**Bulletin of the American Meteorological Society**
MED-CORDEX initiative for Mediterranean Climate studies.
--Manuscript Draft--

<table>
<thead>
<tr>
<th>Manuscript Number:</th>
<th>BAMS-D-14-00176</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Title:</td>
<td>MED-CORDEX initiative for Mediterranean Climate studies.</td>
</tr>
<tr>
<td>Article Type:</td>
<td>Article</td>
</tr>
</tbody>
</table>
| Corresponding Author: | Paolo Ruti, PhD  
ENEA  
Roma, ITALY |
| Corresponding Author's Institution: | ENEA |
| First Author:      | Paolo Ruti, PhD |
| Order of Authors:  | Paolo Ruti, PhD  
Samuel Somot  
Filippo Giorgi  
Clotilde Dubois  
Emmanouil Flaounas  
Anika Obermann  
Alessandro Dell'Aquila  
Giovanna Pisacane  
Ali Harzallah  
Emanuele Lombardi  
Bodo Ahrens  
Naveed Akhtar  
Antoinette Alias  
Thomas Arouze  
Rodriguez raznar@puertos.es  
Sophie Bastin  
J Bartholy  
Karine Beranger  
Jonathan Beuvier  
Sophie Bouffies-Cloche  
Jennifer Brauch  
William Cabos  
Sandro Calmanti  
Jean-Christophe Calvet  
Adriana Carillo  
Dario Conte  
Erika Coppola  
Vladimir Djurdjevic  
Philippe Drobinski |
The Mediterranean is expected to be one of the most prominent and vulnerable climate change "hot spots" of the 21st century, and the physical mechanisms underlying this finding are still not clear. Furthermore complex interactions and feedbacks involving ocean-atmosphere-land-biogeochemical processes play a prominent role in modulating the climate and environment of the Mediterranean region on a range of spatial and temporal scales. Therefore it is critical to provide robust climate change information for use in Vulnerability/Impact/Adaptation assessment studies considering the Mediterranean as a fully coupled environmental system. The Med-CORDEX initiative aims at coordinating the Mediterranean climate modeling community towards the development of fully coupled regional climate simulations, improving all relevant components of the system, from atmosphere and ocean dynamics to land surface, hydrology and biogeochemical processes. The primary goals of Med-CORDEX are to improve understanding of past climate variability and trends, and to provide more accurate and reliable future projections, assessing in a quantitative and robust way the added value of using high resolution and coupled regional climate models. The coordination activities and the scientific outcomes of Med-CORDEX can produce an important framework to foster the development of regional earth system models in several key regions worldwide.

Dear Editor,

thanks for you comments on our revised manuscript. We do agree that the table we added is somewhat overwhelming within the context of the present paper, which is not
intended as a comprehensive review of the Med-CORDEX activities but serves to illustrate its main aspects, goals and plans. We thus removed the table and re-organized and streamlined the discussion of relevant examples of achievements, in particular by dividing it into shorter and more direct sub-sections. We feel that the set of illustrative examples we present does provide a good sample of the advantages and achievements of the Med-CORDEX framework, keeping in mind that considerable work is still under way on the analysis of the Med-CORDEX experiments completed to date. We hope that our revisions satisfactorily address your concerns.

Sincerely,
Paolo M Ruti

Suggested Reviewers:

Stefan Sobolowski
stefan.sobolowski@uni.no

William J. Gutowski
gutowski@iastate.edu
Dear Editor,

thanks for you comments on our revised manuscript. We do agree that the table we added is somewhat overwhelming within the context of the present paper, which is not intended as a comprehensive review of the Med-CORDEX activities but serves to illustrate its main aspects, goals and plans. We thus removed the table and re-organized and streamlined the discussion of relevant examples of achievements, in particular by dividing it into shorter and more direct sub-sections. We feel that the set of illustrative examples we present does provides a good sample of the advantages and achievements of the Med-CORDEX framework, keeping in mind that considerable work is still under way on the analysis of the Med-CORDEX experiments completed to date. We hope that our revisions satisfactorily address your concerns.

Sincerely,
Paolo M Ruti
Med-CORDEX initiative for Mediterranean Climate studies.


1. WMO, avenue de la Paix Geneve, Switzerland, pruti@wmo.int
2. NRM/GAME, Météo-France, Toulouse and Grenoble, France
3. ICTP, Trieste, Italy
4. NOA, National Observatory of Athens, Athens, Greece
5. Goethe Universitaet Frankfurt, Institut fuer Atmosphaere und Umwelt, 60438 Frankfurt, Germany
6. ENEA, via Anguillarese 301, Rome, Italy
7. Institut National des Sciences et Technologies de la Mer, 2025 Salammbo, Tunisia
8. ENSTA-ParisTech, 1024, Boulevard des Maréchaux, Palaiseau Cedex, France
9. Puertos de l’Estado, Madrid, Spain
10. Institut Pierre Simon Laplace, Paris, France
11. Dept. of Meteorology, Pf. 32. Budapest, Hungary
12. University of Alcala, Madrid, Spain
13. CMCC, Bologna, Italy
14. Un of Belgrade, Serbia
15. Max Planck Institute for Meteorology, Bundesstr. 53, D-20146 Hamburg, Germany
16. UCLM, Toledo, Spain
17. Universidad Politécnica de Madrid, Madrid, Spain
18. Universidad Politecnica de Catalunia, Barcelona, Spain
19. Barcelona Supercomputing Center, Earth Sciences, Barcelona, Spain
20. IMEDEA, UIB, Palma de Majorca, Spain
21. Dep. Of Physics, University of Lecce, Italy
22. European Commission, Joint Research Centre (JRC), Italy
23. Istanbul Technical University, Istanbul, Turkey

24. Faculty of Physics, Dep. of Meteorology, Belgrade, Serbia

25. Physics Dep., University of Athens, Greece
Abstract.

The Mediterranean is expected to be one of the most prominent and vulnerable climate change “hot spots” of the 21st century, and the physical mechanisms underlying this finding are still not clear. Furthermore, complex interactions and feedbacks involving ocean-atmosphere-land-biogeochemical processes play a prominent role in modulating the climate and environment of the Mediterranean region on a range of spatial and temporal scales. Therefore it is critical to provide robust climate change information for use in Vulnerability/Impact/Adaptation assessment studies considering the Mediterranean as a fully coupled environmental system. The Med-CORDEX initiative aims at coordinating the Mediterranean climate modeling community towards the development of fully coupled regional climate simulations, improving all relevant components of the system, from atmosphere and ocean dynamics to land surface, hydrology and biogeochemical processes. The primary goals of Med-CORDEX are to improve understanding of past climate variability and trends, and to provide more accurate and reliable future projections, assessing in a quantitative and robust way the added value of using high resolution and coupled regional climate models. The coordination activities and the scientific outcomes of Med-CORDEX can produce an important framework to foster the development of regional earth system models in several key regions worldwide.

Capsule Summary: The Med-CORDEX initiative is a unique framework in which the research community makes use of regional earth system models to increase the reliability of past and future regional climate information.
Introduction.

