Chapter 7

Regional Atmospheric, Marine Processes and Climate Modelling

Laurent Li,[1] Alexandra Bozec,[2] Samuel Somot,[3] Karine Béranger,[2] Pascale Bouruet-Aubertot,[2] Florence Sevault[3] and Michel Crépon[2]

[1]*LMD/IPSL/CNRS, Université P. et M. Curie Paris, France (li@lmd.jussieu.fr)*
[2]*LOCEAN/IPSL, Université P. et M. Curie Paris, France (Alexandra.Bozec@lodyc.jussieu.fr, Karine.Beranger@ensta.fr, Pascale.Bouruet-Aubertot@lodyc.jussieu.fr, crepon@lodyc.jussieu.fr)*
[3]*Météo-France, CNRM/GMGEC/EAC, Toulouse, France (samuel.somot@meteo.fr, florence.sevault@meteo.fr)*

7.1. Introduction

The Mediterranean region is rather unique in respect to its geographical position: north of the largest desert in the world – the Sahara, and south of a large temperate climate region – Europe. It is therefore a transition area between tropical and mid-latitude climates. As a transition area, the Mediterranean region shows important local climate variability and rather large gradients, both in the South–North and East–West directions.

The Mediterranean climate is characterized by its strong seasonal contrast. The summer is dry and hot, the winter is humid and mild. The upper panel of Fig. 124 shows the sea-level pressure for the region of the North Atlantic, Europe and Mediterranean for December–January–Feburary as described in the ERA-15 dataset. The remarkable structure of this figure is the Icelandic Low and the Azores High. The main atmospheric center of action affecting the Mediterranean climate is the Azores High, a subtropical anticyclone related to the descending branch of the Hadley cell. The Mediterranean region can thus be related to tropical climate events like El Niño and monsoons (see also Chapter 2). The Mediterranean Sea is an important playground for the North Atlantic Oscillation, a major atmospheric circulation pattern of the Northern

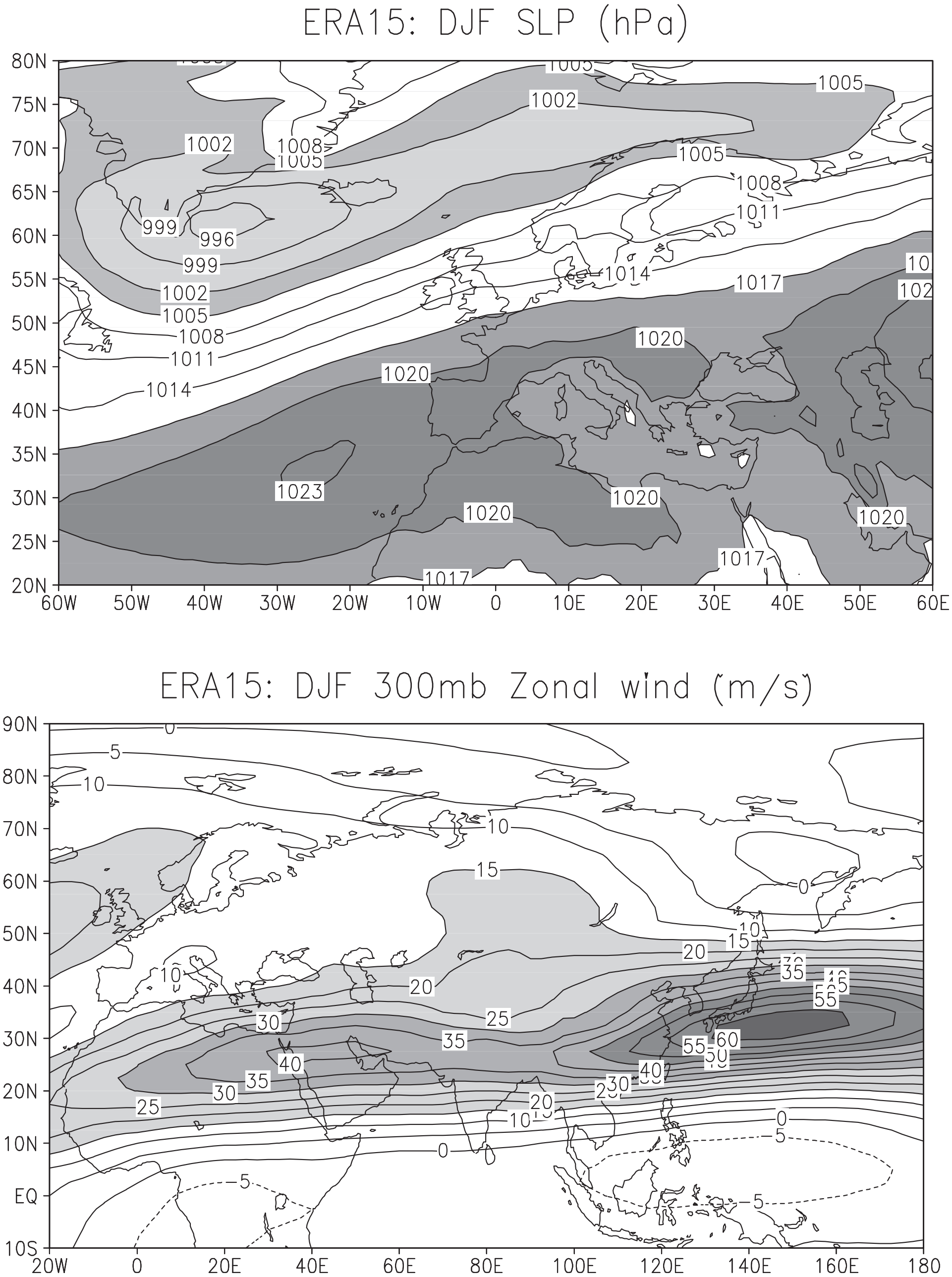

Figure 124: Sea-level pressure (hPa) and 300-hPa zonal wind (m/s) for December–January–February, as depicted in the ECMWF re-analysis dataset from 1979 to 1993.

Hemisphere, characterized by a seesaw between the Icelandic Low and the Azores High. The Mediterranean climate may thus be strongly influenced by processes which can involve the atmosphere only or coupled ocean–atmosphere phenomena in mid and high latitudes (see also Chapters 3 and 6). As depicted in the lower panel of Fig. 124 showing the 300-hPa zonal wind for the whole Eurasian continent and North Africa, the Mediterranean Sea is located in the north flank of the sub-tropical jet stream. The jet stream plays an important role in forming atmospheric teleconnections between the Mediterranean and regions far away.

The Mediterranean Sea is a concentration basin with an evaporation rate much larger than the rainfall rate and river runoff (Mariotti et al., 2002; Struglia et al., 2004), leading to increase in salt content. It is also a source of heat to the atmosphere with annual decreases of temperature for water masses. This particular behaviour of the Mediterranean Sea has its roots and consequences in the Gibraltar Strait, where the inflow is fresh (36.6 psu) and warm (maximum of 21°C in August and minimum of 17°C in March), and the outflow is salty (38.25 psu) and cold (13.3°C). The Mediterranean Sea is thus similar to a thermodynamic engine which transforms the inflowing light Atlantic water into dense deep Mediterranean waters through air–sea coupling (see Chapters 4 and 5 for more descriptions). 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.

The surface circulation in the western Mediterranean can be schematically described as follows. The Atlantic Water (AW) enters the Alboran Sea forming the Alboran gyres (Gascard and Richez, 1985; Heburn and La Violette, 1990), and flows eastward forming the Algerian Current (AC). The AC presents well-marked meanders due to baroclinic instabilities. Then the AC splits into two branches at the Sicily Strait, one entering the Tyrrhenian Sea passing through the Corsica Strait and forming the Northern current, the other entering the eastern Mediterranean (Millot, 1987; Herbaut et al., 1998). The AW entering the eastern Mediterranean divides into two distinct streams (Robinson et al., 1999; Lermusiaux and Robinson, 2001). One flows over the Tunisian shelf, the other forms the Mid Ionian jet. These two currents merge at the level of East of Libya (as seen in Marullo et al., 1999) as a coastal current (Alhammoud et al., 2005; Hamad et al., 2002) flowing eastwards along the Egyptian coast. Then this current flows northwards along the Jordanian–Israel–Lebanon Coast and westwards at the level of Turkey. During its eastward progression, the AW is transformed through convection processes into Western Mediterranean Deep Water (WMDW) in the Gulf of Lion, into Levantine Intermediate Water

(LIW) in the Levantine Basin, into Eastern Mediterranean Deep Water (EMDW) in the Adriatic and Aegean Seas. The LIW flows westwards into the Western Mediterranean at intermediate depth (400 m) through the Sicily Strait and then into the Atlantic Ocean through the Gibraltar Strait, closing the water budget of the Mediterranean Sea.

