CLIMATE CHANGE SCENARIO FOR THE MEDITERRANEAN SEA.

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ABSTRACT

The question of the evolution of the Mediterranean Sea under the climatic change expected for the 21st century is approached by the mean of a scenario run of the high resolution Ocean Regional Circulation Model OPAMED8. The scenario chosen for the atmosphere the IPCC-A2. Present time, scenario and control runs are realized in forced configurations, with daily atmospheric fluxes and Sea Surface Temperature (SST) computed after different experiments of the ARPEGE-Climat global circulation model. There is no salinity relaxation at the surface, but explicit river runoffs taken from a monthly climatology. An Atlantic buffer zone with climatological temperature and salinity relaxation represents the inflow and outflow currents at the Gibraltar Strait. The modifications of the runoffs and of the buffer zone relaxations along the 21st century are presented.

The first result of this study is the stability of the control run, in spite of the absence of sea surface salinity (SSS) relaxation. SST increases by about 2.5°C at the end of the 21st century over all the basin. The SSS evolution depends on the basin, under the influence of the river runoffs, and the increase is largest in the Adriatic and Aegean Seas (respectively 0.48 and 0.38 psu). The penetration of these anomalies to the deep layers is related with the evolution of the winter convection, which remains unchanged in the Adriatic and Aegean basins while it decreases in the Levantine basin and even very strongly in the Western basin. The thermohaline circulation is in consequence affected.

1. INTRODUCTION

Climate change is scientifically established and globally described by global atmospheric scenarios and large-scale coupled ocean-atmosphere simulations. It is natural to refine our knowledge at the regional scale. The Mediterranean Sea is a good candidate for regional-scale studies, because it is at the centre of the life of several millions of people, under a particular climate namely the Mediterranean climate. Following the IPCC-A2 scenario, the climate over the Mediterranean basin may become warmer and drier during the 21st century (IPCC, 2001). The Mediterranean Sea has already begun to undergo a modification of its characteristics, as shown by Bethoux (Bethoux et al, 1990) with a temperature and salinity increase of the deep layers of the western Mediterranean basin observed at the end of the 20th century. Further more it is a region where deep convection occurs in winter, forming the Western Mediterranean Deep Water (WMDW), like as well the Adriatic Sea forming the Eastern Mediterranean Deep Water (EMDW) and the Levantine basin forming the Levantine Intermediate Water (LIW) and the Levantine Deep Water (LDW). Very recently, a temperature and salinity trend has also been reported in the Mediterranean outflow water in the Atlantic Ocean close to the Gibraltar Strait (Potter and Lozier, 2004). The questions to raise are thus numerous, including the following ones: how will this modification evolve, how will the different basins evolve, will there be an impact on the deep and intermediate convection, will the Mediterranean Thermohaline Circulation (MTHC) be affected, what will be the impact of the modified Mediterranean Outflow Water (MOW) getting out in the Atlantic Ocean, and of course how important will be the feedback between the Mediterranean Sea and the atmosphere?

We present here a first attempt of response, by forcing a high resolution ocean regional circulation model (ORCM) by atmospheric fluxes following the IPCC-A2 scenario which prescribes an evolution of greenhouse gases and aerosols, towards a tripling of the CO_2 pre-industrial concentration at the end of the 21st century. The SST used as surface relaxation comes from a large-scale global coupled scenario, and we assume that small-scale structures of the SST modification do not have a major influence on large-scale structures of the atmospheric change. We also assume that at this time scale we can neglect the impact of the feedback of the MOW modifications on the Atlantic inflow through the Gibraltar Strait.

The design of the experiment will be explained, then the salinity and temperature evolution of the main water masses will be shown, as well as the evolution of the intermediate and deep convection.

