-organized with the Medpan association (left). Volunteers recreational divers during the field surveys in Medes Islands at Parc Natural del Montgrí, Illes Medes i Baix Ter (Spain), workshop co-organized with the Seawatchers (Observadores del Mar) project (right).*

After one year, we collected almost 150 observations regarding gorgonian populations from different areas of the NW Mediterranean. We plan to continue the dissemination of the initiative which besides providing valuable data, will also contribute to raise awareness on the climate change effects. We have already established contacts with an Italian association Project Baseline (projectbaseline.org) to organize a training session for Italian recreational divers during the fall 2013. Overall the Observadores del Mar initiative is growing, it has already almost 300 registered users and more than 1400 observations recorded. The publication of the English version of the web platform is an important step to expand the initiative at Mediterranean scale.

Task 2.3. Define tolerance functions vs. T°C conditions for model species

To assess the potential effects of to the expected warming (see Objective 1), it is crucial to define reliable species specific temperature tolerance functions. These functions will inform us on how the species respond to the expected warming. To build up the temperature tolerance functions for key species dwelling in rocky benthic habitats and more particularly in the coralligenous, we complied all data on thermotolerance from the literature and carried out new experiments. Unfortunately the data available in the literature is scarce and most of experiments concerned gorgonian species, although we have found also data for some other anthozoan species and one sponges (Table 1). Besides most of experiments concerned few populations and for most species the experiments lack of replication of treatments which would allow to better assess the potential interpopulation variability on thermotolerance features of the species tested, i.e. thermotolerance experiments should concern several populations from different geographic areas. Facing the lack of data within the ClimCARES project we carried out a set of new thermotolerance experiments involving 5 key macrobenthic species: three sponges species (*Petrosia ficiformis*, *Crambe crambe* and *Dysidea avara*) and two anthozoan species (*Alcyonium acaule* and *Leptosamia pru*voti) in June/July 2012 and 2013. The experiments included hundred of specimens and four temperature treatments (26 to 29 ºC; Figures 23 and 24). On the other hand, besides the mentioned experiments, the project ClimCARES benefited from the results of thermotolerance experiments carried out by the MedRecover team during the past years (Table 1). For building the tolerance functions, we also took into account the temperature conditions recorded during the mass mortality events reported in 1999, 2003 and 2006 to determine the duration and level of thermal stress concomitant with population necrosis observed in the field (Crisci et al. 2011).

The themotolerance functions related the length of exposure (number of days) to different treatment temperatures before the populations showed the first signs of necrosis, (e.g. in the red gorgonian the colour of the tissue had changed from red-yellow to greyish and/or blackish and the affected tissues had started to detach, in some sponges species the development of white veil) (Figure 23 and 24). From the analysis of the data available (Table 1), it is obvious that the red gorgonian *Paramuricea clavata* has the most complete data set with several experiments concerning several populations and wide panel of temperature treatments (23 to 28 ºC). The tolerance function for this species can be considered the most robust and we decided to focus the development of risks associated to climate change (Objective 3) based on the data available on this species.

The red gorgonian was affected on the whole range of temperature tested (Figure 23). However, for some populations necrosis were evident only after few days (1 to 4 days) at 25ºC indicating that this temperature could be considered as the upper thermotolerance limit for this species. Beyond 25 ºC inter-populations differences were largely reduced and only few days of exposure were required to trigger the necrosis of colonies.

Species	Treatment temperatures	Upper T °C tolerance limit	Number of exposure days before showing first signs of necrosis (treatment temperature)	N populations	References
Gorgonians					
Corallium rubrum	24, 25, 27, 30	25	14 (25), 3 (27), 1 (30)	2	Torrents et al. (2008)*
Corallium rubrum	14 to 25	25	3	1	Previati et al. (2010)
Paramuricea clavata	24, 25, 26	24	5 (24), 3 (25), 2 (26)	1	Bally and Garrabou (2007)*
Paramuricea clavata	23,5	23,5	89	1	Coma et al. (2009)
Paramuricea clavata	14 to 25	25	3	1	Previati et al. (2010)
Paramuricea clavata	25, 26, 27, 28	25	4-21(25), 3-5 (26), 2-4 (27), 2-3 (28)	8	Crisci 2011*
Paramuricea clavata	25	25	1-10	4	Kipson 2013*
Paramuricea clavata	25 to 27	25	15 (25), 3 (25 +1 day at 27)	1	La Rivière 2013
Eunicella singularis	24, 26	26 sublethtal effects	1	2	Ferrier-Pagès et al. (2009), Pey et al. 2011
Eunicella singularis	24, 26,27, 28, 30	27/28	1	4	Pey 2012
Eunicella singularis	26,27,28,29	28/29	1/2	2	Linares et al. 2013*
Eunicella singularis	18 to 26	24 (sublethal effects)	No necrosis	1	Ezzat et al. 2013
Eunicella singularis	14 to 25	>25	No necrosis	1	Previati et al. (2010)
Eunicella cavolinii	14 to 25	25	3		Previati et al. (2010)
Anthozoans					
Alcyonium acaule	26,27,28,29	26	12 (26), 8 (27), 4 (28), 2 (29)	1	ClimCARES experiment
Leptosamia pruvoti	26,27,28,29	26 (>21 days) 27	13 (27), 3 (28), 4 (29)	1	ClimCARES experiment
Zooxanthellate corals					
Oculina patagonica	24, 26, 28	28	34		Rodolfo-Metalpa et al. (2006)
Cladocora caespitosa	24, 26, 28	26	48 (24), 34 (26), 34 (28), 21 (28)	1	Rodolfo-Metalpa et al. (2005) and (2006)
Cladocora caespitosa	26,27,28,29,30	>30	No necrosis	2	Linares et al. unpublished data*
Sponges					
Ircinia fasciculata	23, 27	27	4	1	Cebrian et al. 2011*
Crambe crambe	26,27,28,29	26	3 (26), 3 (27), 2 (28), 2 (29)	2	ClimCARES experiment
Petrosia ficiformis	26,27,28,29	26	9 (26), 7 (27), 2 (28), 2 (29)	1	ClimCARES experiment
Dysidea avara	26,27,28,29	26	9 (26), 7 (27), 2 (28), 1 (29)	1	ClimCARES experiment