The Mediterranean basin is characterized by complex coastlines and topographical features, such as the Alpine, Apennine, Pyrenees and Balkan mountain chains, the Italian and Hellenic peninsulas and large islands (Balearic, Sicily, Sardinia, Corsica, Crete and Cyprus). From the meteorological and climatic point of view this morphological complexity leads to fine scale spatial and temporal variability (Ruti et al. 2008, Chronis et al., 2010, Dobrinski et al. 2014), along with the formation of intense weather phenomena (Ducrocq et al. 2014, Tous et al. 2014). A typical example of such phenomena is the Mistral wind, which blows through the Rhone valley into the Gulf of Lions and across to Corsica and Sardinia through the Strait of Bonifacio (Chronis et al., 2010). Another example is the Bora wind, which blows in a north-easterly direction across a series of topographical channels into the North Adriatic Sea. Several coastal areas of the Central (e.g. the Gulf of Genoa) and Eastern (e.g. Cyprus island) Mediterranean are also centers of topographically-induced intense cyclogenesis (e.g. Buzzi and Tibaldi 1978; Alpert et al. 1995). Such events, in addition to having catastrophic consequences on different sectors of society, dramatically influence the Mediterranean ocean circulation (Herrmann and Somot 2008, Durrieu de Madron et al. 2013) through deep and bottom water formation.

The Mediterranean Sea is a semi-enclosed and evaporative basin in which a wide range of oceanic processes and interactions of regional interest occur. It is connected to the Atlantic Ocean by the shallow Strait of Gibraltar and is composed of two basins of similar size, i.e. the Western and the Eastern Mediterranean Seas, separated by the shallow Strait of Sicily. It is also connected to the Black Sea to the northeast through the Bosphorus channel. In the Strait of Gibraltar, the comparatively fresher and warmer Atlantic water flows into the Mediterranean Sea at the surface to compensate for the negative mass balance inside the basin (where evaporation is greater than precipitation and river runoff) and to replace cooler and saltier Mediterranean water flowing out at depth into the Atlantic. Moreover, the Mediterranean water outflow strengthens and stabilizes the Atlantic Meridional Overturning Circulation through warm and saline water input (Artale et al., 2006; Ivaninovic et al., 2014).

Deep Mediterranean water is produced at different locations by intense air–sea interactions: in the Gulf of Lions (western Mediterranean), the Southern Adriatic, the northeast Levantine basin and the Aegean Sea in the eastern Mediterranean (see MEDOC group, 1970; Roether et al. 1996). The basin’s circulation is
characterized by the presence of sub-basin gyres, intense mesoscale variability and a strong seasonal signal. Interannual variability is also observed, mostly related to the interannual variability of atmospheric forcings (Josey 2003; Mertens and Schott 1998; Vilibić and Orlić 2002; Herrmann et al., 2010; Josey et al., 2011; L’Heveder et al. 2013). Such physical processes have two critical characteristics: first, they derive from strong air–sea coupling and, second, they occur at fine spatial scales because the Rossby radius of deformation varies from 5 to 12 Km throughout the Mediterranean, setting the scales at which important energy redistribution processes occur. In order to explicitly resolve with high spatial resolution the two-way interactions at the atmosphere–ocean interface, fully-coupled high resolution atmosphere-ocean regional climate models (RCMs) are needed (Somot et al., 2008, The PROTHEUS group, 2010; Dell’Aquila et al., 2012; Gualdi et al. 2013).

Another important forcing of Mediterranean climate is due to aerosols of natural and anthropogenic sources (Lelieveld et al., 2002). Saharan dust outbreaks can carry large amounts of particulate material over the Mediterranean and Central European regions (Moulin et al., 1998), modifying not only the radiative budget of the basin through their microphysical and optical properties (Bergamo et al., 2008), but also the basin biogeochemical cycle (Guieu et al., 2010). Moreover, air pollution emissions by industries and large urban areas around the Mediterranean and in Central Europe can further affect regional air quality, surface energy and water budgets (Lelieveld et al., 2002). Biomass burning and forest fires constitute another important source of carbonaceous aerosols in summer (Sciare et al., 2008).

It is thus clear that complex interactions and feedbacks involving ocean, atmosphere, land and biogeochemical processes, along with the effects of complex morphological features, play a prominent role in modulating the climate of the Mediterranean region on a range of spatial and temporal scales. In addition, different generations of model projections have indicated that the Mediterranean is expected to be one of the most prominent and vulnerable climate change “hot spots” of the 21st century (Giorgi, 2006; Diffenbaugh and Giorgi 2012), and the physical mechanisms underlying this finding are still not clear. Indeed, several components of the Euro-Mediterranean climate have been already changing in the last decades. Over the Mediterranean, mean temperature has increased more than the global average, mean annual precipitation has decreased since the mid-20th century, and trends towards more frequent and longer heat waves and fewer extremely cold days and nights have been observed (IPCC 2013). Since the 1960s, the mean heat wave intensity, length and number across the Eastern Mediterranean region have increased by a factor of five or more (Kuglitsch et al., 2010; Ulbrich et al., 2012). In a study of European river flows by Stahl et al. (2010), a regionally coherent picture of annual stream-flow trends emerged, with negative trends in the
southern and eastern regions, suggesting that the observed drying trend is reflected in the state of rivers. This hydrologic trend should amplify in the future (Schneider et al., 2013).

These examples show that there is a growing and challenging need to better understand the processes that make the Mediterranean especially sensitive to natural variability, global warming and local/regional forcings, particularly in view of the need to describe the interactions across all components of the regional hydrological cycle. Since the early’ 90s, a number of research and intercomparison projects have focused on downscaling global climate simulations (reanalysis or Global Climate Models [GCMs]) over the Euro-Mediterranean region (RACCS, Machenauer et al., 1996a, Christensen et al., 1997; MERCURE, Machenauer et al., 1996b; STARDEX, Goodess, 2003; PRUDENCE, Christensen et al., 2007; ENSEMBLES, Van der Linden P and Mitchell JFB 2009; CIRCE, Gualdi et al., 2013). Building on these programs, and as part of the CORDEX (COordinated Regional Downscaling EXperiment) international effort (Giorgi et al., 2009), Med-CORDEX is a unique framework in which the research community makes use of coupled regional atmospheric, land surface, river, and ocean climate models, along with individual components of these systems run at very high resolution, to increase the reliability and process-based understanding of past and future fine scale climate information for the region. Med-CORDEX aims at addressing a number of key scientific challenges, including:

- To develop fully-coupled Regional Climate System Models (RCSM) for the Mediterranean basin (Figure 1), considering and improving all relevant components of the system, i.e. atmosphere, ocean, land surface, hydrology and biogeochemistry;
- To improve understanding of past climate variability and trends, and to provide more accurate and reliable future projections at high resolution, with emphasis on the role of coupled component interactions, fine scale processes and extreme events;
- To assess in a quantitative and robust way the Added Value of using high resolution and coupled RCMs;
- To coordinate the Mediterranean RCM community and promote the production of large model ensembles following internationally accepted protocols such as CMIP and CORDEX in order to optimally assess reliability and uncertainties in regional climate projections;
- To promote, gather and organize the use of ground-based and satellite-based observational data into tailored datasets for use in climate process evaluation;
- To strengthen the link with the Vulnerability/Impacts /Adaptation (VIA) research community through the provision of tailored climate information data-sets usable in VIA studies and in the development
of response policies.