2. MODELS AND SIMULATIONS

2.1 The Mediterranean Sea model

The OCRM OPAMED8 is a regional version of the OPA ocean global circulation model (Madec et al, 1998). The resolution is 1/8°x1/8°cos(?) with ? as latitude. This is equivalent to a range of 12 to 9 km from the south to the north of the domain. The grid is slightly stretched in the Gibraltar Strait, to better fit the real direction of the Strait. There is an « Atlantic » box to simulate the currents between the two basins by the mean of a 3D relaxation, and thus allow exchanges which are crucial for the heat and salt equilibrium of the Mediterranean Sea. There are 43 vertical levels. The rigid lid and free-slip conditions are applied. For this study the model runs in forced conditions, and it needs five atmospheric fields: water, solar and non-solar fluxes, wind stress, and river runoff. The heat flux is adjusted to the ORCM SST by a surface relaxation towards the daily SST used by the atmosphere model.

Initial conditions come from the MEDATLAS-II monthly climatology (MEDAR/MEDATLAS Group, 2002). Twenty years of spin-up are realized (two times the same ten years of atmospheric forcing) before the proper experiment.

2.2 Atmospheric forcings

The atmospheric forcings are provided by the ARPEGE-Climat atmosphere global circulation model, with a grid pole located in the Tyrrhenian Sea. Resolution is about 50 km over the Mediterranean Sea and much lower at the antipode (same configuration as in Gibelin and Deque, 2003) . To compute the five daily fields needed by OPAMED8, the model is run in forced configuration, with SST coming from the Reynolds observations for present climate simulations, and for scenario simulations computed as follows: the atmosphere ocean general circulation model

(AOGCM) ARPEGE-Climat/OPA (Royer et al., 2002) is run under control and scenario conditions (again IPCC-A2 climate change scenario); the low resolution and time-filtered SST anomaly is then interpolated to the high resolution ARPEGE-Climat grid and added to the Reynolds observations. The same SST fields will be used for forcing OPAMED8 as indicated below. The years of this simulation do not attempt to simulate the actual individual years, because the only observations used are the Reynolds SST.

2.3 Design of the experiments

- The « present » time simulation runs from 1961 to 1999. In addition with the atmospheric fluxes and SST fields, the temperature and salinity of the Atlantic box of OPAMED8 are relaxed towards the monthly MEDATLAS-II climatology, and the climatological monthly river runoffs of 33 Mediterranean rivers are provided (RivDis database, Vörösmarty et al., 1996). The Black Sea is not included into OPAMED8. Nevertheless, this sea can be considered as one of the major freshwater sources for the Mediterranean Sea. As for the Gibraltar Strait, the exchanges between the Black Sea and the Aegean Sea consist in a two layers flow across the Sea of Marmara and the Dardanelles Strait. In this study, we assume that this two layers flow can be approximated by a freshwater flux and thus the Black Sea is considered as a river for the Aegean Sea. The monthly mean equivalent water flux towards the Aegean Sea is computed as the water budget over the Black Sea surface : Precipitation + Black Sea River Runoff – Evaporation. This parametrization is based on the data collected by Stanev et al. (2000). Thanks to the rivers contribution we do not apply any surface salinity relaxation, which is to our knowledge a new approach for the Mediterranean Sea modelling.
- The « scenario » simulation runs from 2000 to 2099. The SST used for relaxation and the atmospheric fields have been described in section 2.2. The temperature and salinity of the Atlantic box are relaxed towards the monthly MEDATLAS-II climatology to which we add an anomaly derived from the AOGCM ARPEGE-Climat/OPA run mentioned in section 2.2. As for the river runoffs, a special treatment is applied to estimate their evolution along the 21st century: the ARPEGE-Climat scenario run provides daily water fluxes to the TRIP runoff-model with 1° resolution (Oki and Sud, 1998). From the runoffs given by this model we compute a multiplying factor for each decade, which will be applied to the climatological monthly runoffs. The TRIP model uses a mean discharge which delays the arrival of the river runoffs to the coast. For practical reasons, the 33 rivers are arranged in eight main groups to synthesize their responses to climate change, and table 1 presents the evolution of the factors from the 2000-2009 decade to the 2090-2099 decade.