Table 1. *Thermotolerance experiments compiled from the literature and the results from the ClimCARES experiments and MedRecover group (*)*

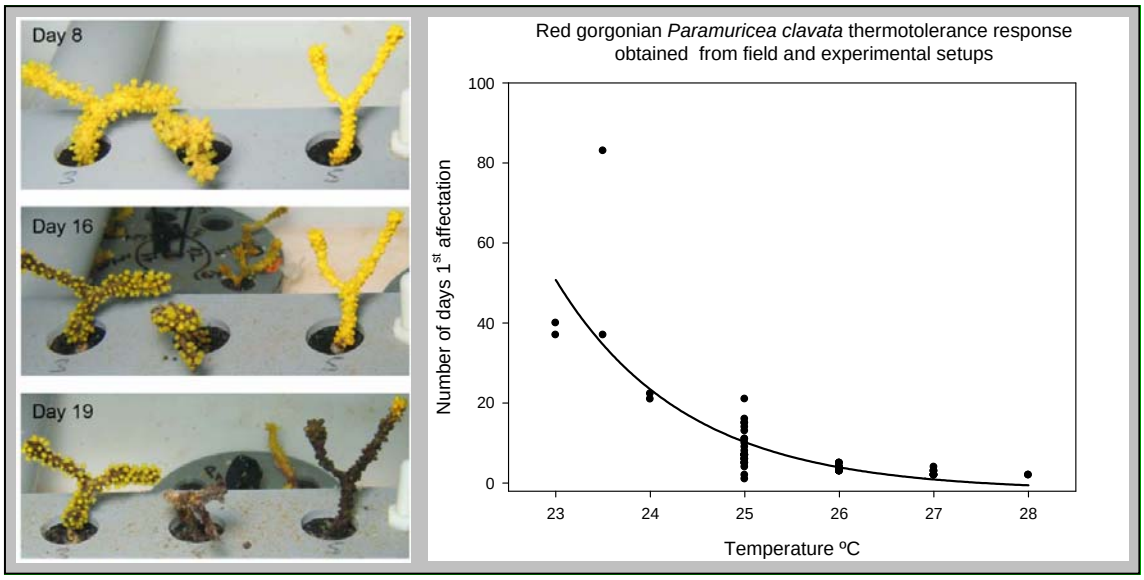

***Figure 23**. Sequence of photos of the evolution of the same set of colonies of the red gorgonian (it has also yellow coloured colonies) Paramuricea clavata submitted to 25 ºC in the aquariums of the Experimental Aquariums area at the Institut de Ciències del Mar during summer 2010 (left). Temperature tolerance function for the red gorgonian P. clavata obtained from thermotolerance experiments and field data (see text and Table XX for references) (right).*