Having defined these primary goals of the program, in the next sections we first provide an historical perspective of Med-CORDEX and present illustrative results from the first Med-CORDEX activities. We then discuss the Med-CORDEX plans and how they will contribute to address the scientific challenges outlined above. Details on the model configurations and simulations can be found in www.medcordex.eu.
**Background of the Med-CORDEX initiative and the production phase.**

The current CORDEX protocol envisions two simulation streams with RCMs run over continental scale domains covering essentially all land regions of the World at ~50 km grid spacing (Giorgi et al. 2009): in the first stream the RCMs are run in the so-called perfect boundary condition experiment mode, in which data from one of the most recent and high-resolution reanalysis (ERA-interim, Dee et al. 2011) provide the lateral meteorological boundary conditions for the RCMs. The ERA-Interim data are available for the period 1979-2013 and these simulations serve the purpose of assessing and optimizing the model performance against observations for the period (Giorgi and Mearns 1999). The second stream, which provides the climate change information for VIA use, consists of climate projections for the late 20th and full 21st century (1950-2100 or 1970-2100) with the RCMs driven at the lateral boundaries by fields from different GCMs from the Climate Model Intercomparison Project 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/). More detail on the CORDEX experimental protocol can be found in http://wcrp-cordex.ipsl.jussieu.fr/.

In order to address the specific research challenges outlined in the previous section, the Med-CORDEX phase 1 protocol adds to this base framework the following tiers:

- Production of ensembles of simulations with coupled Regional Climate System Models (RCSMs) including fully interactive Atmosphere-Land-River-Ocean components, covering the whole Mediterranean basin and its catchment basin at an intermediate grid spacing of ~20-50 km;
- Production of corresponding stand-alone simulations for all individual components in order to assess the importance of the coupled modeling approach;
- Use of the most recent validation data available, including datasets obtained from HyMeX (Ducrocq et al. 2014, Drobinski et al. 2014) field campaigns;
- Production of high-resolution simulations (~12 km grid spacing) to assess the added-value of high resolution in a number of relevant metrics, and in particular topography-forced spatial patterns, the simulation of mesoscale phenomena, precipitation intensity distributions, strong wind systems and extreme events;
- Advancement of regional reanalyses to serve as reference datasets and ocean initial conditions

The Med-CORDEX phase 1 gathers 22 different modelling groups from 9 countries (France, Italy, Spain, Serbia, Greece, Turkey, Tunisia, Germany, Hungary) in Europe, Middle-East and North-Africa and more than
75 active members of the modelling and evaluation teams that can follow the activities through a dedicated emailing list (medcordex@hymex.org) and web page (www.medcordex.eu). Since 2009, yearly side meetings at the HyMeX international workshops as well as four dedicated Med-CORDEX meetings (Toulouse in September 2009, Toulouse in March 2012, Palaiseau in May 2014, Mykonos in September 2015) have been organized thanks to the Mediterranean Integrated Studies at Regional And Local Scales (MISTRALS) meta-program which supports HyMeX.

Twelve coupled RCSMs covering the whole Mediterranean and its catchment basin have been developed, which include coupling of regional atmosphere and ocean components (see www.medcordex.eu for more details). Some models also include coupling with river runoff, thereby closing the water cycle of the basin. Med-CORDEX is therefore the largest international coordinated multi-model initiative using fully-coupled RCSMs to provide long-term projections in a standardized and open way.

In addition to the 12 RCSMs, Med-CORDEX also includes the participation of 13 stand-alone atmosphere RCMs used at various resolutions (150 km, 50 km, 25 km, 12 km), as well as 10 stand-alone ocean models (resolution from 25 km to 3 km) and 4 stand-alone land surface models (50 km). Coordinated hindcast simulation ensembles for each of these components and for the coupled RCSMs have been completed and intercompared (http://www.medcordex.eu/simulations.php). All runs are documented through metadata forms. The ERA-Interim driven runs cover the 1989-2013 or the 1979-2013 periods (the latter having been available only late in the program), with 25 runs completed with atmosphere-only RCMs, 9 runs with coupled RCSMs, 4 runs with land-surface regional models (forced by ERA-Interim fields corrected following the WATCH protocol; Szczypta et al. 2012), and 11 runs with the ocean regional models (forced by ERA-Interim fields; Macias et al. 2013; or by dynamical downscaling of the reanalysis; Herrmann et al. 2010). In addition regional climate change simulations for the atmosphere (15 runs), ocean (1 run) and RCSMs (5 runs) have been performed using the RCP8.5 and RCP4.5 scenarios for the 1950-2100 period, with boundary fields from 6 different CMIP5 GCMs.

A centralized Med-CORDEX database was developed at ENEA in order to host the model outputs in the CORDEX standardized format and to provide information to the data producers and users (www.medcordex.eu). The Med-CORDEX data are freely available for non-commercial use. Ocean, land, river and atmosphere variables are available at various frequencies from monthly to 3-hourly. Currently, the database includes more than 3 Tb of data and 110,000 files. File format standardization, a powerfull search...
tool and on-line computation service, allows an optimal download and use of the data (120,000 data files downloaded for a total of 5 Tb by the 130 registered users). Each simulation is described by the data providers through metadata files completed on-line and hosted by the HyMeX database.

Illustrative examples of Med-CORDEX scientific achievements.

In this section we provide a sample of results from the Phase I Med-CORDEX activities aimed at illustrating the types of analyses which are carried out in order to address the scientific issues highlighted in the previous sections. In particular, the examples below serve to illustrate the added value of the Med-CORDEX strategy based on the use of high resolution and coupled RCMs in better capturing climate statistics important for VIA applications and in improving the understanding of model errors. We also stress that many studies are still ongoing on the analysis of the Med-CORDEX experiments available to date.

The atmospheric component: Mediterranean cyclones and associated extremes

-- Cyclogenesis

Alpine lee cyclogenesis represents a paradigmatic example of a geophysical process which can integrate different spatial and temporal scales. It characterizes most of the winter rainfall variability over the Alpine region and produces orographic rainfall extremes. During the beginning stages of the event, a vortex develops on the cyclonic shear side of the Mistrals in a strong confluent frontogenesis area over the sea. In its mature phase, lee-cyclogenesis has a typical baroclinic evolution with spatial scales of the order of the Rossby radius of deformation (Buzzi and Tibaldi 1978). This type of cyclone draws moisture and energy from the adjacent western Mediterranean Sea and it leads to the occurrence of extreme precipitation events over the surrounding coastal and mountain areas, often causing floods of exceptional severity (Rudari et al 2004; Pfahl and Wernli 2012, Ducrocq et al. 2014).

Figure 2 shows the spatial patterns of cyclone center density (or cyclone frequency) for different ERA-Interim driven Med-CORDEX experiments, along with the driving ERA-interim data themselves, during the autumn and winter seasons for the years 1989-2008 (for methods see Flaounas et al. 2013). Here only two-way coupled RCMs (~25-30 km grid spacing) are considered. Overall, a qualitative agreement between the
ERA-Interim and model simulated spatial structures is found, as all models and reanalysis identify the major oceanic cyclone activity areas over the Western Mediterranean, along the Turkey coast line and over the Black sea. Many cyclones originate around the Alps and the Gulf of Lions and Genoa, over the Aegean sea, and over the Iberian Peninsula and Atlas chain (Campins et al., 2011 and references therein). Moreover, all models reproduce the oceanic cyclone activity over the Adriatic sea. Low pressure centers crossing this small basin surrounded by complex topography are well captured by the RCSMs at high-resolution, while the coarser resolution ERA-interim reanalysis does not simulate such small low centers. This result thus illustrates the added-value of the increase in resolution achievable with RCMs (Flaounas et al. 2013). The role of the ocean-atmosphere coupling in the representation of the Mediterranean cyclone life cycle (cyclogenesis, life time, intensity) has also been assessed by Sanna et al. (2013) and Akhtar et al. (2014), showing an improved representation of SST patterns and lower atmospheric stability compared to atmosphere-alone models.

