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# Modelling regional-scale climate change of the Mediterranean*

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## 1. Regionally-oriented climate scenarios

Regional climate changes under global warming context are the most important motivations for the Mediterranean regional climate modelling. It is generally agreed that the Mediterranean region is one of the sensitive areas on Earth in the context of global climate change, due to its position at the border of the climatologically determined Hadley cell and the consequent transition character between two very different climate regimes in the North and in the South.

In terms of global mean surface air temperature, the Globe has experienced a general warming of 0.6°C over the last century. IPCC estimated changes of the global temperature to be between 2 to 5°C at the end of the 21st century. The global mean temperature is only a mean indicator and changes at regional scales can be much larger. Many global and regional models tend to simulate a warming of several degrees (from 3 to 7°C) on the Mediterranean for the end of the 21st century and the warming in Summer is larger than the global average. There is also a general trend of a mean precipitation decrease for the region (especially in Summer), due mainly to the northward extension of the descending branch of the subtropical Hadley circulation.

In the framework of the French national programme GICC-MedWater, two regionally-oriented atmospheric models, LMDZ-Med (developed in IPSL in Paris) and ARPEGE-Med (developed in Meteo-France in Toulouse), were used to study the Mediterranean climate change for the end of the 21st century. Both models are global atmospheric GCMs, but with stretched grid and increased spatial resolution over the Mediterranean. Unlike limited-area models, LMDZ-Med and ARPEGE-Med need only the SST and greenhouse gaz concentration from global climate models to perform regionally-oriented climate change scenario simulations.

We used only one emission scenario - IPCC SRES A2, but three global climate scenarios provided by three institutions (IPSL, CNRM and GFDL) running global ocean-atmosphere coupled models. Both LMDZ-Med and ARPEGE-Med were firstly run for the period 1970/1999 to produce their respective control simulations. LMDZ-Med was run furthermore for the three future scenarios for the period 2070/2099. ARPEGE-Med was run for the future scenario provided by CNRM. Table 1 summarizes the simulations used in the project GICC-MedWater.

The hydrological cycle is an important component of the Mediterranean regional climate. For the four future scenario runs, Table 2 gives the annual-mean values for changes in E, P and E-minus-P. All the future climate simulations show a decrease of precipitation rate. Evaporation increases for LMDZ/IPSL, LMDZ/CNRM and ARPEGE/CNRM, but there is a very weak, insignificant decrease for LMDZ/GFDL. The net water deficit thus increases in all the four scenarios. The last column of Table 1 shows the gain of total heat flux at the sea surface for the three scenarios compared to the control simulation. We can see that the Mediterranean Sea wins (or loses less) energy from the atmosphere for future climate scenarios. The net gain of heat flux varies from 3.6 to 11.9 W/m2 for different runs.

| Simulation | period | Conditions |
|---|---|---|
| LMDZ/CTRL | 1970/1999 | Control simulation |
| ARPEGE/CTRL | 1970/1999 | Control simulation |
| LMDZ/IPSL | 2070/2099 | Emission SRES-A2<br>Global climate IPSL |
| LMDZ/CNRM | 2070/2099 | Emission SRES-A2<br>Global climate CNRM |

| Simulation | period | Conditions |
|---|---|---|
| LMDZ/GFDL | 2070/2099 | Emission SRES-A2<br>Global climate GFDL |
| ARPEGE/CNRM | 2070/2099 | Emission SRES-A2<br>Global climate CNRM |

*Table 1: Different simulations with the corresponding time periods and boundary conditions.*

| Simulation | E | P | E-P | H |
|---|---|---|---|---|
| LMDZ/IPSL | 39 | -57 | 96 | 3.6 |
| LMDZ/CNRM | 57 | -74 | 131 | 5.8 |
| LMDZ/GFDL | -7 | -20 | 13 | 11.9 |
| ARPEGE/CNRM | 120 | -60 | 180 | 4.9 |

*Table 2: Annual-mean changes of evaporation (E: mm/yr), precipitation (P: mm/yr), water deficit (E-P: mm/yr) and gain of heat flux (H: W/m2) for the whole Mediterranean Sea and for the four scenarios respectively.*

**2. Sensitivity of the Mediterranean thermohaline circulation to anthropogenic global warming**

The Mediterranean Sea is a concentration basin with an evaporation rate much larger than the rainfall rate and river runoff, leading to increase in salt content. It is also a heating source to the atmosphere with annual decrease of temperature for water masses. The Mediterranean Sea is similar to a thermodynamic engine which transforms the inflowing light Atlantic water into dense deep Mediterranean waters through air-sea coupling. This water transformation process generates thermohaline forcing which drives, in a large proportion, the Mediterranean marine general circulation. Convection can thus be observed in several places of the Mediterranean Sea, particularly, in the Gulf of Lions, Adriatic Sea, Aegean Sea and Levantine basin.