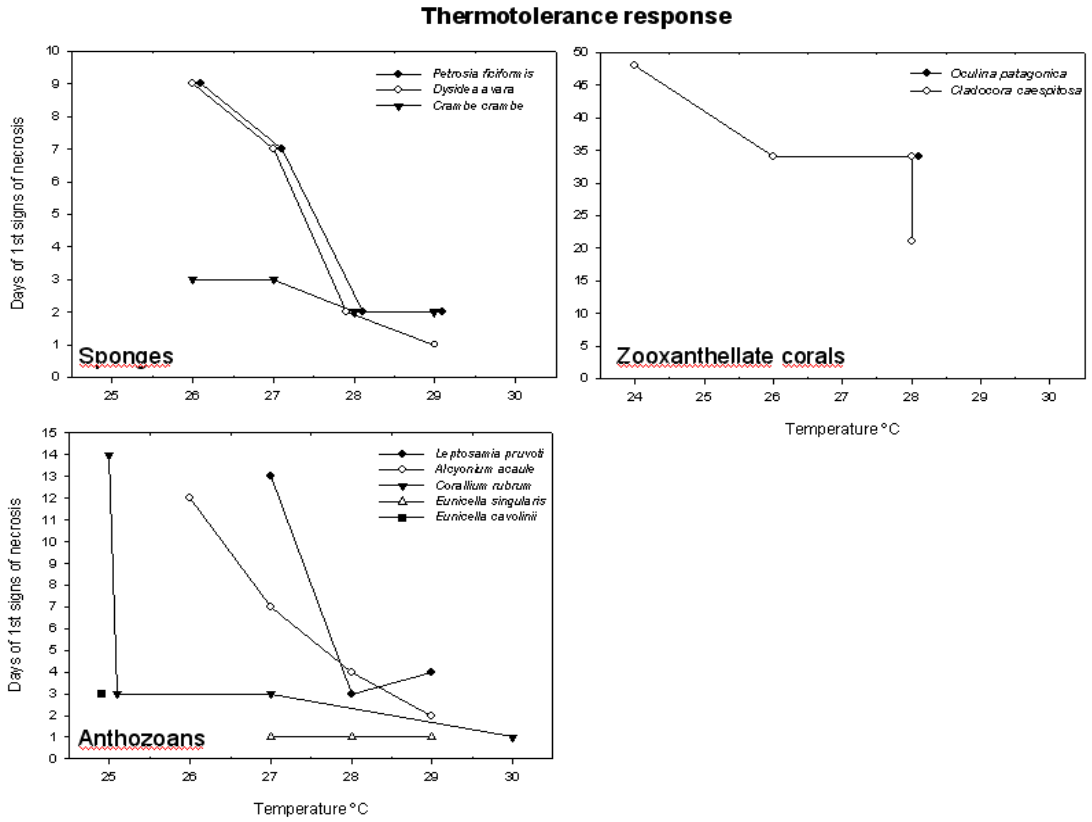

***Figure 24**. Number of days of exposure at different temperature treatments (from 24 to 30 ºC) obtained from the experiments carried out at the Experimental Aquariums area at the Institut de Ciències del Mar during summer 2012 and 2013 and from literature data (see Table XX for references).*

Regarding the other species tested, interspecific differences were evident. The most resistant species were the symbiotic zooxanthellate scleractinian corals which can resist almost 7 weeks under 24ºC, 5 weeks at 26 ºC and 3 to 5 weeks at 28 ºC without suffering necrosis. On the other hand, the species most sensible to temperature stress were the sponges and the anthozoans although the temperature thresholds ranged from 25 to 28 ºC depending on the species. In any case, the exposure to temperatures between 25 and 26 ºC during one or two weeks affected most species. Finally all species develop necrosis in few days after the exposure to temperatures above 27 ºC (Figure 24).

Task 2.4. Definition of mortality risk level associated to temperature conditions

From thermo-tolerance data available for the red gorgonian *Paramuricea clavata*, we established different mortality risk levels associated to thermal stress. Four risk levels were considered: sub-lethal, moderate, high, and extreme. The last three were defined respectively as the minimum, mean and maximum number of days of exposure at each temperature required to observe the first signs of tissue necrosis (mortality) were observed on the gorgonian populations (see Table 2). 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 2 shows the results of several thermotolerance experiments with red gorgonian *Paramuricea clavata*. As mentioned above tissue necrosis developed after several weeks of exposure to warm temperatures (24-25°C) or short exposure (duration of the order of the day) to high temperatures (26-28°C). One should note that the highest the exposure temperature, the less variability in the biological response (e.g. all gorgonian show signs of necrosis after 2 days at 28°C).

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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

Table 2*. Minimum, mean and maximum number of days of exposure to experimental temperatures to develop the first signs of tissue necrosis and the associated mortality risk levels*

Objective 3. To assess potential impacts of climate change on benthic coralligenous assemblages from coastal areas at NWM basin scale

Main tasks	Main activities
3.1. Development of methods for the assessment of climate change impacts in the coastal habitats NW Mediterranean basin	• Protocol for the assessment of mortality risks on gorgonian dominated communities associated to warming trend.
3.2. Acquisition of information on geographic and depth range distribution of key gorgonian species in the NW Mediterranean basin	• Questionnaire to MPAs managers and researche from Spain, France and Italy • Input from citizen science initiatives • Literature review
3.3. Mass mortality risk assessment under current temperature conditions	• Analysis of 2000-2010 MENOR (validated) simulations were combined with data on species distribution and thermotolerance data
3.4. Mass mortality risk assessment by the end of the 21st century	• NEMO-MED8 2001-2008 and NEMO-MED8 2091-2098

Task 3.1. Development of methods for the assessment of climate change impacts in the coastal habitats NW Mediterranean basin

In order to assess the climate change impacts on NW Mediterranean coastal habitats, we developed a novel methodology combining hydrodynamic simulations, physical and biological coastal observations, and thermo-tolerance experiments. More precisely within ClimCares we combined adjusted modeled temperatures attended by the end of the 21st century (Objective 1) with information on biological responses to warming (Objective 2) and their geographic and upper distribution limits (see Task 3.2). The final goal within ClimCares was to provide risk maps on the occurrence of mass mortalities in the coralligenous communities dominated by gorgonian species. The risk maps were obtained for the simulated current conditions (2001 to 2010) and compared with the risk associated to the expected warming by the end of the 21st century (2091-2098).

The method for assessment of potential risk of mortality outbreaks consisted of the following 3 steps:

1- From the refined coastal stripes obtained from Objective 1, we calculated the number of days when the temperature was above given thresholds, from 23 °C to 28 °C for each site/depth. The maximum temperature stress over the pluri-annual period

was calculated, thus taking into account composite data integrating the pluri-annual variability.

2- 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 considered. Temperature impacts were classified in four risk levels obtained from thermotolerance functions: sub-lethal, moderate, high, and extreme lethal impact.

3- The resulting 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. We plan to extend the same kind of analysis to other key species for which we have compiled tolerance functions.

Task 3.2. Acquisition of information on geographic and depth range distribution of key gorgonian species in the NW Mediterranean basin

From a questionnaire to MPAs managers and researchers from Spain, France and Italy, inputs from citizen science initiatives and literature review, we gathered information on the geographic and depth range distribution of the main gorgonian Mediterranean species over the NW Mediterranean basin (i.e. spatial domain of numerical ocean models used within the ClimCARES project). The gorgonians considered were the red gorgonian *Paramuricea clavata*, the white gorgonian *Eunicella singularis*, the yellow gorgonian *Eunicella cavolinii*, the red coral *Corallium rubrum*, the *Leptogorgia sarmentosa*. Most of these species are considered key species of the rich coralligenous assemblages.
For the survey, the coastline was first divided in 14 "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 'm') data concerning gorgonian species were pooled inside these sub-areas. For each sub-area, and species, the UDL was calculated as the average of observations or integrative expert knowledge. Limits of the different sub-areas, presence and UDLs of the red gorgonian *Paramuricea clavata* are shown in the Figure 25.