Numerical modelling, both global and regional, is an important tool to understand physical mechanisms controlling climate change and variability at different spatio-temporal scales. It also provides the unique possibility to construct physically based and comprehensive future climate scenarios, the starting point for many socio-economical impact considerations. Sections 7.2, 7.3 and 7.4 will present several studies on the physical mechanisms controlling the Mediterranean climate variation and change. Sections 7.5 and 7.6 will then present the current status of the Mediterranean regional climate modelling and the preliminary results of a regional coupled model. Perspectives will be given in Section 7.7.

7.2. Teleconnection Patterns from the Mediterranean Region

The Mediterranean Sea plays an important role in determining the climate of the nearby regions (Millan et al., 2005a,b). It is also believed that the Mediterranean Sea can exert influences on the climate of regions far away. The first mechanism may be through the Mediterranean outflow water (about 1 Sverdrup of warm and salty water) flowing out of the Gibraltar Strait into the North Atlantic. The Mediterranean Sea can thus contribute to the global climate variation by altering the oceanic overturning circulation (see Chapter 5). Teleconnection patterns in the atmosphere can also be initiated from the Mediterranean region. Rowell (2003) reported that a warming of the Mediterranean Sea Surface Temperature (SST) can increase the Sahelian rainfall during Summer through an increase of moisture transport in the eastern part of the Sahara. He remarked that the rainfall increase is also amplified by a more intense moisture flux from the tropical Atlantic ocean and a more intense local water re-cycling. The Mediterranean Sea may also regulate the northward progress of the African summer monsoon by changing the meridional thermal contrast.

The Mediterranean Sea is an important playground for the North Atlantic Oscillation (NAO), a major atmospheric circulation pattern of the Northern Hemisphere. In particular, the Polar–Mediterranean mode, as classified by Kodera and Kuroda (2003), can exert important influences on the Eurasian climate. Yu and Zhou (2004) reported that the cooling trend observed during the recent half century for the subtropical Eurasian continents and for the month of

March is strongly correlated with the DJF (December–January–February) NAO index. They found also that the relation was the strongest with a lag of two months, the time necessary for the cooling signal to propagate from North Africa to Central Asia, in a quasi-barotropic structure for the whole troposphere. The mechanism responsible for this linkage is however still unclear.

The existence of large-scale zonally propagated teleconnection structures was already pointed out by Branstator (2002). He demonstrated that the Asian jet-stream beginning over North Africa played the role of waveguide by trapping disturbances inside the jet-stream and propagating them from west to east. Watanabe (2004) also found that there is a downstream extension of the NAO during late winter through wavetrain structure. This wavetrain is furthermore interpreted as composed of quasi-stationary Rossby waves trapped on the Asian jet waveguide and excited by the anomalous upper-level convergence over the Mediterranean Sea. He concluded that the Mediterranean convergence associated with the NAO may have some predictability for the medium-range weather forecast in East Asian countries.

Li (2005) uses an atmospheric GCM to study the influences of the Mediterranean Sea on the atmosphere. An idealized homogeneous cooling of 2°C for the Mediterranean Sea is imposed as forcing. The model used is the LMDZ, an atmospheric general circulation model with a resolution of 4° in latitude and 5° in longitude. The model was run 9,000 days under perpetual January mode for respectively normal boundary conditions and conditions of an idealized Mediterranean cooling. Figure 125 plots the simulated geopotential height anomalies for 1,000, 850, 500 and 300 hPa respectively. A baroclinic structure is created downstream of the cooling location, across the entire Eurasian continent, roughly following the subtropical jet-stream. There are high (low) pressure anomalies in the lower (upper) atmosphere. Over South Asia, an opposite-sign baroclinic structure is obtained and it is believed to be the consequence of tropical rainfall anomaly. All other remote structures are quasi-barotropic and the most remarkable ones are the deepening of the Aleutian Low in the North Pacific and the weakening of the Icelandic Low in the North Atlantic.

In order to study the temporal evolution of the response and the physical mechanisms at different time scales, an ensemble of transient simulations, parallel to the equilibrium runs, are also performed. Each of them lasts 30 days and the ensemble size reaches the huge number of 3,000 to ensure a good statistical significance and an entire coverage of all possible atmospheric states. The approach of the ensemble transient simulations is found very useful in showing the temporal evolution of the response (Li and Conil, 2003). The two tele-connections need several days in the North Pacific and even several tens of days in the North Atlantic to form and to grow. Both of them have a quasi-barotropic

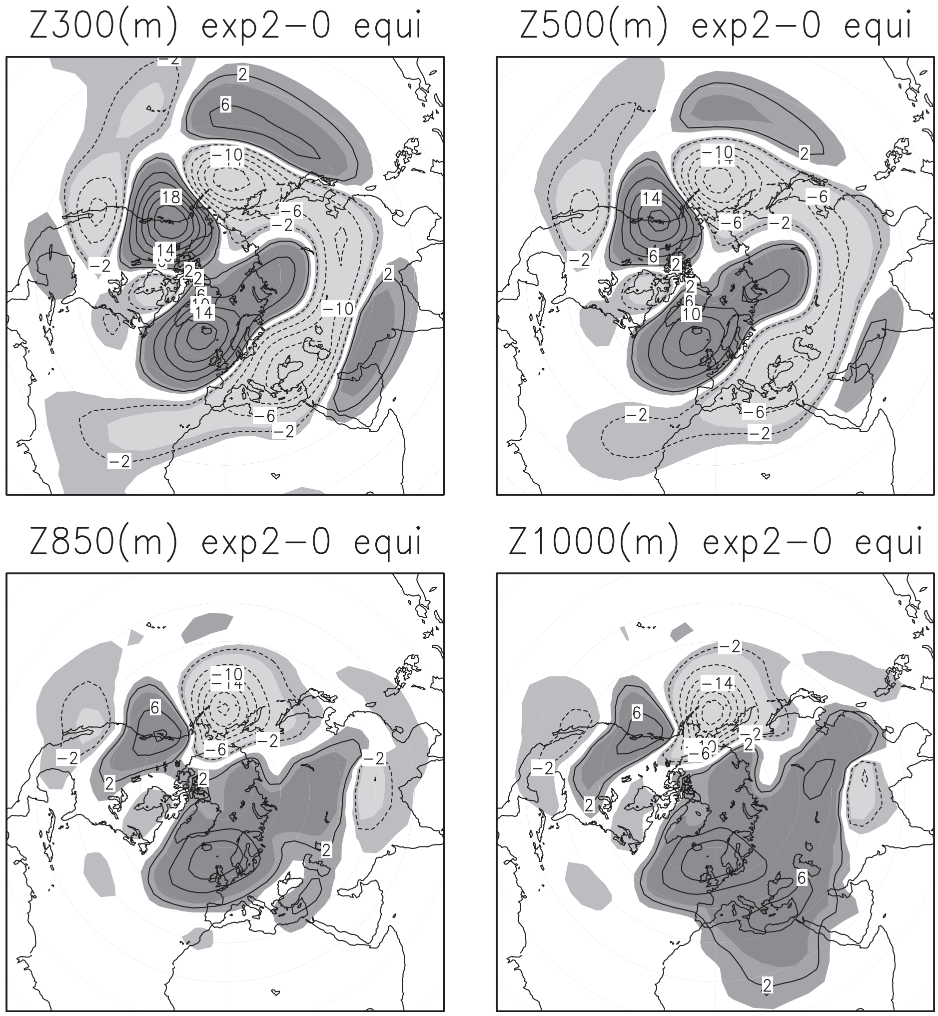

Figure 125: January geopotential height changes (m) at levels of 1,000, 850, 500 and 300-hPa for a homogeneous cooling of 2°C of the Mediterranean sea surface temperature, as simulated in the atmospheric general circulation model LMDZ.

vertical structure. It is believed that they are the consequence of complex interactions between the mean flow and the transient eddies in the atmosphere. It is interesting to note that the North Atlantic response is not directly from the Mediterranean Sea, the source of the perturbations, but through a long circle around the world, following roughly the Asian jet-stream and then the North Atlantic sub-polar jet-stream.