Rivers	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**
Rhone	0.98	0.95	0.97	0.93	0.92	0.90	0.89	0.86	0.81	0.80
Po	0.92	0.86	0.84	0.79	0.82	0.82	0.79	0.79	0.79	0.81
Italy others	1.05	1.02	0.94	0.86	0.87	0.90	0.91	0.91	0.88	0.88

Rivers	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090
Ebre and Africa	0.93	0.75	0.80	0.75	0.74	0.72	0.64	0.64	0.46	0.44
Nile	1.08	1.09	1.10	1.04	1.06	0.94	1.00	0.98	1.03	0.93
Turkey	0.79	0.81	0.77	0.78	0.75	0.70	0.61	0.47	0.44	0.43
Greece	1.04	0.96	0.88	0.78	0.79	0.83	0.79	0.75	0.66	0.60
Black Sea	0.86	0.75	0.70	0.61	0.55	0.58	0.57	0.50	0.36	0.29

Table 1: Factors applied to the climatological monthly runoffs during one decade, for the eight chosen series

- Finally a « control » run is realized, with the 1960-1980 atmospheric forcings used again all through the period 1961-2099. Its analysis will show the ability of OPAMED8 to run 140 years without any drift under present climate conditions. Figure 1 shows the interactions of the three models used for designing the scenario.

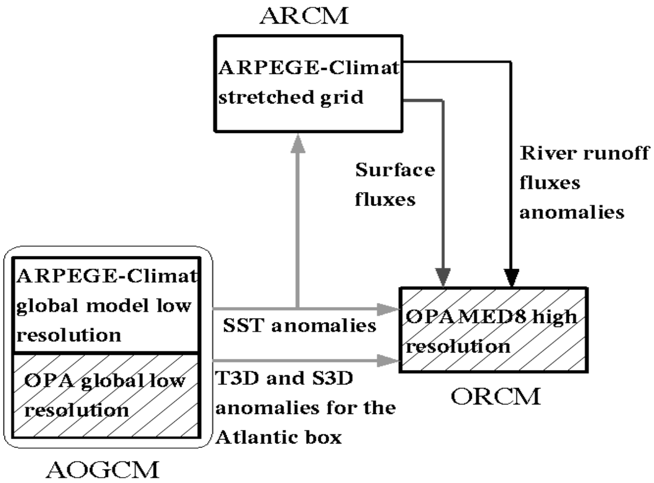

Figure 1: Simple diagram expliciting the forcing links between the three models used in the study

3. RESULTS AND DISCUSSION

3.1 Temperature

Figure 2 shows the surface temperature for the present time simulation, the end of the control and scenario simulations. Comparing with the MEDATLAS-II climatology (not shown), the present time SST field is too cold by about 1°C everywhere, due to an initial drift which takes place during the spin-up of the model. There are two interesting remarks following this figure: firstly the control run is very stable, and secondly the scenario conditions imply an increase of 2.5°C, spatially homogeneous. This evolution is mainly driven by the SST forcing coming from a low resolution model, and so with a few regional structures.

The heat content shows more differences between the basins. As seen in figure 4a and 4b showing the annual means, the control run (in black) is again very stable, with only a decrease of 0.14°C for the entire basin in 140 years. The global basin, the Eastern and Western ones, and the Levantine Sea undergo an increase of respectively 1.0°C, 0.9°C, 1.1°C and 0.8°C. The heat content of the Aegean and Adriatic Seas increases more, up to 1.7°C and 2.1°C respectively. In the first years, the heat content of the Aegean and Levantine basins can be distinguished by the more noisy curve for the Aegean Sea.