Here we investigate the sensitivity of the Mediterranean thermohaline circulation to global warming. As indicated in Table 2, the simultaneous increase of both surface temperature and water deficit could counteract each other in the possible evolution of the Mediterranean Sea thermohaline circulation (MTHC). A weakening or strengthening of the MTHC due to climate change could have an impact on the Mediterranean sea surface temperature and consequently on the climate of the surrounding areas. Through the Mediterranean Outflow Waters, changes of MTHC can furthermore influence the Atlantic Ocean and then the Atlantic and global thermohaline circulation. The Mediterranean marine ecosystems are also expected to be strongly influenced by the variation of marine circulation.

By using the regionally-oriented climate scenarios, as described in Table 1, Somot (2005) and Bozec (2006) studied the impact of global warming on the Mediterranean Sea thermohaline circulation. The Mediterranean Sea general circulation model is MED8, derived from the OPA oceanic model, with the horizontal resolution at 1/8 degree. Results on water mass properties are reported in Table 3. The increase of temperature and salinity is observed in the whole Mediterranean. In the case of LMDZ-Med, the increase of salinity is quite weak, due to an irrealistic restoring of the salinity to current climate values for the control and scenario runs.

| | temperature (°C) | | | salinity (PSU) | | |
|---|---|---|---|---|---|---|
| | total | upper | lower | total | upper | lower |
| LMDZ/CTRL | 13.91 | 15.33 | 13.79 | 38.59 | 38.43 | 38.66 |
| ARPEGE/CTRL | 13.2 | 14.2 | 13.1 | 38.61 | 38.27 | 38.66 |
| LMDZ/IPSL | 0.31 | 1.25 | 0.15 | 0.02 | 0.08 | 0.00 |
| LMDZ/CNRM | 0.43 | 1.81 | 0.20 | 0.02 | 0.09 | 0.00 |
| LMDZ/GFDL | 0.49 | 2.13 | 0.22 | 0.02 | 0.07 | 0.00 |
| ARPEGE/CNRM | 1.0 | 2.0 | 0.8 | 0.18 | 0.31 | 0.16 |

*Table 3: Temperature (°C) and salinity (PSU) for the control simulations LMDZ/CTRL and ARPEGE/CTRL, and their changes for the four scenario runs (LMDZ/IPSL, LMDZ/CNRM, LMDZ/GFDL and ARPEGE/CNRM). "total" indicates the whole Mediterranean. "upper" indicates from 0 to 250 m. "lower" indicates from 250 m to the bottom.*

Since the Gibraltar Strait is the only connection of the Mediterranean Sea with the global ocean, the water mass transport and the associated properties can give an integrated indication of climate variation and changes in the Mediterranean basin. Table 4 gives the mass transport, temperature and salinity in the Gibraltar Strait simulated by MED8 using atmospheric forcings from LMDZ-Med and ARPEGE-Med for the control runs and scenario runs. We can see that the water mass transport is diminished when the climate is warmed. This diminition is also larger when the warming is stronger. In the case of LMDZ-Med, the proprieties of incoming water do not change very much, since the buffer zone in the Atlantic was not allowed to change. For the Mediterranean outflow on the bottom, both temperature and salinity are increased. This conclusion is confirmed in the ARPEGE/CNRM scenario, with the outflow slower, saltier and warmer for the end of the 21st century. Some recent observation-based studies revealed also a warmer and saltier trend for the Mediterranean deep water masses (Bethoux et al. 1990; Potter and Lozier 2004; Rixen et al. 2005), which is probably the manifestation of the ongoing anthropogenic global warming.