7.3. Mediterranean Thermohaline Circulation and its Sensitivity to Atmospheric Forcing

The overturning circulation driven by the thermohaline forcing is a particular character of the Mediterranean Sea general circulation. Since the pioneering work of the MEDOC group (MEDOC group, 1970), a large number of studies has been dedicated to water formation in the Mediterranean Sea. An extensive summary can be found in Madec et al. (1991, 1996), Marshall and Schott (1999), Castellari et al. (1998), Lascaratos and Nittis (1998), Lascaratos et al. (1999) and Korres et al. (2000), Beckers et al. (2002) concerning physical mechanisms and numerical modelling.

Several factors participate in deep water formation. Firstly, cyclonic structures in the horizontal circulation play an important pre-conditioning role by imposing the dense water in formation to stay at the same place and not to be advected off the formation zone. A second ingredient is the presence of strong atmospheric forcing for both heat flux and wind stress. Convection in the Gulf of Lions and the Adriatic Sea is particularly sensitive to the Mistral and Bora winds which create strong evaporative cooling and wind stress curl when they blow into the sea from the Alps. Intuitively, we can imagine that the performance of the Mediterranean Sea general circulation modelling is quite dependent on the atmospheric forcing and in particular, the intensity of wind stress.

This is confirmed by recent experiments performed with the OPA Mediterranean general circulation model at the resolution of 1/8° (MED8, conducted by A. Bozec, unpublished results) and of 1/16° (MED16, conducted by K. Béranger, unpublished results). Two datasets of atmospheric forcing are used, one is from ERA40 – the ECMWF re-analysis (T159 model), the other the ECMWF operational analysis (T319). The period used from the re-analysis is from 1990 to 1999 and that from the operational analysis is from August 1998 to August 2002. The ERA run lasts almost 10 years and the ECMWF run is repeated two times to have a simulation of 8 years (in order to have a comparable length with ERA run). It appears that the ERA run is unable to generate convection unless a strong probably unrealistic restoring to winter temperature and salinity is applied, while ECMWF run is able to trigger convection.

Figure 126 shows time series of the maximum depth reached by the mixed layer in the Gulf of Lions and in the Levantine basin for the two simulations using MED8 (very similar results are obtained by using MED16). For both Gulf of Lions and Levantine basin, the mixed layer is much deeper in ECMWF run than in ERA run. A stronger interannual variability is also observed in ECMWF run. Although our experimental design does not allow a perfect comparison between the operational analysis and the re-analysis, since they are not over a same time

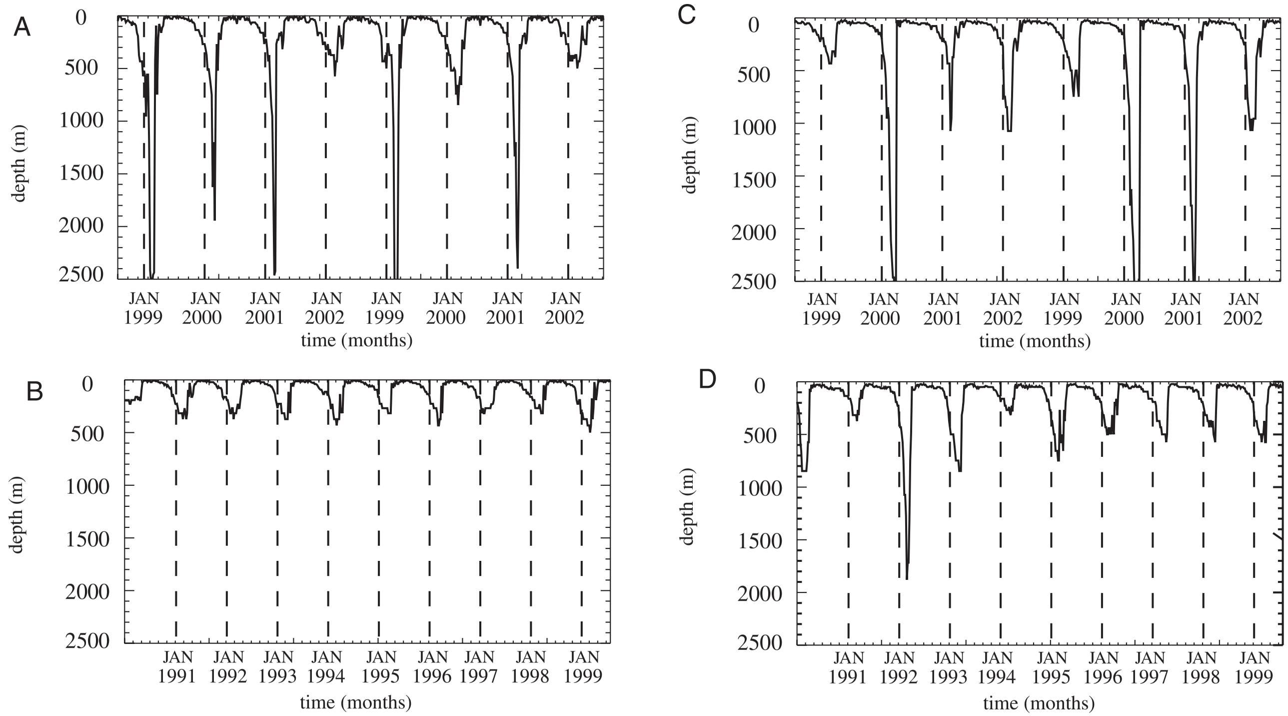

Figure 126: Time series of the maximum mixed-layer depth (m) in the Gulf of Lion (left panels, A and B) and in the Levantine basin (right panel, C and D) for the model MED8, forced respectively by ECMWF operational analysis (top panels, A and C) and re-analysis ERA40 (bottom panels, B and D).

period, we think that the explanation of such large differences is the fact that the ECMWF winds are stronger than those provided by ERA40. A comparison of wind stress for the average of Jan–Feb–Mar between the two datasets is shown in Fig. 127. Although the spatial structure is similar, the intensity in ERA40 seems significantly under-estimated. This is confirmed by S. Marullo (personal communication) who compared both datasets against measurements through wind sensors installed on surface buoys in three locations of the Mediterranean Sea. It is revealed that ECMWF operational analysis winds are quite close to those of the buoy sensors, but the re-analysis winds are under-estimated.

The difference in spatial resolution (50 km for ECMWF against 120 km for ERA) is believed to be the main reason to explain the discrepancy of the two datasets. As presented in the following section, the same MED8 model, when forced by Arpege-Climate model stretched to have 50 km for the Mediterranean, did produce marine convection. We may thus generalize the above results and tentatively conclude that the necessary atmospheric resolution is about 50 km in order to simulate the Mediterranean convection and deep water formation.