**Intense precipitation events**

Most of the severe rainfall events observed over the complex topography surrounding the Mediterranean basin occur in autumn, and model resolution is expected to be a key factor in simulating such events. Figure 3 shows the 99% quantile of autumn daily precipitation (mm/day) for the period 1989-2008 for ERA-interim (Panel 3a) and the COSMO-CLM and ALADIN regional simulations (driven by ERA-Interim fields) at 50 km (Panels 3c and 3e) and 12 km (Panels 3d and 3f) grid spacing over the Med-CORDEX domain. In order to measure the model performance in reproducing the tail of the distribution with respect to an observation-based fine scale dataset, the same results are shown over France in Figure 4, where they are compared to a high-resolution mesoscale atmospheric analysis for rainfall (Système d’analyse fournissant des renseignements atmosphériques à la neige, SAFRAN, Quintana-Seguí et al., 2008). The results of Figure 3 and 4 clearly show that ALADIN and COSMO-CLM are able to simulate the tail of the probability distribution function of rainfall intensity with an increasing accuracy going from 50 to 12 km grid spacing. In particular, the 12 km versions are able to capture not only the topographic effect on extreme rainfall events but also the land-sea contrast along the Mediterranean coasts. By contrast, the ERA-Interim reanalysis and the coarse resolution ALADIN model strongly underestimate the magnitudes of these precipitation extremes (Figures 3a, b; 4a). The results shown in Figure 3 and 4 where also confirmed by the study of Harader et al. (2015) based on different quantitative metrics of model performance.
The added-value highlighted over France in Figure 4 is found also when the regional models are forced by GCMs. For example, Torma et al. (2015) found a strong improvement in the simulation of precipitation spatial patterns, daily precipitation distributions and extremes over the Alpine region in high resolution RCMs compared to the driving GCMs (not shown). They also showed how the high resolution representation of topography can substantially affect the precipitation change signal, for example during the summer when high elevation heating induces a positive precipitation change over the high elevations of the Alpine chain. In addition, the influence of high-frequency ocean-atmosphere coupling on heavy precipitation case studies was investigated using twin experiments with a RCSM and the associated atmospheric RCM driven by observed SST and by the RCSM SST (Lebeaupin-Brossier et al. 2013; Berthou et al. 2014, 2015). These studies found that the coupling significantly influences the event intensity and position.

--- Intense wind events

Another extreme phenomenon often associated with Mediterranean cyclones is the occurrence of strong winds over the sea (Ruti et al. 2008; Herrmann et al. 2011) accompanied by intense air-sea exchanges (Herrmann and Somot 2008, Durrieu de Madron et al. 2013) which can lead to ocean deep convection in various sites of the Mediterranean Sea (Herrmann and Somot 2008, Herrmann et al. 2010, Beuvier et al. 2010). In such phenomena, the wind strength and direction are fundamental parameters which determine the vorticity and turbulent forcing for the ocean. Following two pioneering studies (Ruti et al 2008, Herrmann and Somot 2008) and new satellite-based datasets (Chronis et al. 2010), from an analysis of Med-CORDEX experiments with the regional model ALADIN at various resolutions (grid spacing of 125 km, 50 km and 12 km), Herrmann et al. (2011) confirmed the added-value of using high-resolution RCMs in simulating the wind field over the sea. They demonstrated that the 50-km resolution is a minimum to reproduce the sea wind field and that the 12-km resolution adds value close to the coastline. Note that the conclusions of this study were then used to design some of the Med-CORDEX RCSM experiments (Sevault et al. 2014, Nabat et al. 2014).

Figure 5 generalizes this result in a multi-model context. It shows plots of wind speed distribution over two main convective sites, the Gulf of Lion and the Ligurian sea, for several models (coupled and uncoupled, 50 km and 12 km resolution) compared to Quikscat, ERA-interim and buoy (LION and AZUR) wind speed data. The models capture most of the observed variability at the LION buoy, while some discrepancies are seen at the AZUR site. The main wind regime into the Gulf of Lion is associated to the Tramontane and Mistral strong northwesterly winds which blow through the Garonne and Rhone valleys driven by large scale
pressure patterns. Over the Côte d'Azur site, two main regimes are present, i.e. from the northeast (associated to the Mistral) and from the southwest, due to atmospheric highs entering the gulf of Lion from the west or southwest and stationing over the Gulf of Genoa. The latter regime is not well reproduced by both the models and the reanalysis (Ruti et al., 2008). During the winter season, the wind forcing over the Gulf of Lion is reproduced reasonably well, suggesting a good skill in simulating related convective processes, however, the winter high wind speed tail is not well captured. Overall, Figure 5 shows that the 12km RCMs (COSMO-CLM, ALADIN-Climate) improve the representation of the wind probability density function at both locations with respect to the corresponding 50km versions and the coarse resolution ERA-Interim reanalysis. Conversely, the coupled model (PROTHEUS) does not show a clear improvement with respect to the uncoupled model for this specific variable and site (Herrmann et al. 2011).

Other components of the system: Mediterranean Sea, river discharge and aerosols

-- SST and water and heat budgets

The Mediterranean sea is characterized by a negative water budget (excess evaporation compared to freshwater input) balanced by a two-layer exchange at the Strait of Gibraltar composed of a warm and fresh upper water inflow from the Atlantic superimposed to a cooler and saltier Mediterranean outflow. Light and fresh Atlantic water is transformed into denser water through interactions with the atmosphere that renew the Mediterranean waters at intermediate and deep levels and drive the Mediterranean thermohaline circulation.

The Mediterranean Sea water and heat budgets (MSWB and MSHB, respectively) can be seen as good integrators of climate variability at seasonal to interannual and decadal scales. A series of Med-CORDEX articles demonstrated how they are also main drivers for key Mediterranean phenomena, such as open-sea deep convection (Josey et al. 2011, Papadopoulos et al. 2012), Mediterranean thermohaline circulation (Adloff et al. 2015), strait transport (Soto-Navarro et al. 2014), river discharge (Sevault et al. 2014), energy and water sources for Mediterranean cyclones (Sanna et al. 2013, Akthar et al. 2014) and coastal heavy precipitation events (Berthou et al. 2014, 2015). In addition, the feedback of the Mediterranean Sea on the atmosphere through water and energy exchanges is of paramount importance to evaluate the impact of climate variability and change on human activities in the context of global warming. In this regard, of particular relevance is the effect of an increase of ocean heat content on the frequency and intensity of high-impact weather events and on sea level rise.
Two multi-model studies within the frame of the ENSEMBLES and CIRCE projects (Sanchez-Gomez et al. 2011 and Dubois et al. 2012) demonstrated that (i) the observed references for the MSWB and MSHB terms (evaporation, precipitation, river runoff, Black Sea freshwater inputs, shortwave radiation, longwave radiation, sensible heat flux, latent heat flux) are far from being accurate and (ii) state-of-the-art RCMs still show large deficiencies in reproducing these terms at various scale (mean state, spatial pattern, interannual variability and trends). Due to the central role of the MSWB and MSHB in the Mediterranean climate, improving their representation in climate models and understanding their variability is one of the key challenge in Med-CORDEX. A large number of studies on this topic using Med-CORDEX simulations are still on-going but preliminary results are summarized here.