| | surface inflow | | | bottom outflow | | |
|---|---|---|---|---|---|---|
| | Tr | T | S | Tr | T | S |
| LMDZ/CTRL | 0.656 | 16.44 | 36.45 | 0.656 | 13.53 | 38.26 |
| ARPEGE/CTRL | 1.18 | 15.69 | 36.35 | 1.18 | 12.43 | 38.28 |

| | | | | | | |
|---|---|---|---|---|---|---|
| LMDZ/IPSL | -0.070 | 0.02 | 0.00 | -0.070 | 1.15 | 0.15 |
| LMDZ/CNRM | -0.013 | 0.16 | 0.00 | -0.013 | 1.57 | 0.13 |
| LMDZ/GFDL | -0.150 | 0.25 | 0.00 | -0.150 | 1.84 | 0.09 |
| ARPEGE/CNRM | -0.09 | 1.40 | 0.19 | -0.09 | 2.01 | 0.44 |

*Table 4: Mass transport (Tr: Sv), temperature (T: °C) and salinity (S: psu) in the Gibraltar Strait for the control simulations LMDZ/CTRL and ARPEGE/CTRL, and their changes for the four scenario runs (LMDZ/IPSL, LMDZ/CNRM, LMDZ/GFDL and ARPEGE/CNRM). Surface inflow and bottom outflow are presented seperately.*

## 3. Perspectives and Outlooks

By using a sequential and one-way approach, we show here that, under the global warming context, the Mediterranean Sea will have an increased water deficit and will enter into a stage with a weaker overturning circulation. This may further impact the marine ecosystem. Our study is only a first step toward an integated study on the Mediterranean climate change and impact. Two important issues can be foreseen for the Mediterranean regional climate modelling in the next few years.

### 3.1 Toward high-resolution Mediterranean climate modelling

The spatial resolution of future modelling systems will be further increased. It is expected to have regional atmospheric models with resolution around 10 to 20 kilometres in the next few years. Experience with numerical weather forecasting shows that higher spatial resolution usually leads to better prediction, mainly due to improvements in the representation of atmospheric instability which is crucially dependent on the model's spatial resolution. In climate modelling, higher spatial resolution may lead to improvements in some aspects and degradation in others. Climate is in fact more related to the sources and sinks of energy, moisture and momentum. Mechanisms controlling their budgets and evolution at different spatio-temporal scales are thus crucial for climate. In general higher spatial resolution models can provide a more comfortable background to incorporate sophisticated physics and the latter will improve the performance of regional climate models. For the Mediterranean region, high resolution is particularly important, since there is a very complex terrain surrounding the Mediterranean Sea, responsible for intense wind events, such as Mistral and Bora which contribute largely to oceanic convection in the Mediterranean (Gulf of Lions, Adriatic Sea, and Aegean Sea).

The overall studies reported in the current scientific literature seem to show improved model performance with higher spatial resolution, especially in reproducing extreme events, such as strong precipitation episodes and cyclogenesis often related to the specific surface orography. But there is indeed a need to further evaluate and quantify the impacts of spatial resolution on regional climate simulation. Even in the most advanced high-resolution regional climate models, it will be difficult, in some cases, to determine dynamically the hydrological variables, such as run-off. Application of statistical methods will always be necessary to provide appropriate solutions for climate change impact studies.

### 3.2 Development and validation of integrated regional modelling systems

Other components controlling the regional climate will enter interactively into the regional modelling system. They include, through the most important items, the Mediterranean Sea general circulation, basin-scale hydrology, dynamic surface vegetation, land use, atmospheric chemistry, air pollution and man-made or desert-originated aerosols, marine and land-surface ecosystems. It is expected that new climate feedbacks and modes derived from the complex interaction among different components of the Mediterranean climate system might be discovered and quantified. Especially the regional atmosphere and Mediterranean Sea coupled models should receive high priority for their development and utilisation in the Mediterranean climate studies.

It is also necessary to emphasize the perspectives of multi-model ensemble approach for future Mediterranean regional climate modelling activities. This is the only way to assess the uncertainties of numerical modelling for climate variation and probabilistic estimates for changes at long terms. Any climate impact considerations should take into account this aspect of probability.

In terms of global mean surface air temperature, it is generally agreed that the changes of the global temperature will be between 2 to 5 degrees at the end of the present century. In broad terms, the current thinking attributes about half of this range of uncertainty to uncertainties in the emission scenarios and half to uncertainties in the construction and use of global climate models. The use of regional climate models will further increase the uncertainty range. We need thus to use a hierarchy of global and regional models and to run ensemble simulations. This is just at the limit of our current computing capacity. A close cooperation with computer industry is thus necessary in the future to accomplish this task.

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