7.4. Sensitivity of the Mediterranean Thermohaline Circulation to Anthropogenic Global Warming

Regional climate changes under global warming context (Jones et al., 1995, 1997; Machenhauer et al., 1998; Frei et al., 2002; Gibelin and Déqué, 2003) 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 (2001) estimated changes of the global temperature to be between 2 to 5°C at the end of the present 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 twenty-first 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 (IPCC, 2001). Examples and studies concerning the regional projections of global warming are given

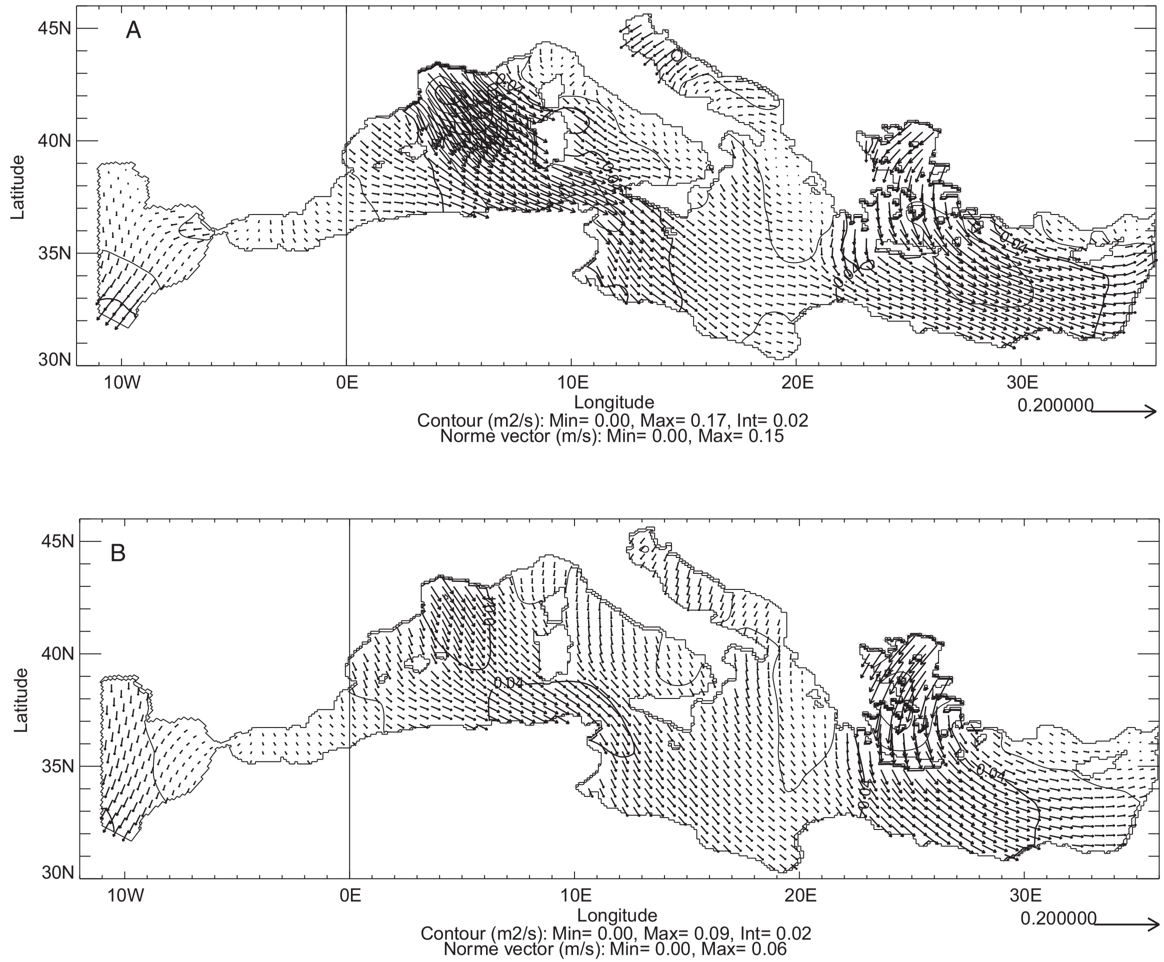

Figure 127: Wind stress (Pa) for January–February–March, as depicted in ECMWF operational analysis (top) and re-analysis ERA40. The top panel is from 5 years from 1998 to 2002 and the bottom 12 years from 1988 to 1999.

in Chapter 8. Here we only investigate the sensitivity of the Mediterranean thermohaline circulation to global warming.

The simultaneous increase of both surface temperature and water deficit (Gibelin and Déqué, 2003; Li, 2003; Giorgi et al., 2004b) 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. With a Mediterranean model at 1/4-degree resolution, Thorpe and Bigg (2000) found that a global warming would lead to a reduced deep water formation in the Mediterranean Sea and to a warmer and saltier outflow.

Through the Mediterranean Outflow Waters (MOW), changes of MTHC can furthermore influence the Atlantic Ocean and then the Atlantic thermohaline circulation. The Mediterranean marine ecosystems are also expected to be strongly influenced by the variation of marine circulation. Vichi et al. (2003) investigated the climate change impact on the northern Adriatic Sea and found that an enhanced stratification of the water column, particularly in Summer may reduce the vertical diffusion of oxygen and nutrients.

Somot et al. (2005) reported a study employing the Arpege-Climate stretched-grid model (Déqué and Piedelievre, 1995; Déqué et al., 1998; Gibelin and Déqué, 2003) with local spatial resolution around 50 km for the Mediterranean basin. The IPCC-A2 global scenario for the end of the twenty-first century was used. Regional patterns of climate change are similar to those presented in Chapter 8, with a general warming of about 3°C and a decrease of precipitation around the Mediterranean basin. Somot et al. (2005) used furthermore the corresponding changes of atmospheric forcing (wind stress, heat flux, damping SST and water flux) at the sea surface and of river runoff to force a Mediterranean Sea general circulation model at the resolution of 1/8 degree (MED8 model).

For the whole Mediterranean Sea and at the end of the twenty-first century, the net heat loss by the surface is lower in the scenario run (1.6 $W.m^{-2}$) than in the control run (6.1 $W.m^{-2}$) but the water loss (Evaporation – Precipitation – River runoff) is higher (0.98 vs. 0.72 m/year). This leads to an increase in temperature and salinity for the Mediterranean Sea (see Table 8) and for each sub-basins. The increase in SST is nearly homogeneous whereas a heterogeneous SSS increase is produced by the model (from +0.36 psu in the Gulf of Lions to +0.87 psu in the Aegean Sea). The pattern of SSS anomalies is mainly driven by the river runoff decrease and especially the behaviour of the Po and Black Sea.

The competing changes in SST and SSS lead finally to a decrease in surface density and thus a weakening of the MTHC. This weakening is estimated to about 60% for the deep circulation (WMDW: Western Mediterranean Deep Water, EMDW: Eastern Mediterranean Deep Water) and 20% for the

Table 8: Temperature (in °C) and salinity (in psu) averaged over different layers of the Mediterranean Sea. "Control" indicates the current climate and "Scenario" at the end of the 21st century.

	SST	T (0–500m)	T (500-m bottom)	SSS	S (0–500m)	S (500-m bottom)
Control	18.7	13.8	13.0	38.18	38.44	38.66
Scenario	21.7	15.9	13.9	38.61	38.84	38.84
Diff.	+3	+2.1	+0.9	+0.43	+0.40	+0.18

intermediate circulation (LIW: Levantine Intermediate Water). The strength of the thermohaline overturning cell can be seen in the Mediterranean zonal overturning stream function (ZOF) following Myers and Haines (2002). The top panel of Fig. 128 plots the ZOF for the control run (30-year average at the end of the control run). The intermediate circulation is seen as a clockwise vertical circulation (positive values) with a maximum value of 1.2 Sv in the Eastern Basin and 1.5 Sv in the Western Basin. This represents mainly the circulations of the Modified Atlantic Water (MAW) and the LIW. The counter-clockwise circulation in the deep part of the Eastern Basin shows the EMDW circulation. A 0.5-Sv circulation is found in the control run. The WMDW path can not be seen by a ZOF. A Western Mediterranean meridional overturning stream function is needed instead. The bottom panel of Fig. 128 plots the ZOF at the end of the scenario simulation (average over the 2070–2099 period). A decrease in the strength and extension of the intermediate thermohaline overturning cell is observed. The deep cell has almost completely vanished. We can thus conclude that the MTHC weakens and becomes shallower during global warming, at least for the IPCC-A2 scenario.

Behaviours of the MOW give an integrated mesurement of the Mediterranean Sea evolution. Warmer (+1.9°C) and saltier (+0.5 psu) waters are simulated for the end of the twenty-first century. Warm and salty tendencies have also been reported during recent years for the Mediterranean deep waters (Béthoux et al., 1990; Rohling and Bryden, 1992; Fuda et al., 2002; Rixen et al., 2005) and the MOW (Curry et al., 2003; Potter and Lozier, 2004) from hydrographic data for the last decades. This might be already a manifestation of climate change and global warming for the Mediterranean Sea.