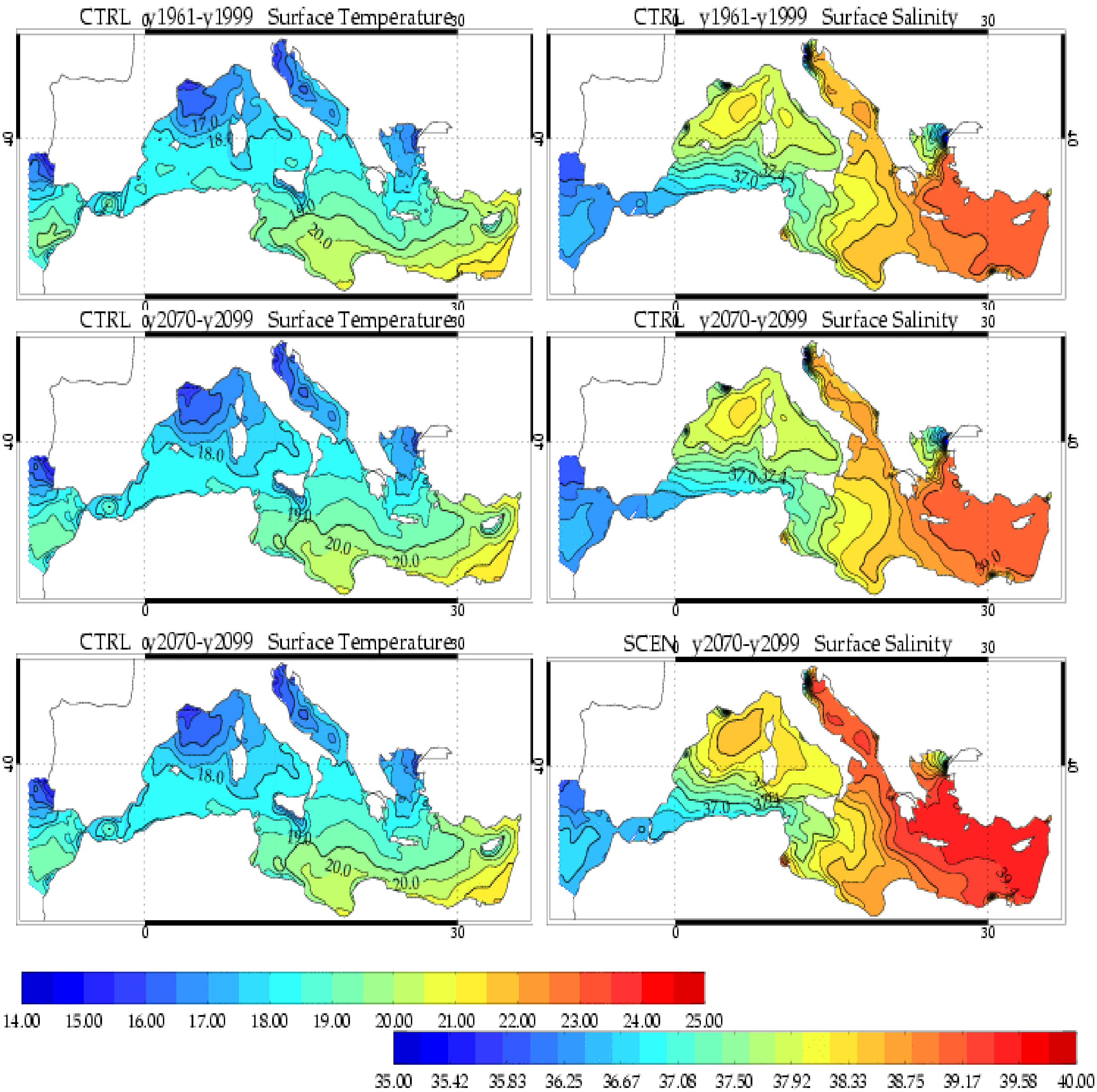

Figure 2 (left): Sea Surface Temperature (°C) averaged for the present time run (top), the last thirty years of the control run (middle), and the last thirty years of the scenario run (bottom)

Figure 3 (right): Same as fig. 2 for the Sea Surface Salinity (psu)

3.2 Salinity

The control run is again very stable, as seen in fig. 3 and 5. At the surface (fig. 3), the salinity remains close to the MEDATLAS-II climatology (not shown), even without any salinity relaxation. It means that there is at least a good balance between the ARPEGE-Climat fluxes, the climatology of the runoffs used, and the Gibraltar salt exchanges. The most important increase observed at the end of the scenario run are located in the Adriatic Sea (+0.61 psu) and the Aegean Sea (+0.70 psu), where the Po and the Black Sea play an important role and follow a large decrease as for the Back Sea.

For the salinity content, the Mediterranean basins can again be divided in two groups (fig. 5a and 5b, control in black, scenario in red):

- the global, Eastern, Western, and Levantine basins, with an increase between 0.12 and 0.19 psu;
- the Aegean and Adriatic Seas, with respectively 0.38 and 0.48 psu increases.