Dubois et al. (2012) demonstrated that the SST is one of the main factors driving the errors in the MSWB and MSHB terms. Figure 6 shows the interannual time series of SST averaged over the whole Mediterranean basin for ERA-Interim driven runs. Over the period 1980-2010, the interannual variability is well reproduced in all simulations, however a cold bias is found in most experiments. This error could be related to the model configurations, since in most Med-CORDEX models the first ocean level is about 5 meters deep, while the models with a reduced bias have a thinner first ocean level, about 1 m (yellow, light blue and green lines in the figure). It is also found that the SST trend is weaker in the models than in observations, perhaps as a result of the lack of representation of aerosol effects (see below).

Local evaluations of SST can be carried out using sea buoy data. Figure 7 shows a comparison between the LION buoy SST data (42.1°N, 4.7°E, North-West Mediterranean) and four Med-CORDEX coupled RCSMs at the daily temporal scale. The four coupled simulations agree in reproducing the seasonal cycle (Figure 7a) and the inter-annual variability of the observed SST (Figure 7b). The simulated SST distributions are then compared with observed SSTs in daily quantile-quantile plots for Winter (Figure 7c) and Summer (Figure 7d). In Winter, the central quantiles of the distribution are overestimated by all models, while the high end of the range is underestimated, a behavior which is probably due to the misrepresentation of ocean deep convective phenomena. In summer (Figure 7d), however, most of the models are able to reproduce the observed distribution (with two exceptions of underestimation).

Finally, the evaluation of various terms of the surface MSWB and MSHB in some of the Med-CORDEX RCSMs and the corresponding RCMs is reported in L’Heveder et al. (2013), Sevault et al. (2014),
Lebeaupin-Brossier et al. (2015). Despite remaining biases in some the terms, these studies consistently demonstrate the added-value of the coupled vs. the uncoupled approach to reproduce the Mediterranean water and heat budgets.

--- Mediterranean ocean circulations, temperature and salinity

The ocean surface and thermohaline circulations are the engines of the heat and salt spatial redistribution and, in the vertical, determine the penetration of the climate change signal into the deep layers of the Mediterranean Sea. Within Med-CORDEX, various elements of the Mediterranean Sea circulation have been evaluated either in the RCSMs or in the stand-alone regional ocean models. For example, Soto-Navarro et al. (2014) evaluated the Strait of Gibraltar flow in an ensemble of NEMO-MED models using various horizontal and vertical resolutions and different forcings, while Pascual et al. (2014) and Meissignac et al. (2011) evaluated the eddy turbulent kinetic energy and sea level variability in a flux-driven ocean model.

The Mediterranean Sea thermohaline circulation is a complex and challenging phenomenon (MEDOC group 1970, Mertens and Schott 1998). It has been evaluated in many configurations of the Med-CORDEX models for the Eastern Mediterranean Basin in relation to the so-called Eastern Mediterranean Transient (Vervatis et al. 2013, Georgiou et al. 2014, Sevault et al. 2014) and for the Western Mediterranean Basin targeting the understanding of deep water formation (Beuvier et al. 2012, L’Heveder et al. 2013, Sevault et al. 2014). Note that RCSMs often show very good behaviours in simulating the interannual to decadal variability of the Mediterranean Sea thermohaline circulation (L’Heveder et al. 2013, Sevault et al. 2014) and sometimes are even better than the comparable flux-driven ocean runs (compare for example Sevault et al. 2014 and Beuvier et al. 2010).

Med-CORDEX offers a unique framework to intercompare various ocean models and better understand the way they reproduce the Mediterranean Sea circulation. We present here a first multi-model diagnostic study of stand-alone Med-CORDEX regional ocean models (figure 8) by analysing the heat and salt content of the whole Mediterranean Sea (expressed as average temperature and salinity). The ocean models are driven by different atmospheric forcings produced by dynamical downscaling of the ERA-40 or ERA-interim reanalyses. Two quality controlled subsurface ocean temperature and salinity observational data-sets are used for evaluation purposes (MedAtlas-II, Rixen et al 2005 and EN3, Ingleby and Huddleston 2007). The models represent quite well the inter-annual variability and long term trend of temperature, although
significant biases and differences can be found across the models. The choice of physical parameterizations (Sanchez-Gomez et al. 2011, Di Luca et al. 2012), and in particular the representation of clouds and turbulent fluxes, as well as the choice of system components (aerosols, ocean coupling, river coupling) are the dominant factors explaining the model biases and spread.

By comparison, the reproduction of salinity seems to be quite problematic both in terms of inter-annual variability and long term trends, also probably due to deficiencies in the observation sampling. In fact, the number, spatio-temporal coverage and quality of salinity in-situ observations is worse than for temperature, leading to sampling errors when producing the gridded-products (Rixen et al. 2005, Jordà and Gomis 2013, Llasses et al. 2015).

**River discharge**

Med-CORDEX is also contributing to the integration of all components of the hydrological cycle throughout the coupling of land and ocean via river discharge. As an example of this contribution, Figure 9 shows the seasonal cycle of runoff for the most important Mediterranean rivers in observations and as computed by the river routing models embedded in two of the Med-CORDEX RCSMs. It can be seen that, although the amplitude of the seasonal cycle of discharge is mostly overestimated, the phase of this cycle, and in particular the peak discharge months, are well captured for all catchments. River discharge is an integrator of different processes, such as precipitation, soil infiltration, snowmelt and river routing, so that such type of analysis can provide valuable information on the ability of the coupled RCSMs to simulate the full hydrologic cycle of the basin. Other evaluations of river discharge can be found in Szczypta et al. (2012) for stand-alone land-hydrology models and in Sevault et al. (2014) for the CNRM coupled model RCSM4.

**Aerosols**

Aerosols of natural and anthropogenic sources are an important component of the Mediterranean climate system. Within the Med-CORDEX context, the influence of the aerosol direct effect on biases, interannual variability and long-term trends of temperature and shortwave and longwave radiation have been investigated by Nabat et al. (2014, 2015a,b). In particular, Nabat et al. (2014) showed that the underestimation of the SST trend by the Med-CORDEX models noted in previous sections is at least partly due to the lack of the representation in the models of the decrease in European anthropogenic aerosol
emissions starting from the 1980s, which resulted from stricter air pollution legislations and the economic crisis in Eastern Europe. This aerosol decreasing trend induces a positive surface shortwave trend and a detectable SST warming trend. Nabat et al. (2015a,b) then demonstrate the clear added-value in using coupled RCSMs with respect to SST-driven RCMs for the simulation of regional aerosol effects. These effects are indeed amplified when the Mediterranean SST is able to cool or warm in response to the aerosol radiative forcing over the sea. Aerosol-ocean-atmosphere regional feedbacks were highlighted by Nabat et al. (2015a,b) as important factors for the low-level humidity advection from the Eastern Mediterranean Sea towards the Sahara with a potential effect on the African monsoon.