The robustness of the results presented by Somot et al. (2005) using only one scenario and one particular model needs, however, to be confirmed by other models and other groups. It will be interesting to explore the validity of the results by incorporating uncertainties in different stages of the investigation

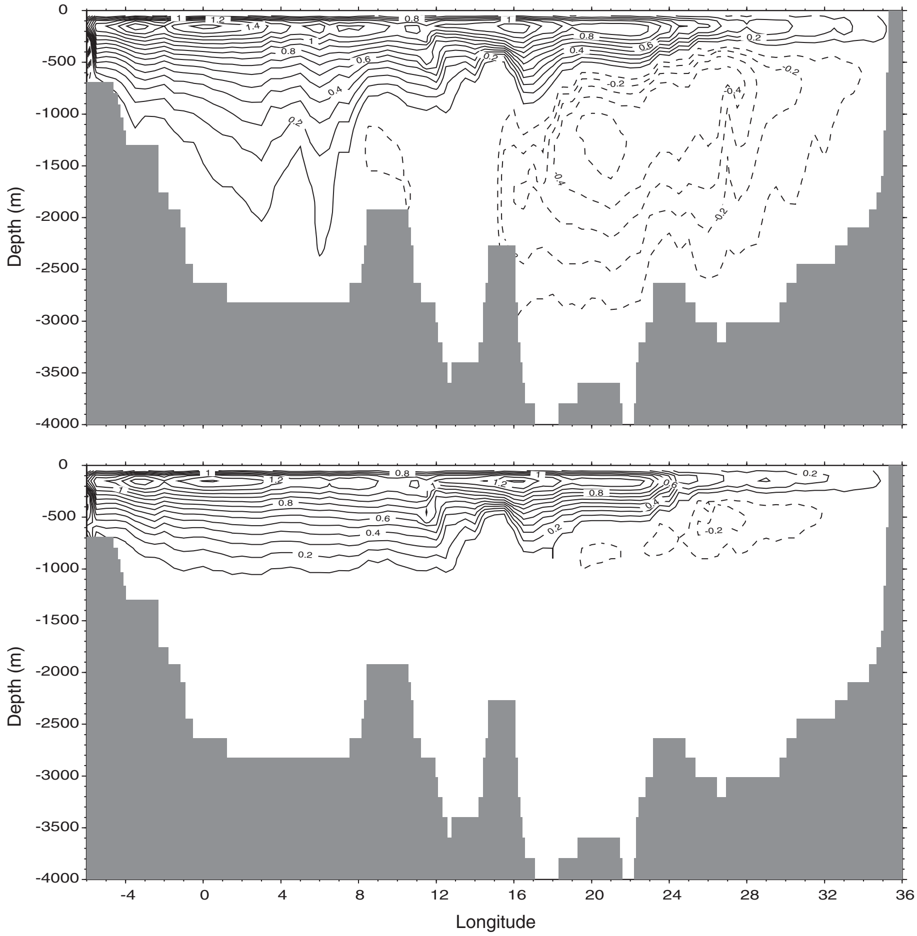

Figure 128: Vertical sections averaged over the 2070–2099 period for Mediterranean Zonal Overturning stream Function for the control run (top) and for the scenario run (bottom).

in relation to the emission scenarios, climate projection scenarios, regional downscaling methods and the tunable parameters of the Mediterranean Sea model itself. It will be extremely useful if the multi-model ensemble approach can be performed by different research groups in a coordinated manner.

Furthermore, it is worthwhile to note that SST anomalies coming from global coupled model are used for the relaxation of the SST in the regional marine model. This overlooks for example the feedback of the MTHC change to the large-scale SST. As shown by Räisänen et al. (2004) for the Baltic Sea, a more suitable way to overcome this problem is to use an atmosphere–ocean-coupled regional climate model focused on the Mediterranean Basin.

7.5. Current Status of Mediterranean Regional Climate Modelling

Global and regional modellings complement each other. While the global-coupled ocean–atmosphere General Circulation Models (GCM) are the best tools to predict large-scale climate variations at seasonal and interannual scales, and to estimate climate changes at longer time scales, especially those related to the anthropogenic modification of atmospheric composition or surface characteristics, they can not however be directly used in impact-oriented applications because of their relatively coarse spatial scale (typically several hundreds of kilometres). Furthermore, while coarse-resolution coupled GCMs may be capable of capturing the mean climate behaviour, they are usually not successful in reproducing higher order statistics and extreme values. Regional climate modelling has been introduced to fill the gap between the global climate models and the growing demand of climate predictions and scenarios on shorter spatio-temporal scales.

Few studies dedicated to the Mediterranean regional climate modelling have been reported so far. Most of the existing research works on climate variability and change over Europe include only partially the Mediterranean basin as the southernmost part of their considered domain. Due to the marginal effects (Giorgi and Francisco, 2000a,b), simulated climates over the Mediterranean basin are often biased by the prescription of the boundary conditions. This decreases the validity of such studies on the Mediterranean climate. One can note however that in Giorgi et al. (2004a,b) and Gibelin and Déqué (2003), the whole Mediterranean basin is quite in the central part of their regionally oriented studies.

The most important regional climate forcing in the Mediterranean region is associated with the complex orography, characterized in many coastal regions by steep mountain slopes, and the large land–sea contrast. These provide a very good testbed but also a big challenge for regional climate modelling. Determination of the Mediterranean regional climate is currently undertaken through several different approaches. The most popular one is the use of (usually atmospheric only) regional climate models (RCM) (Giorgi and Mearns, 1999). The spatial resolution of such models varies from a few kilometres to several tens of kilometres. Models running at resolution less than 10 km are normally based on the full non-hydrostatic equations. Regional climate models (for example, those used in Jones et al., 1995; Christensen et al., 1997; Giorgi and Mearns, 1999; and many others) need to be nested into coarser-resolution global models in order to get the necessary driving information through the lateral boundaries of the domain. This approach allows implementation of highly detailed physical parameterizations in the RCM to ensure a better simulation of local weather and climate events. Another existing approach is based on the use of variable grid (zoomed) general circulation models (GCM) with higher resolution for the Mediterranean basin (for example, Déqué and Piedelievre, 1995; Li and Conil, 2003). This ensures a smooth downscaling of information from large scale to regional scale, but the resolution limit is currently thought to be around 50 kilometres, due to limitations in computing capacity and physical parameterizations implemented in such GCMs. A third approach for high-resolution determination of climate parameters over the Mediterranean region is associated with the application of statistical methods for the downscaling of results simulated by large-scale GCMs (Wilby et al., 1998).

Several high resolution models of the Mediterranean Sea have been developed during the last decade. These models accurately reproduce the Mediterranean thermohaline circulation and the intermediate and deep water formations which drive it. Among these models, we can mention several 1/8° grid mesh models like OPA (Béranger et al., 2004, 2005) and the POM model (Nittis et al., 2003). A 1/16° grid mesh version is also running in the framework of the European Commission-funded programme MFSTEP (Mediterranean Forecasting System: Toward Environmental Predictions) and at IPSL (Béranger et al., 2005).

7.6. Atmosphere–Sea Coupled Modelling

Obtaining a good representation of the Mediterranean thermohaline circulation is a great challenge for the ocean modelling community because air–sea fluxes need to be simulated with very high accuracy. In the past, many modelling groups were involved in such a challenge, but their oceanic general circulation models were forced by atmospheric fluxes and their sea surface temperatures were relaxed to the observed ones. This relaxation term is a strong constraint for many studies such as the Mediterranean Sea interannual variability and regional climate change projection. Indeed, the impact of the relaxation term on the interannual variability is uncontrolled and often unrealistic. Moreover, in the framework of climate change studies, we do not know how to compute the future SST needed for the surface relaxation. Besides, it is completely impossible, in projecting future scenarios, to take into account the feedback of the evolution of the Mediterranean SST on the local (or global) climate. This justifies the development of an Atmosphere–Ocean Regional Climate Model devoted to Mediterranean studies.