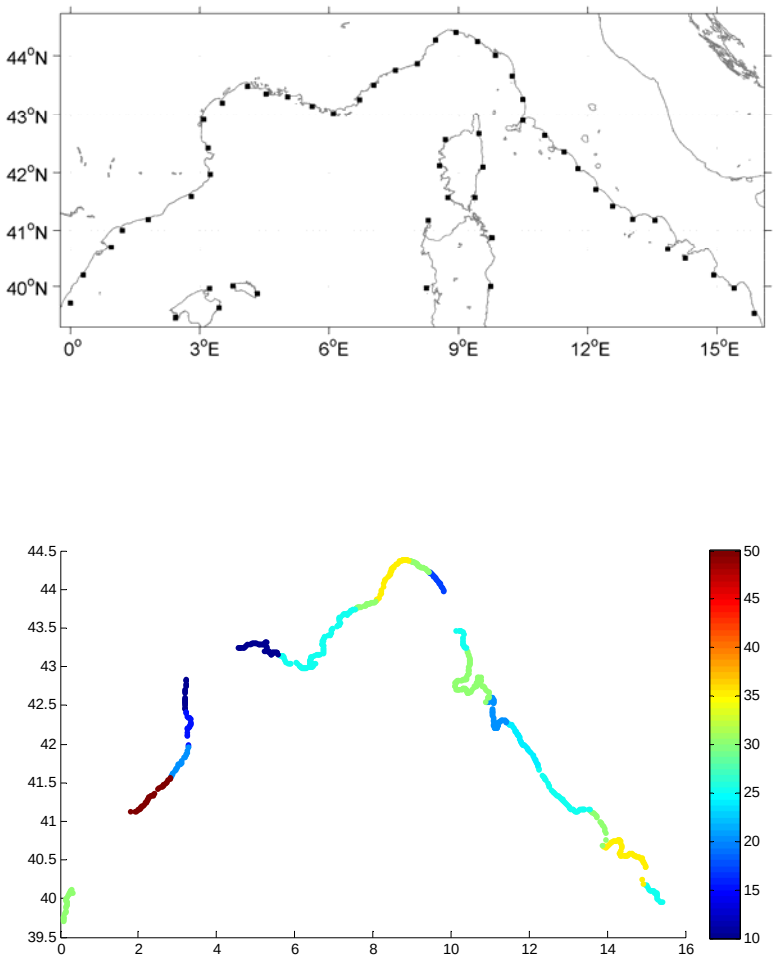

Figure 25. *Top: limits of the different sub-areas considered for distribution of benthic communities. Bottom: presence and upper distribution limit of the red gorgonian Paramuricea clavata.*

Over the entire area, the upper distribution limit (UDL) of *P. clavata* ranged from 10 to 50 m depth. Populations are thus exposed to contrasted conditions depending on the areas considered. The shallowest populations were found near the Gulf of Lions and the deepest along the Catalan coast.

Task 3.3. Mass mortality risk assessment under current temperature conditions

The temperature summer conditions obtained from the MENOR hindcast for the period 2001 to 2010 were used to assess the current mass mortality risks. As mentioned, the comparison of model temperature hindcasts with available *in situ* temperature time series allowed us to assess the model's ability to reproduce the summer warming conditions. According to the comparison between MENOR hincasts and recorded temperatures during warming events, a mean estimated bias of 2.5 °C was added to

the model temperature from Cote Bleue (5°E, 43.3°N) to Monaco (7.9°E, 43.8°N) and a mean estimated bias of 1 °C was added to the rest of the domain except for the area extending from Medes to Banyuls.

As an example of the results obtained, in Figure 26a maximum exposure duration to temperatures above 23 °C over the coastal stripe during the 2001-2010 period is shown. The same kind of information was obtained for the other temperature thresholds considered 23 to 28 ºC. Combining this information with *P. clavata* response function to temperature and geographic distribution, we were able to qualify the potential risk level for each area and depth range in areas where *P. clavata* is found (Figure 26b). Finally, the risk of mortality for *P. clavata* populations was determined considering the mortality risk level attributed at the depth corresponding to the upper distribution limit of the populations for each area (Figure 26c).

Interestingly, we noted that the upper distribution limit of populations matched quite well the distribution of moderate-high lethal risk obtained for the period 2001 to 2010 (Figure 26b). This observed "correspondance", except for the deep populations of Catalonia (around 2°E) (which dwell in deep reefs because there are not shallow vertical walls) may have resulted by repeated thermal stress over the past decades, and illustrate the potential long term effect of temperature on species UDL, although other factors such as competition, success in reproductive effort or food availability could also be involved in the observed distribution.

From Figure 26c, the highest impacts were observed in the Marseilles area and in the Gulf of Genoa, while lower mortality risks were lower along the Catalan coast. This pattern is in agreement with observations on population impacted during the large mass mortality events in different areas of the NW Mediterranean (Garrabou et al. 2009, Crisci et al. 2011). However, some of the areas which suffered severe impacts during the 2003 mass mortality events (Garrabou et al. 2009) were not identified as impacted areas in our modelling study. This is the case for the area of Port-Cros (6.5°E, 43°N), and for the Naples area, where the risk was high only in near surface layers for the model whereas relatively deep *P. clavata* populations were seen to be strongly affected during the 2003 mass mortality event (Garrabou et al. 2009).