**Strengthening the link with the VIA research community**

An important connection has been established between Med-CORDEX climate modeling groups and key impact sectors (ocean acidification, forest ecosystem, marine ecosystem, sea level). Through the use of Med-CORDEX simulations, several studies have been conducted to evaluate the climate variability and change impact on the Mediterranean region, here we provide key examples to marine ecosystems. Although marine ecosystems are influenced by many factors such as eutrophication and overfishing, rising atmospheric CO2 and climate change are associated with shifts in temperature, circulation, stratification, and ocean acidification, with potentially wide-ranging biological impacts. A certain effort has been devoted to better link climate models with ecosystem models. It has been demonstrated that the use of modeled weather data can yield predictions similar to those generated from measured data, but only when data are provided at relatively high frequency. Montalto et al. (2014) modeled the effects of environmental change on the physiological response of an ecologically and commercially important species of mussel in the Mediterranean. Their results suggest that ecosystem model skill can be significantly influenced by the temporal resolution of environmental data. In addition, a better use of Mediterranean climate model information into community ecology models limits the uncertainty of future ranges of marine species (Hattab et al., 2014). Auger et al. (2014) analyzed the role of the winter mixing on the inter-annual variability of Mediterranean plankton dynamics using a high-resolution coupled hydrodynamic-biogeochemical model. They demonstrated how winter mixing induced inter-annual variability of winter nutrient contents controls spring primary production. Going from sub-regional to local impacts, Andrello et al. (2015) analyzed how the climate change will influence connectivity of marine protected areas over the period 1970-2099.
Med-CORDEX future plans.

While considerable work is still ongoing on the analysis of the Med-CORDEX experiments completed to date, the discussion has started on the identification of key future challenges to be addressed by Med-CORDEX within the context of the next cycle of climate change research activities (e.g. the phase 6 of CMIP). Here we highlight three main foci for future Med-CORDEX activities:

A. Understand the past variability of the Mediterranean regional climate system and characterize its possible future evolution, with emphasis on an integrated multi-component approach and on the study and attribution of the relative role of different regional/local climate drivers (natural and anthropogenic aerosols, high-resolution SST, land-use) with respect to the large-scale forcings (climate natural variability, greenhouse gas induced global climate change).

Motivations: Over the Mediterranean area, recent studies have shown that natural and anthropogenic aerosols can improve the representation of the regional climate mean state (Nabat et al. 2015a), shortwave and temperature daily variability (Nabat et al. 2015b) and long-term trends (Nabat et al. 2014). In addition, Anav et al. (2010) show that human-induced land-use and land-cover changes can influence the Mediterranean climate, while Stéfanon et al. (2014) illustrate how an interactive representation of vegetation can contribute to develop positive feedbacks during extreme climate events such as droughts and heat waves. Auger et al. (2014) and Palmieri et al. (2015) suggest that long-term Mediterranean Sea biogeochemistry is reaching a mature state allowing the coupling with the other climate system components, and ocean waves not yet commonly represented in RCMs could also play a key role at the atmosphere-ocean interface (Kudryavtsev et al. 2014) and in influencing the regional aerosol load (Ovadnevaite et al. 2014). Finally, the key role of complex topography and coastlines in modulating regional climates and extreme events has been amply illustrated above. It is thus clear that an increased understanding of the role of regional/local vs. global drivers of climate change within the context of a fully interactive regional climate system is central for a better understanding of the impacts of global warming in the Mediterranean.

Examples of scientific questions to be addressed within this challenge: What are the main drivers of the observed trends in Mediterranean SST? Can we characterize, reproduce and explain the interannual variability of the Mediterranean salinity? Can we quantify the role of the massive decrease in anthropogenic
aerosols in Europe on the Mediterranean climate trends since 1980? Can we reproduce and attribute the trends in latent heat loss and water mass observed over the Mediterranean Sea? Can we reproduce and understand the regional/local sea level variability and change of the Mediterranean? What are the main drivers of the Mediterranean river runoff long-term variability? What are the main global and regional drivers of the climate variability of the Mediterranean aerosol load? Can we characterize, reproduce and explain the interannual variability of the Mediterranean marine ecosystems? Can we characterize, reproduce and explain the interannual variability and long-term trends of the Mediterranean climate extremes? How will the Mediterranean regional climate and its various regional components evolve? How does the complex physiography of the Mediterranean region affect current and future climate trends over the region?

Modelling framework: Exploring the relative role of the large-scale drivers versus regional forcings on the regional climate variability and change requires the development, evaluation and use of a new generation of Mediterranean Regional Earth System Models (RESMs) in which the various components of the climate system are fully coupled (as in RCSMs) and the human component if adequately considered. This new generation RESMs will allow the Med-CORDEX community to explore the complex interactions and regional feedbacks which modulate the climate of the region and will need to have sufficient horizontal resolution to adequately capture the Mediterranean topography and coastline features. Specifically, an innovative aspect of this coupling exercise will be the better representation in the models of the influence of human activities on regional climate drivers, such as aerosols land-use and land-cover, urbanization, dams, reservoirs and irrigation, air quality.

Model evaluation: Evaluating RCSMs (or RESMs) is a new open challenge for the climate modelling community. Indeed high-resolution and multi-component observations are often missing at the regional scale. The future Med-CORDEX evaluation strategy will have to rely on a hierarchy of approaches: model evaluation on detailed case studies taken, for example, from the HyMeX, MerMex or Charmex programmes, model evaluation against long-term multi-component in-situ super sites, evaluation using multi-component gridded products coming from satellite products or model-data regional reanalyses.

B. Investigate, understand and improve the description of regional climate phenomena critical for determining past climate variability and future evolution of Mediterranean climate, with emphasis on phenomena of importance for VIA applications.
Motivations: The Mediterranean is characterized by a plethora of phenomena of relevance not only for the climate of the region, but also for impacts on ecosystem and society: among others, heavy precipitation events, flash floods, Mediterranean cyclones and associated strong winds, strong air-sea exchanges and associated open-sea deep water formation, aerosol-radiation-cloud interactions, Mediterranean surface circulations, Mediterranean dense water formation and associated Mediterranean thermohaline circulation, droughts, heat waves, medicanes, strait transports, Mediterranean Sea oligotrophy and dynamic of the deep chlorophyll maximum. Med-CORDEX has evidenced a number of limitations of the present generation of models in simulating such events, tied to the coarse model resolution, drawbacks in model physics and dynamics representations, lack of descriptions of key feedbacks and interactions. Targeted activities will thus need to be designed in order to improve knowledge and modeling of these processes.

Examples of scientific questions to be addressed: What are the main processes underlying the triggering and evolution of the Mediterranean heavy precipitation events (e.g. > 100 mm/d)? Can we improve the representation and characterization of the Mediterranean cyclogenesis? Are "Medicanes" going to be more frequent in the future? Can we improve the understanding and representation of the interactions and feedbacks that can enhance Mediterranean drought events? Can we improve the understanding and representation of Mediterranean dense water formation phenomena in climate models? Can we improve the representation of the occurrence and characteristics of intense wind events (e.g. Mistral, Bora)? Can we improve the characterization of changes in storm surges as affected by regional sea level rise and the occurrence of intense storms?

Modelling framework: RCMs allow us to test in a well-constrained framework many modeling options targeting the understanding and representation of key climate phenomena and their variability for a given region. Case studies, long-term hindcast and historical-scenario configurations can be used towards this goal. Model improvements can be achieved by increasing the spatial resolution up to convection-resolving Atmosphere-RCMs or eddy-resolving Ocean-RCMs, by adding new components in the RCSMs (e.g. towards the development of RESMs including the human component) or by developing new targeted physical parameterizations.

Model evaluation: This task will require the development of high quality, fine scale datasets suitable for the process-based assessments of the models. Improving the representation of regional phenomena in the Mediterranean RCMs will also strengthen collaborations with the observation and process-based analysis
communities (e.g. HyMeX), the numerical weather prediction communities and the global circulation model
development community, as weather forecast models, RCMs and GCMs often share common deficiencies in
reproducing some of the key regional climate phenomena. A further goal of this challenge is to provide a
robust and quantitative assessment of the added value obtained in using RCSMs to simulate important
regional phenomena over the region.