The SAMM model (Sea–Atmosphere Mediterranean Model, Sevault et al., 2002) has been developed at CNRM (Centre National de Recherches Météorologiques, Météo-France) coupling the stretched version of Arpege-Climate (Déqué and Piedelievre, 1995) and MED8 as used in the previous sections. The atmospheric component has a horizontal resolution of 50 km over the Mediterranean Basin and the Mediterranean Sea component has a resolution of about 10 km. Each day, the two components exchange SST as well as momentum, water and heat fluxes. At the surface, the interaction between the Mediterranean Sea and the atmosphere is completely free because the simulation has been run without relaxation or flux correction. For the river runoff fluxes, a monthly climatology is computed from the RivDis database (Vörösmarty et al., 1996). Specific parameterizations are used for the Black Sea (based on salt conservation) and for the Nile (in order to obtain realistic runoff for the period after the building of the Aswan dam). Outside the Mediterranean Sea, the SST used in the atmospheric model is prescribed from interannual monthly mean observed data, reconstructed with in situ and satellite data (Smith et al., 1996). A 38-year simulation has been performed with SAMM following a 20-year spin-up. The area and the coast line of the model are presented in Fig. 129 as well as the winter averaged 34 m-depth temperatures and horizontal currents.

For comparison purposes, a parallel experiment has been carried out with MED8 forced by air–sea fluxes coming from a previously run using only the atmospheric Arpege-Climate model. The only difference between the simulations is thus the way of taking into account the air–sea fluxes, which permits one to quantify the differences between fully coupled and uncoupled models.

The surface water flux (Evaporation–Precipitation) for the SAMM simulation and over the whole basin is equal to 0.77 m/year with a weak standard deviation in agreement with observed evidence. Note that the river runoff flux is prescribed according to its seasonally-varied obervation-based estimation with an annual average of 0.18 m/year. The same computation for the surface net heat flux gives a value of -7.1 W/m^2 (heat loss for the Mediterranean Sea) with a standard deviation of 5.0 W/m^2. These values are in agreement with observed data and other modelling studies. In SAMM as in the real world, the surface heat loss is compensated by a positive heat transport across the Gibraltar Strait (+5.5 W/m^2, with a weak standard deviation of 0.3 W/m^2). Note that the values are normalized by the surface of the Mediterranean area to be consistent with the surface flux. The small negative total heat budget, -1.6 W/m^2 ($-7.1 + 5.5$ W/m^2) implies a weak cooling drift occurring along the simulation. But it is not statistically different from zero due to the large interannual variability of the heat content change (standard deviation of 5.1 W/m^2). The time series of the net surface heat flux, the Gibraltar heat transport and the heat content change are plotted in Fig. 130 for the coupled simulation (left panel) and for the forced simulation (right panel).

The time correlation between the surface flux and the heat content is equal to 0.98 for both simulations. The comparison of the interannual variability of these 3 terms implies that all the surface flux variability is damped by the heat

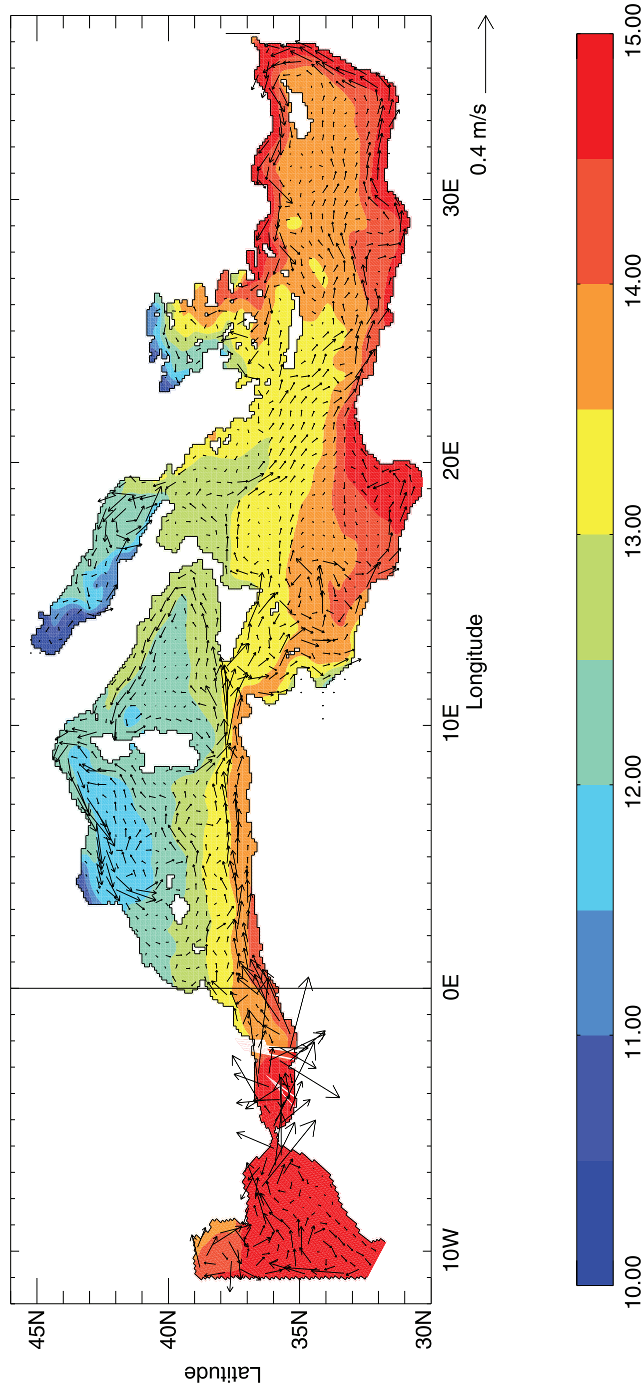

Figure 129: Winter (January, February, March) 34-m depth horizontal currents (arrow, in m/s) and potential temperature (colour, in °C), averaged over the whole coupled simulation (38 years).

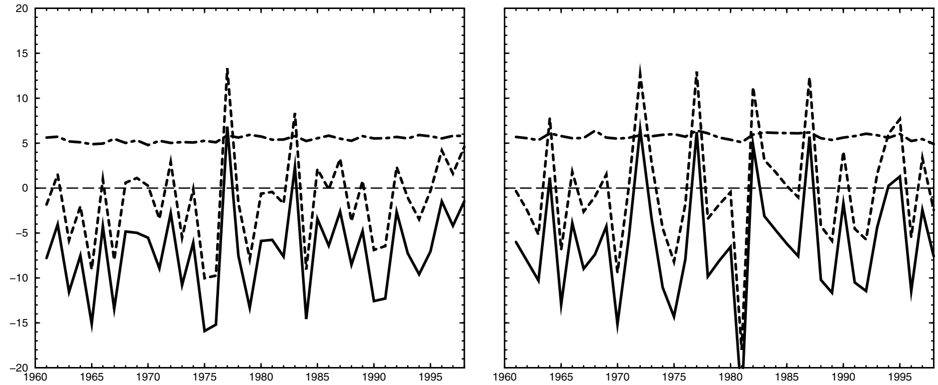

Figure 130: Time evolution of the Mediterranean Sea heat budget components (in W/m^2) computed from the coupled simulation (left) and from the forced simulation (right). The surface heat flux is plotted in solid line, the Gibraltar heat transport in dashed line and the heat content change term in dotted line.

content of the Mediterranean Sea and not exported across the Gibraltar Strait. Indeed, the physical constraints due to the shape of the strait lead to a filtering of the interannual variability.

Another interesting feature is that the interannual variability (standard deviation) simulated in the coupled model is always lower than in the forced model. Even if the simulations are not long enough to obtain statistically significant results, this variability difference is obtained for many variables, both globally and locally. For example, this is true for the surface heat flux and the heat content averaged over the Mediterranean Sea but also in the Gulf of Lions area and in the Adriatic Sea. For these two sub-basins of deep water formation, a lower interannual variability in the coupled model is also observed for the water mass formation rate and the deep water volume transport. Further work is needed to better understand this behaviour but the coupled model seems to simulate an additional air–sea feedback which is not represented in the forced ocean model. We are thus convinced that regional coupled models are much more suitable to study physical mechanisms and climate interannual variability, and to make future projections of regional climate change (see also Section 7.7.2).