Overall, the lethal thermal stress conditions rarely reached a depth of 30 m in the model (Figure 26b), suggesting that only marginal populations have been exposed since 2001. This is not in agreement with observations of deeper populations which have been locally affected in the past decade at sub-regional scale after the 1999 summer due to moderate but long-lived warming event down to 40 to 50 m in depth. The current risk level should thus be extended to deeper areas than those shown in Figure 26b by modeling years of particular interest (e.g. 1999) and improving the model's representation of deeper extreme temperature. Errors in the model temperature hindcasts at the different sites have to be better integrated to correct the scores in cases in which the intensity or duration of summer temperature extremes were not well reproduced by the MENOR model. This is particularly critical at intermediate depths given the range of upper distribution limits of the populations and the strong vertical gradients in this depth range.

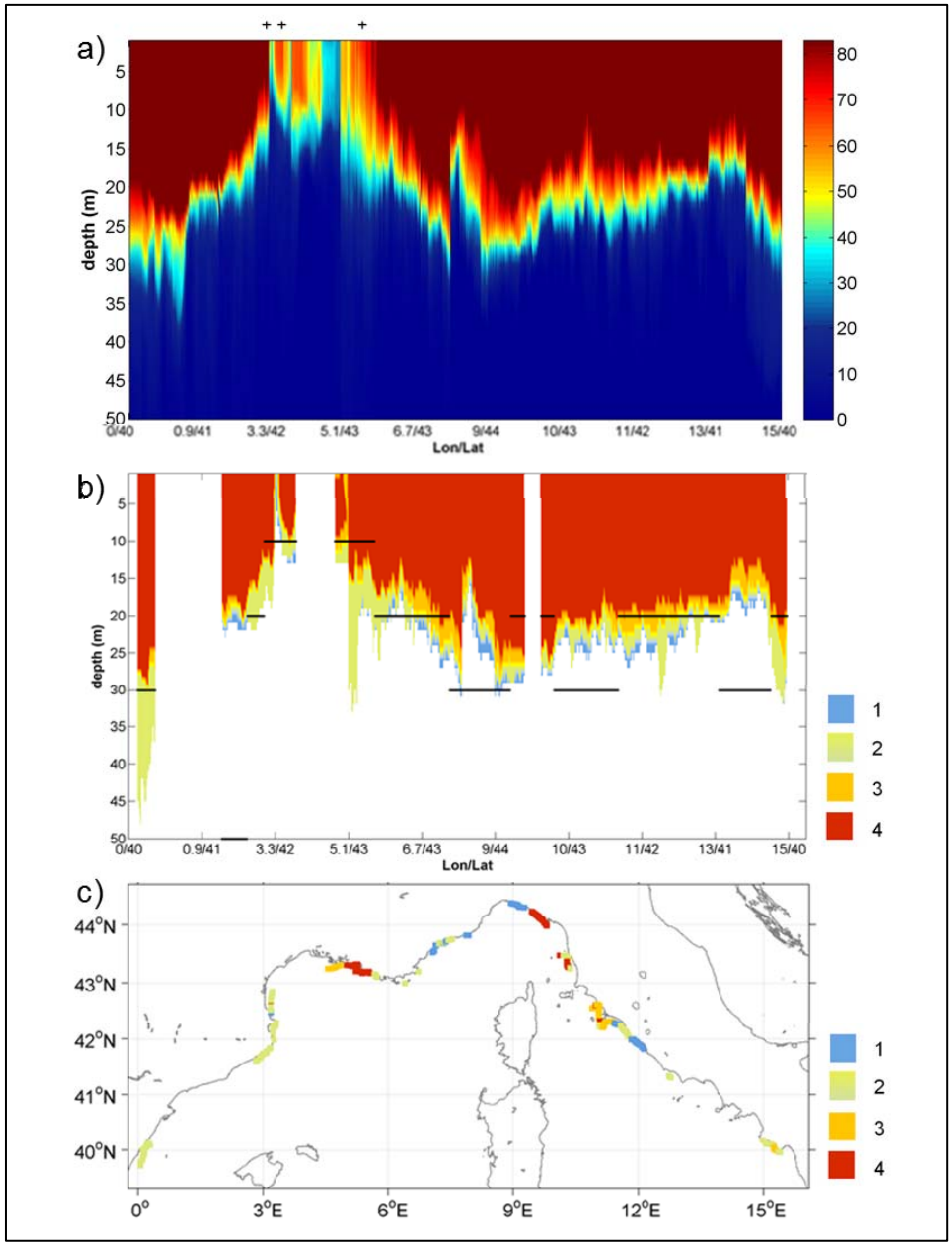

Figure 26. The different steps conducting to risk assessment regarding thermal stress for the red gorgonian *Paramuricea clavata* under present conditions (period 2001-2010). a) Distribution of the number of days with temperature upper than 23°C during summer (max of years 2001-2010). b) Distribution of the risk level obtained after crossing the various temperature stresses (23-28°C) with *P. clavata* response function to temperature increase, from sub-lethal to medium, high and extreme lethal risk (color scale from 1 to 4) for coastal areas hosting *P. clavata*. The gorgonian upper distribution limit is shown as black horizontal lines with a 10 m vertical resolution. c) Map of sub-lethal to extreme lethal temperature stress impacts on *P. clavata* populations for the years 2001-2010 (adapted from Pairaud et al. (in rev.)).