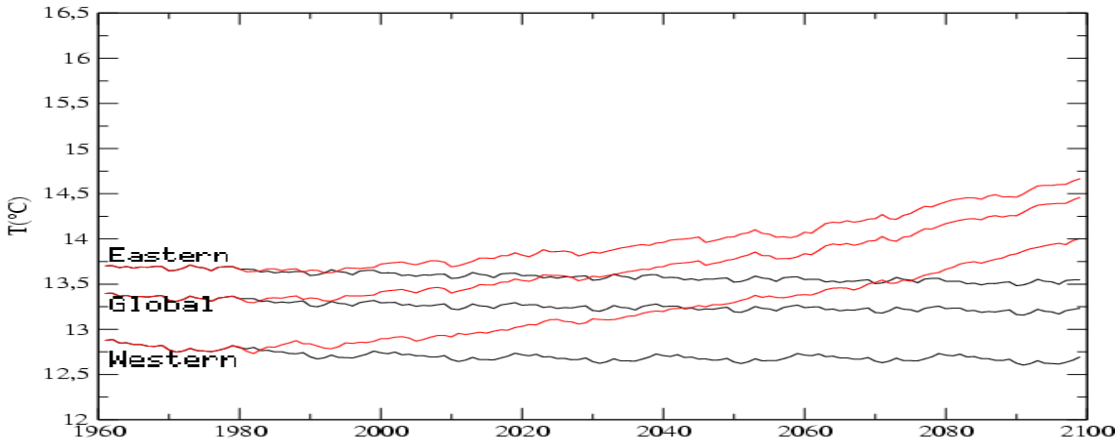

Figure 4a

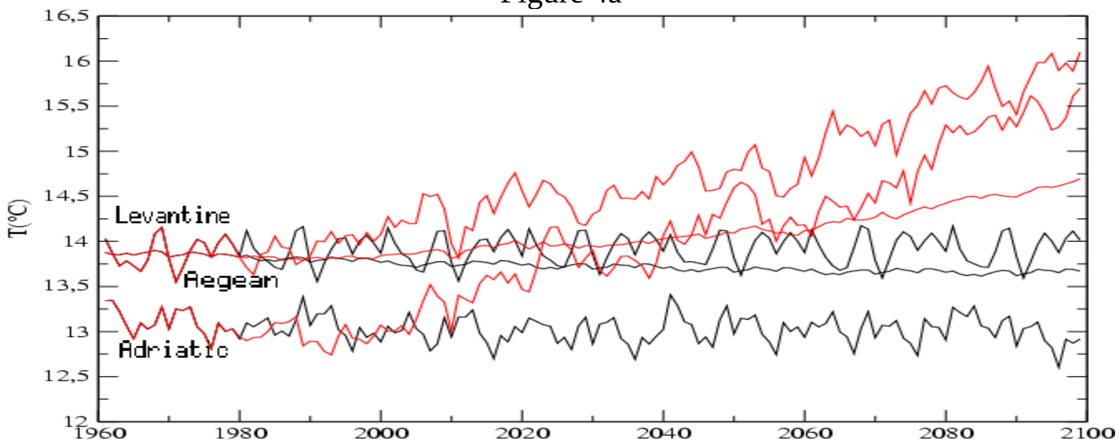

Figure 4b

Figure 4a and 4b: Yearly average of the heat content (°C), control run in black, scenario run in red

3.3 Intermediate and deep convection

Figure 6 represents the winter (JFM) mixed layer depth (MLD) averaged over the 2070-2099 period of the control and the scenario runs. The MLD computation is based on a vertical eddy diffusivity criterion (limit = 5 cm^2/s). The shaded areas identify the areas of winter convection in OPAMED8 and they correspond to those mentioned in the literature, namely, the Gulf of Lions, the south of the Adriatic Sea, the Levantine basin and the south of the Aegean Sea. The winter convection is a process known to be very variable from one year to another. So the MLD averaged value can mask different reality.

In the Adriatic and Aegean Seas, the winter convection remains quite unchanged. It decreases in the Levantine basin, where the LIW and the LDW are formed. In fact, this strong weakening is due to a decrease in LDW formation frequency. Indeed, the LIW formation remains yearly even if it occurs with a shallower maximum depth.