7.7. Perspectives and Outlooks

In this chapter, we have shown several examples where numerical modelling was used to investigate physical mechanisms controlling the Mediterranean climate variation and change. Due to its particular geographical position, the Mediterranean region is quite strongly related to other major climate phenomena of the globe, such as tropical monsoons and the North Atlantic Oscillation. The Mediterranean Sea can also exert its climatic influence on the nearby and remote regions in Africa, Europe and Asia through complex atmospheric processes. It is also believed that the Mediterranean outflow water plays an important role for the Atlantic overturning circulation and ultimately the global climate. Under the global warming context, current atmospheric models seem to converge on the conclusion that both water stress on the nearby lands and water deficit of the Mediterranean Sea itself increase. This may further impact the marine overturning circulation and the marine ecosystem. Considering the results reviewed in this chapter, two important issues can be foreseen for the Mediterranean regional climate modelling in the next few years.

7.7.1. High-Resolution Mediterranean Climate Modelling Systems

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 (May and Roeckner, 2001; Leung et al., 2003). 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, as shown in Section 7.4, 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.

In the next few years, high-resolution Mediterranean climate modelling systems are expected to be used to produce consistent data for the Mediterranean basin during the last 40 years, which can not be achieved by global re-analysis performed at weather prediction centres (such as NCEP and ERA40) due to the too coarse spatial resolution and the deficiency in the hydrological cycle. By performing a special calibration through the regional atmospheric/land-surface climate models covering a quite large domain around the Mediterranean, it is in principle possible to reduce the hydrological bias of the re-analysis products. Such simulations of the Mediterranean climate over the last 40 years will be very useful to study the dynamical and physical processes controlling the climate in the Mediterranean region. They are also useful for climate trend detection for the last 40 years.

7.7.2. 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 topics, 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.

With increasing complexity of numerical modelling systems, validation against appropriate observational data is becoming an important issue. This will require however a significant improvement of the currently existing data bases for the region and an increasing capacity to obtain and analyse new measurements with different geophysical characteristics of the region like soil moisture, soil types, vegetation coverage, dust sources and transport, etc. The current observational network around the Mediterranean basin is still scarce and accuracy of measured geophysical parameters in this region is also significantly lower than that over more developed areas like Europe. Special emphasis will be made on the processing of satellite data dedicated to measure surface processes such as sea surface temperature and height, and vegetation. Initiatives as those managed by CIESM to monitor deep sea hydrology will be encouraged as they provide mandatory controls for the climate models.

Putting the numerical systems in the configuration of paleoclimate will be an interesting exercise to test the robustness of the numerical models because it is the only way to test the sensitivity of our complex models to documented climate changes. Paleoclimate simulations will allow to test not only the ability of models to simulate the correct amplitude but also the geographical pattern of climate changes thanks to a large number of dated samples all around the Mediterranean basin. It should be noted that climate studies on these timescales require also outputs from global general circulation models.

Acknowledgements

This work is supported by the French national programme GICC (Gestion et Impact du Changement Climatique). Many people have contributed to the present paper or its earlier versions: S. Hagemann, D. Jacob, R. Jones, E. Kaas, S. Krichak, P. Lionello, A. Mariotti, B. Weare, among others.

References

Alhammoud, B., Béranger, K., Mortier, L., & Crépon, M. (2005). Surface circulation of the Levantine Basin: comparison of model results with observations. *Progress in Oceanography*, **66**, 299–320.

Beckers, J. M., & 23 co-authors (2002). Model intercomparison in the Mediterranean: MEDMEX simulation of the seasonal cycle. *J. of Marine Systems*, **33–34**, 215–251.

Béranger, K., Mortier, L., Gasparini, G. P., Gervasio, L., Astraldi, M., & Crépon, M. (2004). The dynamics of the Sicily Strait: a comprehensive study from observations and models. *Deep-sea Reasearch II*, **51**, 411–440.

Béranger, K., Mortier, L., & Crépon, M. (2005). Seasonal variability of water transport through the Straits of Gibraltar, Sicily and Corsica, derived from a high-resolution model of the Mediterranean circulation. *Progress in Oceanography*, **66**, 341–364.

Bethoux, J. P., Gentili, B., Raunet, J., & Tailliez, D. (1990). Warming trend in the Western Mediterranean deep water. *Nature*, **347**, 660–662.

Branstator, G. (2002). Circumglobal teleconnections, the jet stream waveguide, and the north atlantic oscillation. *J. of Climate*, **15**, 1893–1910.

Castellari, S. N., Pinardi, & Leaman, K. D. (1998). A model study of air-sea interactions in the Mediterranean Sea. *J. of Marine Systems*, **18**, 89–114.

Christensen, J. H., Machenhauer, B., Jones, R. G., Schär, C., Ruti, P. M., Castro, M., & Visconti, G. (1997). Validation of present-day climate simulations over Europe: LAM simulations with observed boundary conditions. *Climate Dynamics*, **13**, 489–506.

Curry, R., Dickson, B., & Yashayaev, I. (2003). A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, **426**(**6968**), 826–828.

Déqué, M., & Piedelievre, J. P. (1995). High-resolution climate simulation over Europe. *Climate Dynamics*, **11**, 321–339.

Déqué, M., Marquet, P., & Jones, R. G. (1998). Simulation of climate change over Europe using a global variable resolution general circulation model. *Climate Dynamics*, **14**, 173–189.

Frei, C., Christensen, J. H., Déqué, M., Jacob, D., Jones, R. G., & Vidale, P. L. (2002). Daily precipitation statistics in regional climate models: evaluation and intercomparison for the European Alps. *J. of Geophysical Research*, **108(D3)**, 4124–4142.

Fuda, J. L., Etiope, G., Millot, C., Favali, P., Calcara, M., Smirglio, G., & Boschi, E. (2002). Warming, salting and origin of the Tyrrhenian Deep Water. *Geophysical Research Letters*, **29**(**19**), 1898, doi:10.1029/2001GL014072.

Gascard, J. C., & Richez, C. (1985). Water masses and circulation in the western Alboran Sea and in the Strait of Gibraltar. *Progress in Oceanography*, **15**(**3**), 157–216.

Gibelin, A. L., & Déqué, M. (2003). Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. *Climate Dynamics*, **20**, 327–339.

Giorgi, F., & Francisco, R. (2000a). Evaluating uncertainties in the predictioon of regional climate change. *Geophysical Research Letters*, **27**, 1295–1298.

Giorgi, F., & Francisco, R. (2000b). Uncertainties in regional climate prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM. *Climate Dynamics*, **16**, 169–182.

Giorgi, F., & Mearns, L. O. (1999). Introduction to special section: regional climate modelling revisited. *J. of Geophysical Research*, **104**, 6335–6352.

Giorgi, F., Bi, X., & Pal, J. S. (2004a). Mean, interannual variability and trends in a regional climate change experiment over Europe. I. present-day climate (1961–1990). *Climate Dynamics*, **22**, 733–756.

Giorgi, F., Bi, X., & Pal, J. (2004b). Mean, interannual variability and trends in a regional climate change experiment over Europe. II. climate change scenarios (2071–2100). *Climate Dynamics*, **23**, 839–858.

Hamad, N., Millot, C., & Taupier-Letage, I. (2002). The surface circulation in the eastern basin of the Mediterranean Sea: new elements, in: *Proceedings of the 2nd International Conference on Oceanography of the eastern Mediterranean and Black Sea: similarities and difference of two interconnected basins*, Ankara, Turkey 14–18 October, 2002.

Heburn, G. W., & La Violette, P. E. (1990). Variations in the structure of the anticyclonic gyres found in the Alboran Sea. *J. of Geophysical Research*, **95**, 1599–1613.

Herbaut, C., Codron, F., & Crépon, M. (1998). Separation of a costal current at a strait level: case of the Strait of Sicily. *J. of Physical Oceanography*, **28**, 1346–1362.

Jones, R. G., Murphy, J. M., & Noguer, M. (1995). Simulation of climate change over Europe using a nested regional-climate model: I: assessment of control climate, including sensitivity to location of lateral boundaries. *Quarterly Journal of the Royal Meteorological Society*, **121**, 1413–1449.

Jones, R. G., Murphy, J. M., Noguer, M., & Keen, A. B. (1997). Simulation of climate change over Europe using a nested regional-climate model. II: comparison of driving and regional model responses to a doubling of carbon dioxide. *Quarterly Journal of the Royal Meteorological Society*, **123**, 265–292.