Task 3.4. Mass mortality risk assessment by the end of the 21st century

We used the NEMOMED8 model to obtain the temperature conditions by the end of the 21st century (Objective 1). We applied the corrections to the model's outputs described previously to obtain the most reliable expected warming conditions (Objective 1, Task 1.6).

As an example, maximum exposure duration to temperatures above 23 °C over the coastal stripe during 8 years at the beginning and end of the 21st century are shown in Figure 27. As can be seen from iso-duration 80 days (critic duration for *P. clavata* at this temperature), the thermal stress is expected to severely increase over the entire domain, and to reach deeper depth levels.

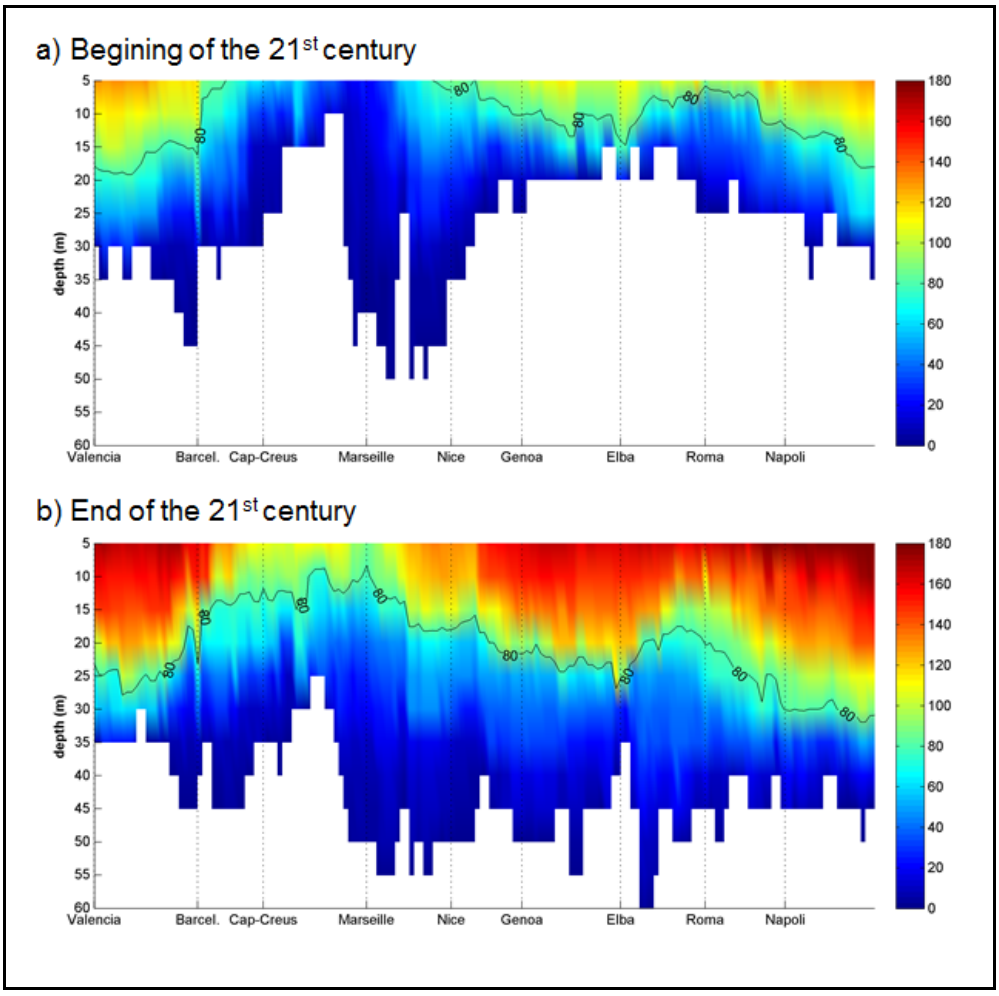

***Figure 27**. Comparison of best estimate temperatures along the continental coastal stripe for the beginning and end of the 21st century using NEMO under IPCC-A2 scenario. The maximum total duration (in days) above T threshold of 23°C reached in the upper 60 m for 8 years period is shown.*

As we described before we combined the information on durations above the various T thresholds (23:28°C) with *P. clavata* response function to temperature and geographic distribution. With these data we were able to qualify the potential risk level for each area and depth range in areas where *P. clavata* is found. Finally, the risk of mortality for *P. clavata* populations was determined considering the mortality risk level attributed at the depth corresponding to the upper distribution limit of the populations for each area (Figure 28).