C. Improve the characterization of the impacts of the Mediterranean climate variability and climate
change on human activities and natural ecosystems, towards the development of actionable
Mediterranean climate services.

Motivations: The increasing need to assess the impacts of climate variability and change over the
Mediterranean requires a better characterization, in particular, of the uncertainties associated with regional
climate projections. This in turn requires the completion of large ensembles of coordinated model
experiments, both for the historical past and future climate conditions, with multiple models, scenarios,
realizations and model configurations. Providing consistent and comprehensive scenarios for the various
regional components of the Mediterranean climate system is also a key challenge.

Climate services to be addressed: Covering the whole range of potential climate services is not feasible,
thus the Med-CORDEX efforts will be directed towards providing climate information, and evaluation of
related uncertainties, for areas that are specific to the Mediterranean, e.g.: maritime activities (ocean
biodiversity and marine protected areas, maritime transport, ocean pollution, fish and fisheries, aquaculture),
coastal activities such as tourism (coastal, islands, sea-related tourism), sustainable energy (solar energy,
wave energy, wind farm, ...), water resources and agriculture (combining human and climate influence),
regional/local geoengineering, biodiversity conservation planning.

Modelling framework: Targeted experiments will be designed to explore the importance of specific forcings
(e.g. aerosols, land use, wave) in shaping the future of the Mediterranean climate. This will complement the
completion of a large coordinated multi-model ensemble of regional climate change scenarios using RESMs
and very high resolution atmospheric RCMs in coordination with the CMIP6 and CORDEX frameworks. This
will require the development of strategies for the selection of CMIP6 GCMs to be used to drive the regional
simulations. Climate change information concerning all the components of the regional climate will be
provided in user-friendly format and with associated metadata. Post-processing techniques will be needed to
distill the most robust and accurate information for use in VIA studies (e.g. model weighting, bias correction, local scale downscaling, specific sectorial indicators) and techniques will need to be developed for a quantitative estimation of uncertainties within a risk-based probabilistic approach (e.g. Bayesian approaches). This activity will allow a strong interaction with the Med-CLIVAR community and will promote the Med-CORDEX results within the context of the next Intergovernmental Panel on Climate Change (IPCC) report or of a possible forthcoming Regional Assessment of Climate Change in the Mediterranean (RACCM).

Future Med-CORDEX activities will gather momentum in the next decades for a number of reasons. The Mediterranean has been recognized as a hotspot for climate change, vulnerability, adaptation issues and biodiversity loss; the Mediterranean has been selected as a GEWEX region (HyMeX) and a CLIVAR focus area (Med-CLIVAR); the contacts between the RCM community and the observation and process community are already very strong, in particular due to long term initiatives such as HyMeX and Med-CLIVAR. In addition, most of the new Grand Challenges identified by the WCRP are particularly relevant within the Mediterranean context: (1) Clouds, Circulation and Climate Sensitivity can be explored at regional scale for an area that is particularly sensitive to global climate change, (2) Changes in the cryosphere can profoundly affect Alpine glaciers, (3) Climate Extremes are one of the key challenges for impacts in the Mediterranean, (5) Regional Sea-level Rise is highly relevant for Mediterranean coastal activities and ecosystems, and (6) Water Availability is a central issue in many water stressed areas of the Mediterranean.

Med-CORDEX will provide an optimal framework for coordinating the modeling activities in the region towards addressing these challenges with common simulation protocols. We also envision an enhanced coordination with other CORDEX regional programs for which the Med-CORDEX specificities (coupled regional modeling, high resolution modeling, aerosol and land-use modeling) are especially relevant; for example CORDEX Africa on the key topics of the dust aerosols and on the effect of the Mediterranean Sea on the African monsoon; Euro-CORDEX on the development of convection-resolving RCMs and the study of land use effects; Middle Eastern North Africa (MENA) domain concerning the water resources issue; and Arctic and Baltic communities for common developments of coupled RESMs. The discussion on specific future experiment strategies and protocols for Med-CORDEX are currently under way and they will be finalized during the next Pan-CORDEX conference to take place in Stockholm in May 2016.
References


Lebeaupin-Brossier C., Drobinski P., Beranger K., Bastin S., Orain F. (2013). Ocean memory effect on the dynamics of coastal heavy precipitation preceded by a mistral event in the North-Western mediterranean. QJRMS, 139 (675), 1583-1597, 2013


Machenhauer B, Windelband M, Botzet M, Christensen JH, Déqué M, Jones J, Ruti PM, Visconti G (1998) Validation and analysis of regional present-day climate and climate change simulations over Europe. MPI Report No 275, MPI, Hamburg, Germany, 87 pp


http://dx.doi.org/10.1175/BAMS-D-11-00154.1


effect of anthropogenic vegetation land cover on heatwave temperatures over central France. Climate research, 60(2), 133-146.


Torma Cs, Giorgi F and Coppola E (2015). Added value of regional climate modeling over areas characterized by complex terrain - Precipitation over the Alps. (Submitted to Journal of Geophysical Research: Atmospheres.)


Captions.

Figure 1. Maximum model integration area for coupled systems.

Figure 2. Frequency of cyclone occurrence per 1000km² per 25 days for autumns and winters of the period 1989-2008.

For example, a 10% value suggests the occurrence of 10 cyclones in a 1000km² area in 25 days. Values exceeding 100% suggest the occurrence of more than one cyclone a) ERA-Interim; b) Protheus coupled run; c) Morce-Med coupled run; d) CNRM-RCSM4 coupled run.

Figure 3. 99% quantile of daily precipitation (mm/day) in SON for the period 1989-2008: a) ERA-interim reanalysis; b) ALADIN-Climat model 150 Kms; c) COSMO-CLM model 50kms forced by ERA-interim reanalysis; d) COSMO-CLM model 12kms; e) ALADIN-Climat model 50 kms; f) idem for 12 kms.

Figure 4. 99% quantile of daily precipitation (mm/day) in SON for the period 1989-2008: a) ERA-interim reanalysis; b) SAFRAN reanalysis 9 kms; c) COSMO-CLM model 50kms; d) COSMO-CLM model 12kms; e) ALADIN-Climat model 50 kms; f) idem for 12 kms.

Figure 5. Plots of wind speed distribution at Lion and Azur buoy locations for several models in comparing to Quikscat, ERAinterim and buoy wind speed. Whole time period (2000-2008) and the seasons.

Figure 6. SST interannual variability time series for the values averaged over the Med Sea basin. In grey the observed references: (Satellite, Rixen, EN4), in Black dashed: ERA-Interim. All coupled simulations are in colors. In red: CNRM, in blue: LMDZ, in brown: INSTM, in yellow: GUF, in purple:ENEA-PROTHEUS, in pink:UniBel, in light blue:CMCC and in green: MORCE-MED.

Figure 7: SST validation of the SST at the Lion buoy location (Lat: 42.10N, Lon: 4.70E) for different coupled models over the ERA-interim period: a) the time series; b) the annual cycle; c) DJF qq-plot; d) JJA qq-plot. CNRM coupled model, coupling the Limited Area Model ALADIN-Climate with the ocean model NEMOMED8 (red), CMCC, COSMO atmospheric model coupled with OPA ocean model (green), ENEA, RegCM4 regional atmospheric model coupled with MIT ocean model (blue), LATMOS, WRF atmospheric model coupled with NEMOMED8 ocean model (orange).