Kodera, K., & Kuroda, Y. (2003). Regional and hemispheric circulation patterns in the Northern Hemisphere winter, or the NAO and the AO. *Geophysical Research Letters*, **30**, 1934, doi:10.1029/2003GL017290.

Korres, G., Pinardi, N., & Lascaratos, A. (2000). The ocean response to low-frequency interannual atmospheric variability in the mediterranean Sea. Part I: sensitivity experiments and energy analysis. *J. of Climate*, 705–731.

Lascaratos, A., & Nittis, K. (1998). A high-resolution three-dimensional numerical study of Intermediate Water formation in the Levantine Sea. *J. of Geophysical Research*, **103(C9)**, 18497–18511.

Lascaratos, A., Roether, W., Nittis, K., & Klein, B. (1999). Recent changes in deep water formation and spreading in the Eastern Mediterranean Sea: a review. *Progress in Oceanography*, **44**, 5–36.

Leung, L. R., Means, L. O., Giogi, F., & Wilby, R. L. (2003). Regional climate research, needs and opportunities. *Bulletin of the American Meteorological Society*, **84**, 89–95.

Lermusiaux, P. F. J., & Robinson, A. R. (2001). Features of dominant mesoscale variability, circulation patterns and dynamics in the Strait of Sicily. *Deep-sea reasearch I*, **48**, 1953–1997.

Li, L. (2003). Evolution future du climat en Méditerranée: vers un état de sécheresse accru? Rapport CNFGG 2003, 220–223, Paris, France. Also available at http://www.omp.obs-mip.fr/cnfgg/UGGI2003.pdf.

Li, Z. X. (2005). Atmospheric GCM response to an idealized anomaly of the Mediterranean Sea surface temperature. *Clim. Dyn.*, submitted.

Li, Z. X., & Conil, S. (2003). Transient response of an atmospheric GCM to North Atlantic SST anomalies. *J. of Climate*, **16**, 3993–3998.

Machenhauer, B., Windelband, M., Botzet, M., Christensen, J. H., Déqué M., Jones, R. G., Ruti, P. M., & Visconti, G. (1998). Validation and analysis of regional present-day climate and climate change simulations over Europe. MPI Report No. 275, MPI, Hamburg, Germany.

Madec, G., Chartier, M., Delecluse, P., & Crépon, M. (1991). A three-dimensional numerical study of deep-water formation in the northwestern Mediterranean Sea. *J. of Physical Oceanography*, **21**, 1349–1371.

Madec, G., Lott, F., Delecluse, P., & Crépon, M. (1996). Large-scale preconditioning of deep-water formation in the Western Mediterranean Sea. *J. of Physical Oceanography*, **26**, 1393–1408.

Mariotti, A., Struglia, M. V., Zeng, N., & Lau, K. M. (2002). The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean Sea. *J. of Climate*, **15**, 1674–1690.

Marshall, J., & Schott, F. (1999). Open-ocean convection: observations, theory and models. *Reviews of Geophysics*, **37(1)**, 1–64.

Marullo, S., Santoleri, R., Malanotte-Rizzoli, P., & Bergamasco, A. (1999). Atlantic water in the Strait of Sicily. *J. of Geophysical Research*, **95**, 1569–1575.

May, W., & Roeckner, E. (2001). A time-slice experiment with the ECHAM4 AGCM at high horizontal resolution: the impact of the horizontal resolution on annual mean climatic change. *Climate Dynamics*, **17**, 407–420.

Mearns, L. O., Bogardi, I., Giorgi, F., Matyasovszky, I., & Palecki, M. (1999). Comparison of climate change scenarios generated from regional climate model experiments and statistical downscaling. *J. of Geophysical Research*, **104**, 6603–6621.

MEDOC Group (1970). Observation of formation of deep water in the Mediterranean in 1969. *Nature*, **227**, 1037–1040.

Millan, M. M., & 21 co-authors (2005a). Climatic feedbacks and desertification: the mediterranean model. *J. of Climate*, **18**, 684–701.

Millan, M. M., Estrela, M. J., & Miro, J. J. (2005b). Rainfall components: variability and spatial distribution in a mediterranean area (Valencia region). *J. of Climate*, **18**, 2682–2705.

Millot, C. (1987). Circulation in the Western Mediterranean Sea. *Oceanologica Acta*, **10**, 143–149.

Myers, P., & Haines, K. (2002). Stability of the Mediterranean's thermohaline circulation under modified surface evaporative fluxes. *J. of Geophysical Research*, **107(C3)**, 3021, doi:10.1029/2000JC000550.

Nittis, K., Lascaratos, A., & Theocharis, A. (2003). Dense water formation in the Aegean Sea: numerical simulations during the Eastern Mediterranean Transient. *Journal of Geophysical Research*, **108(C9)**, 8120, doi:10.1029/2002JC001352.

Potter, R., & Lozier, S. (2004). On the warming and salinification of the Mediterranean outflow waters in the North Atlantic. *Geophysical Research Letters*, **31**, 01202, doi:10.1029/2003GL018161.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P., Jones, C., Meier, H. E. M., Samuelsson, P., & Willén, U. (2004). European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Climate Dynamics*, **22**, 13–31.

Rixen, M., & 16 co-authors (2005). The Western Mediterranean Deep water: a proxy for climate change. *Geophysical Research Letters*, **32**, L12608, doi: 10.1029/2005GL022702.

Robinson, A. R., Sellschopp, J., Warn-Varnas, A., Leslie, W. G., Lozano, C. J. Jr., Haley, P. J., Anderson, L. A., & Lermusiaux, P. F. J. (1999). The Atlantic Ionian stream. *J. of Marine Systems*, **20**, 129–156.

Rohling, E., & Bryden, H. (1992). Man-induced salinity and temperature increases in the Western Mediterranean deep water. *J. of Geophysical Research*, **97**, 11191–11198.

Rowell, D. P. (2003). The impact of Mediterranean SSTs on the Sahelian rainfall season. *J. of Climate*, **16**, 849–862.

Schar, C., Vidale, P. L., Luthi, D., Frei, C., Haberli, C., Liniger, M. A., & Appenzeller, C. (2004). The role of increasing temperature variability in European summer heatwaves. *Nature*, **427**, 332–336.

Sevault, F., Somot, S., & Déqué, M. (2002). Couplage ARPEGE-MEDIAS -OPA-MEDITERRANEE. Les étapes, Note de Centre, CNRM, GMGEC, n. 84, Meteo-France, Toulouse, France (in French, available at samuel.somot@meteo.fr).

Smith, T., Reynolds, R., Livezey, R., & Stokes, D. (1996). Reconstruction of historical sea surface temperatures using empirical orthogonal functions. *J. of Climate*, **9**, 1403–1420.

Somot, S., Sevault, F., & Déqué, M. (2005). Is the Mediterranean Sea thermohaline circulation stable in a climate change scenario? *Climate Dynamics*, in revision.

Struglia, M. V., Mariotti, A., & Filograsso, A. (2004). River discharge in the Mediterranean Sea: climatology and aspects of the observed variability. *J. of Climate*, **17**, 4740–4750.

Thorpe, R. B., & Bigg, G. R. (2000). Modelling the sensitivity of Mediterranean outflow to anthropogenically forced climate change. *Climate Dynamics*, **16**, 355–368.

Vichi, M., May, W., & Navarra, A. (2003). Response of a complex ecosystem model of the northern Adriatic Sea to a regional climate change scenario. *Climate Research*, **24**, 141–159.

Vörösmarty, C., Fekete, B., & Tucker, B. (1996). Global river discharge database, RivDis, vol. 0 to 7. International Hydrological Program, Global Hydrological Archive and Analysis Systems, UNESCO, Paris, France.

Watanabe, M. (2004). Asian jet waveguide and a downstream extension of the North Atlantic Oscillation. *J. of Climate*, **17**, 4674–4691.

Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J., & Wilks, D. S. (1998). Statistical downscaling of general circulation model output: A comparison of methods. *Water Resources Research*, **34**, 2995–3008.

Yu, R., & Zhou, T. (2004). Impacts of winter-NAO on March cooling trends over subtropical Eurasia continent in the recent half century. *Geophysical Research Letters*, **31**, 12204, doi: 10.1029/2004GL019814.