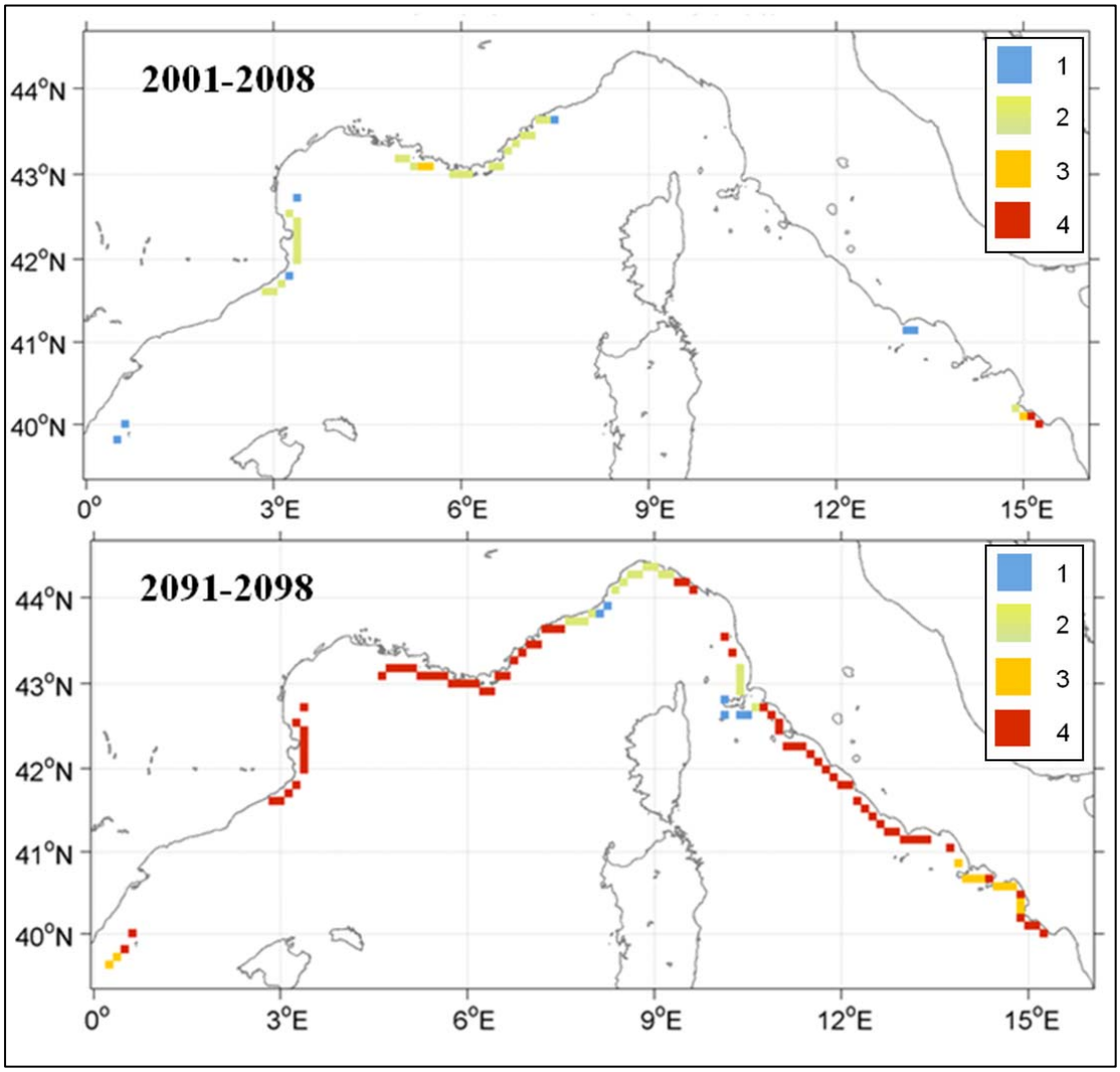

Figure 28. *Impact mapping on the risk of mortality outbreak for Paramuricea clavata at the beginning (Top) and end (Bottom) of the 21st century along the continental coastal stripe north of 39°N in the NW-Mediterranean Sea. The color scale, from 1 to 4, corresponds to sub-lethal, moderate, high and extreme lethal impacts respectively.*

The risk of mortality showed dramatic increase over the whole domain analyzed by the end of the 21st century. The increase of the mortality risk concern areas for which the level at the beginning of the century was low or null are expected to suffer severe mass mortality events by the end of the 21st century. Given the extreme risk level observed, shift down in the upper distribution limit of gorgonian species is expected to occur. Besides many other species dwelling in the communities dominated by the red gorgonian *P. clavata* are also expected to suffer the effects of thermal stress as

occurred during the reported mass mortality events. Overall, the impact of climate change in the NW Mediterranean area could have dramatic consequences for the conservation of the rich marine biodiversity.

Project meetings, dissemination and scientific outputs.

ClimCares web site

The ClimCares web site has been published and updated: climcares.medrecover.org

Dissemination

-2011. Garrabou J. The project ClimCares: assessing the climate change impacts on Mediterranean biota. Insititut de Ciències del Mar-CSIC (Spain)

-2012. Interview for Medpan: http://www.medpan.org/?arbo=zoom&sel=ID&val=756

-2012. Workshop on the effects of climate change in the Mediterranean with MPA managers in the Réserve Naturelle de Scandola (France) with 20 participants from 5 countries

-Garrabou J (2012) T-MEDNet: when local actions become global. Presentation at the Centre d'Estudis Avançats de Blanes-CSIC, (Spain)

-Bensoussan N, Garrabou J, Pairaud I, Garreau P (2012) Assessing climate change impacts on marine biodiversity conservation: The case study of mass mortality eventsin the NW Mediterranean basin. Workshop on total Foundation Projects September.Rhodes (Greece)

-2013. Radio broadcast interview (Radio Mataro) Ones de Mar emission (listen the poadcast)

-2013. Workshop on the effects of climate change in the Mediterranean with recreational divers.

ClimCares Meetings

-ClimCares Kick-off meeting 24-25 may 2011 Station Marine d'Endoume, Marseilles (France). Participants: Bensoussan, N. (IPSO FACTO), Garrabou, J. (ICM-CSIC), Pairaud, I. (IFREMER-LERPAC), Garreau, P. (IFREMER-DYNECO).