Figure 8. Time series of Mediterranean heat and salt content, defined as volume average of temperature (a) and salinity (b) for ocean stand-alone simulations using different atmospheric forcing produced by downscaling global reanalysis.

Figure 9. Seasonal cycle of runoff for the most important Mediterranean rivers. Black, ENEA coupled system; red, CNRM; green, observations. Average for the reference period 1970-2000. The four catchments are: the Ebro in Spain, the Rhone in France and Switzerland, the Po plus Adige in Northern Italy, the Danube.
Figure 1. Maximum model integration area for coupled systems.
Figure 2. Frequency of cyclone occurrence per 1000km² per 25 days for autumns and winters of the period 1989-2008. For example, a 10% value suggests the occurrence of 10 cyclones in a 1000km² area in 25 days. Values exceeding 100% suggest the occurrence of more than one cyclone a) ERA-Interim; b) Protheus coupled run; c) Morce-Med coupled run; d) CNRM-RCSM4 coupled run.
Figure 3. 99% quantile of daily precipitation (mm/day) in SON for the period 1989-2008: a) ERA-interim reanalysis; b) ALADIN-Climat model 150 Kms; c) COSMO-CLM model 50kms forced by ERA-interim reanalysis; d) COSMO-CLM model 12kms; e) ALADIN-Climat model 50 kms; f) idem for 12 kms.
Figure 4. 99% quantile of daily precipitation (mm/day) in SON for the period 1989-2008: a) ERA-interim reanalysis; b) SAFRAN reanalysis 9 kms; c) COSMO-CLM model 50kms; d) COSMO-CLM model 12kms; e) ALADIN-Climat model 50kms; f) idem for 12 kms.
Figure 5. Plots of wind speed distribution at Lion and Azur buoy locations for several models in comparing to Quikscat, ERAinterim and buoy wind speed. Whole time period (2000-2008) and the seasons.
Figure 6. SST interannual variability time series for the values averaged over the Med Sea basin. In grey the observed references: (Satellite, Rixen, EN4), in Black dashed: ERA-Interim. All coupled simulations are in colors. In red: CNRM, in blue: LMDZ, in brown: INSTM, in yellow: GUF, in purple: ENEA-PROTHEUS, in pink: UniBel, in light blue: CMCC and in green: MOCCE-MED.
Figure 7: SST validation of the SST at the Lion buoy location (Lat: 42.10N, Lon: 4.70E) for different coupled models over the ERA-interim period: a) the time series; b) the annual cycle; c) DJF qq-plot; d) JJA qq-plot. CNRM coupled model, coupling the Limited Area Model ALADIN-Climate with the ocean model NEMOMED8 (red), CMCC, COSMO atmospheric model coupled with OPA ocean model (green), ENEA, RegCM4 regional atmospheric model coupled with MIT ocean model (blue), LATMOS, WRF atmospheric model coupled with NEMOMED8 ocean model (orange).
Figure 8. Time series of Mediterranean heat and salt content, defined as volume average of temperature (a) and salinity (b) for ocean stand-alone simulations using different atmospheric forcing produced by downscaling global reanalysis.
Figure 9. Seasonal cycle of runoff for the most important Mediterranean rivers. Black, ENEA coupled system; red, CNRM; green, observations. Average for the reference period 1970-2000. The four catchments are: the Ebro in Spain, the Rhone in France and Switzerland, the Po plus Adige in Northern Italy, the Danube.
Acronyms list.

ALADIN  Aire Limitée Adaptation dynamique Développement InterNational
http://www.cnrm.meteo.fr/aladin/?lang=en

ALPEX  Alpine Experiment

CIRCE  Climate Change and Impact Research: the Mediterranean Environment
http://www.circeproject.eu/

CMIP5  Coupled Model Intercomparison Project Phase 5

CNRM  Centre National de Recherches Météorologiques – France

CNRM-ALADIN  Regional Climate Model of CNRM, France

CNRM-RCSM4  Regional Climate System Model, version 4, of CNRM, France

CORDEX  COrordinated Regional Downscaling Experiment

COSMO-CLM or CCLM  Consortium for SSmall-scale Modeling – Climate Limited Area Modeling
http://www.cosmo-model.org

EN3-EN4  Quality controlled ocean temperature and salinity profiles and monthly
objective analyses with uncertainty estimates

ENEA-PROTHEUS  Regional coupled model or the Energy, New Technologies, Environment and
Sustainable Development Italy

ENEA-REGM  Regional atmospheric model or the Energy, New Technologies, Environment
and Sustainable Development Italy

ENSEMBLES  Ensembles-Based Predictions of Climate Changes and Their Impacts
http://ensembles-eu.metoffice.com/index.html

ERA-interim  European reanalysis

GCM  Global Circulation Models

GPCP  Global Precipitation Climatological Project

GUF  Goethe University Frankfurt coupled model

HyMeX  Hydrological cycle in Mediterranean Experiment
http://www.hymex.org

LMD  Laboratoire de Meteorologie Dynamique, France

LMDZ  Stretched model of the Laboratoire de Meteorologie Dynamique, France
coupled with NEMO-MED8

INSTM  Institut National des Sciences et Technologies de la Mer

IPCC  Intergovernmental Panel on Climate Change

Med-CORDEX  Mediterranean COordinated Regional Downscaling Experiment
(www.medcordex.eu)

MORCE-MED  Mediterranean Regional Coupled Model, Ecole Polytechnique, Paris,
France. WRF coupled with NEMO-MED12
MSWB, MSHB Mediterranean Sea water and heat budgets
MERCURE Modelling European Regional Climate, Understanding and Reducing Errors
http://www.pa.op.dlr.de/climate/mercure.html
MISTRAL Mediterranean Integrated Studies at Regional And Local Scales
http://www.mistrals-home.org/spip/?lang=en
MITGCM-REMO Massachusset Institute of Technology General Circulation ocean Model -
Max Planck Institute for Meteorology REgional MOdel
NAO North Atlantic Oscillation
NEMO NEMO Mediterranean Ocean Model at different resolution, MED8 at 1/8
horizontal resolution, MED12 at 1/12
NM8-ARPERA NEMO Mediterranean Ocean Model at 1/8° horizontal resolution – ARPEGE
Atmospheric model downscaling ERA data set.
PRUDENCE Prediction of Regional scenarios and Uncertainties for Defining EuropeaN
Climate change risks and Effects
http://prudence.dmi.dk/
RACCS Regionalization of Anthropogenic Climate Change Simulations
RCSM Regional climate system models
RCM Regional Coupled Models
REMS Regional Earth System Model
RIXEN Observed hydrological (Temp. and Sal.) data
SST Sea surface temperatures
SAFRAN Système d’analyse fournissant des renseignements atmosphériques à la
neige
STARDEX Statistical and Regional dynamical Downscaling of Extremes for European
regions
http://www.cru.uea.ac.uk/projects/stardex/
UniBel University of Belgrade coupled model
VIA Impact, adaptation and vulnerability
WCRP World Climate Research Program
WMDW West Mediterranean Deep Water
Figure 1
Click here to download Non-Rendered Figure: BAMS_Figure1_TBS_5May.pdf
Figure 2
Click here to download Non-Rendered Figure: BAMS_Figure2_TBS_5May.pdf
Figure 5
Click here to download Non-Rendered Figure: BAMS_Figure5_TBS_5May.pdf