The most important and alarming decrease of the winter convection appears in the Gulf of Lions area, where the WMDW is formed. A time evolution of the maximum of MLD in winter would show that it decreases very quickly, and the situation remains quite stable from 2020, not exceeding 300m in average. However, at the end of the scenario, convection deeper than 1000 m is still possible some year.

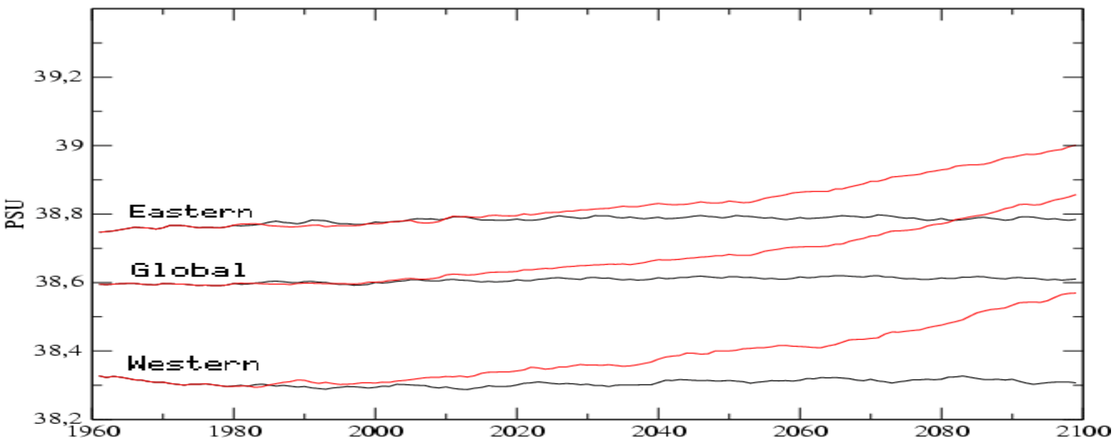

Figure 5a

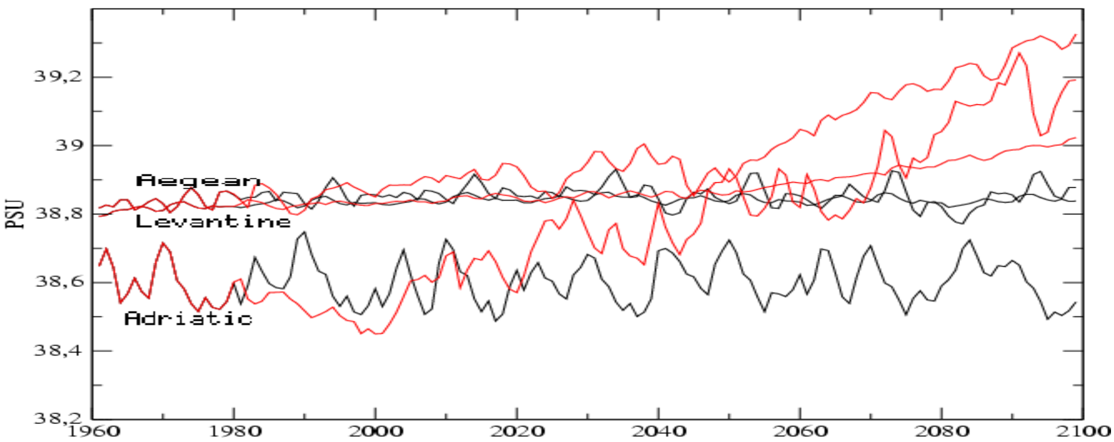

Figure 5b

Figure 5a and 5b: Same as fig. 4 for the salinity content (psu)

3.4 Discussion

Increasing the surface temperature or salinity may lead to opposite effects on the density: an increase in temperature implies a decrease in density, whereas an increase in salinity implies an increase in density. Yet the thermohaline circulation is driven by the differences of density. In the Western basin and the Levantine basin, the decrease of the winter convection shows that the effect of the increase of temperature is stronger. On the contrary, the more important salinity increase in the Adriatic and Aegean Seas allows the winter convection to remain unchanged, and a consequence is the transmission of the surface temperature increase to the deep layers.