-First ClimCares intermediate meeting 6-7 February 2012 Institut de Ciències del Mar-CSIC, Barcelona (Spain). Participants: Bensoussan, N. (IPSO FACTO), Garrabou, J. (ICM-CSIC), Salat, J. (ICM-CSIC), Ledoux, J.B. (ICM-CSIC), Pairaud, I. (IFREMER-LERPAC), Garreau, P. (IFREMER-DYNECO).

-Second ClimCares intermediate meeting 16 November 2012 Skype conference Participants: Bensoussan, N. (IPSO FACTO), Garrabou, J. (ICM-CSIC), Pairaud, I. (IFREMER-LERPAC), Garreau, P. (IFREMER-DYNECO).

-Final **ClimCARES** meeting 8th april 2013 at Station Marine d'Endoume Marseilles (France) Participants: Bensoussan, N. (IPSO FACTO), Garrabou, J. (ICM-CSIC), Pairaud, I. (IFREMER-LERPAC), Garreau, P. (IFREMER-DYNECO).

Scientific papers

Pairaud, I., Bensoussan N., Garreau, P., Faure, V., Garrabou, J. (in revision) Impacts of climate change on coastal benthic ecosystems: assessing potential risk of mortality outbreaks under thermal stress in the NW Mediterranean coastal areas. *Ocean dynamics*

Bensoussan N, Pairaud I, Garreau P, Somot S, Garrabou J (2013) Multidisciplinary approach to assess potential risk of mortality of benthic ecosystems facing climate change in the NW Mediterranean Sea. OCEANS'13 MTS/IEEE Technical Program 23-26 September 2013 San Diego, USA

Scientific communications

1. Bensoussan N, Pairaud I, Garreau P, Somot S, Garrabou J (2013) Climate change impacts on coastal benthic ecosystems in the nw mediterranean sea: assessing potential risk from field, laboratory and numerical experiments. 40th CIESM congress, 28 october- 1 november Marseilles, France

2. Bensoussan N, Pairaud I, Garreau P, Somot S, Garrabou J (2013) Climate change impacts on benthic ecosystems in Marine Protected Areas of the NW Mediterranean Sea: assessing potential risk from field, laboratory and numerical experiments. IMPAC3 3rd International Marine Protected Areas Congress, 21-27 October Marseilles-Corsica, France

3. Pairaud I, Bensoussan N, Garreau P, Somot S, Garrabou J (2013) Multidisciplinary approach to assess potential risk of mortality of benthic ecosystems facing climate change in the NW Mediterranean Sea. OCEANS'13 MTS/IEEE Technical Program 23-26 September 2013 San Diego, USA

4. Bensoussan N., Garrabou J. (2013) T-MEDNet: from local initiatives to a Mediterranean network. MerMEX international workshop, 10-12 June 2013, Zagreb, (Croatia).

5. Garrabou J, Arizmendi R, Ballesteros E, Bally M, Bensousan N, Casas E, Cebrian E, Crisci C, Hereu B, Kersting DK, Kipson S, Ledoux JB, La Rivière M, Linares C, Romano JC, Sala E, Teixidó N, Zabala M (2012) Assessing conservation status of mediterranean rocky benthic communities dominated by long-lived species: insights on effective conservation and managements plans. Forum Mediterranean Marine Protected Areas, 25-28 November 2012, Antalya (Turkey).

6. Bensoussan N, Linares C, Cebrian E, Crisci C, Kipson S, Teixidó N, Romano JC, Bianchimani O, Ramos-Esplà A, Kersting DK, Lorente A, Riera V, Cadene F, Laffon JF, Payrot J, Blouet S, Bachet F, Charbonnel E, Zuberer F, Pairaud I, Sartoretto S, Bergere H, Houard T,: Dominici JM, Culioli JM, Harmelin JG, Garrabou J (2012) T-MEDNET: a climatic network for large scale, high resolution and long term monitoring of mediterranean coastal waters. Forum Mediterranean Marine Protected Areas, 25-28 November 2012,, Antalya (Turkey).

7. Pairaud, I, Garreau, P., Bensoussan, N., Garrabou, J. (2012) NW Mediterranean sea model toward the study of the climate change impacts on the coastal ecosystems 16th Biennial Workshop Joint Numerical Sea Modelling Group (JONSMOD) 21-22-23 May 2012 Brest (France)

8. Garrabou, J., Bensoussan, N., Somot, S., Pairaud, I., Garreau, P. (2011) ClimCares: a new research project to assess the climate change impacts on NW Mediterranean coastal benthic ecosystems. Vulnerability of coastal ecosystems to global change and extreme events - At the crossroads of knowledge to the benefit of coastal and marine ecosystem services. 18 - 21 october 2011, Biarritz, (France)

9. Bensoussan N., Linares C., Cebrian E.,Crisci, C., Kipson, S., Teixido, N.,Romano, J.C., Bianchimani, O.,Kersting DK., Lorente, A., Riera i Arago, V., Cadene, F., Laffon, JF., Payrot, J.,Bachet, F., Charbonnel, E. Zuberer, F.,Pairaud, I., Sartoretto, S., Bergere, H., Houard, T.,Dominici, J.M., Harmelin, J.G., Garrabou, J. (2011) T-MedNet: a temperature network for high resolution and long term monitoring of Mediterranean coastal waters stratification. Vulnerability of coastal ecosystems to global change and extreme events - At the crossroads of knowledge to the benefit of coastal and marine ecosystem services. 18 - 21 october 2011, Biarritz, (France)

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