These modifications of the characteristics of the water masses and of the winter convection will certainly lead to a modification of the thermohaline circulation, for there will be less formation of intermediate (LIW) and deep waters (LDW, EMDW and WMDW), with then a slowing down of the intermediate and deep circulation.

We can finally compare our evolution of the heat and salt content under 800 m in the Western basin with the values derived by Bethoux et al. (1990) from observations at the end of the 20th century, and attributed to the climatic change (Bethoux et al., 1998). Bethoux et al. (1990) give an increase of temperature of 3.47 10^{-3} °C/year, and of salinity of 1.07 10^{-3} psu/year. Our values for the 100 years of the scenario run are respectively 7.9 10^{-3} °C/year and 1.4 10^{-3} psu/year. Thus the increase that we predict for the 21st century follows the same slope as observed for the salinity, and a faster one for the temperature.

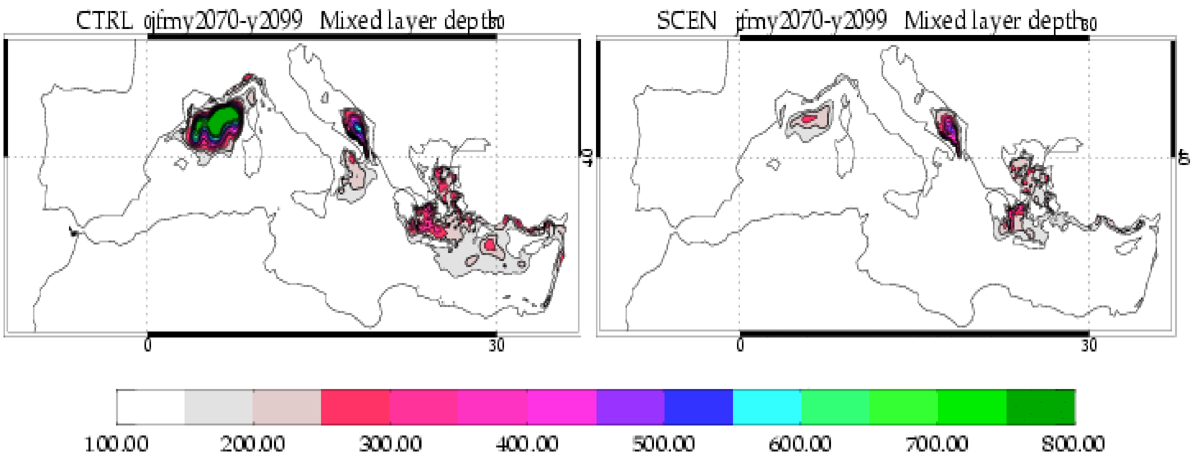

Figure 6: Winter (jfm) mixed layer depth (m) averaged on the thirty last years of the control run (left) and the scenario run (right)

4. CONCLUSION

The experiment described here provides an element of answer to the question of the evolution of the Mediterranean Sea under a climate change.

The increase of SST is homogeneous spatially and amounts to 2.5°C at the end of the 21st century. The increase in SSS is more regionally dependant, and goes from 0.23 psu to 0.70 psu, maximum value in the Aegean Sea, due to the strong decrease of the Black Sea freshwater input.

We have seen that the evolution of the surface temperature is mainly driven by the surface temperature forcing, and the surface salinity by the evolution of the river runoffs. The winter convection is then affected, indeed nearly stopped in the Gulf of

Lions area, and there will be consequences on the thermohaline circulation. These consequences are not explicitly studied in this paper. The first effect is that the heat and salinity contents are all the more positively modified as the winter convection decreases.

Of course, many uncertainties remain to explore after this first scenario. For example, only one climatic scenario is used, and we should test other ones. The evolution of the SST comes from a low resolution scenario, with no small scale effects and no ocean feedback. The evolution of the river runoffs, including the Black Sea, is hypothetic. The evolution of the Atlantic box is also arguable. A step towards more realism is to perform an high resolution coupled ocean-atmosphere scenario.

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