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MED-CORDEX INITIATIVE FOR MEDITERRANEAN CLIMATE STUDIES

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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.

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 finescale spatial and temporal variability (Ruti et al. 2008; Chronis et al. 2011; Drobinski et al. 2014), along with the formation of intense weather phenomena (Ducrocq et al. 2014; Tous et al. 2013). A typical example of such phenomena is the mistral wind, which blows through the Rhone valley into the Gulf of Lion and across to Corsica and Sardinia through the Strait of Bonifacio (Chronis et al. 2011). Another example is the bora wind, which blows in a northeasterly 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 semienclosed 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: that is, 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; Ivanovic et al. 2014).

Deep Mediterranean Water is produced at different locations by intense air–sea interactions: in the Gulf of Lion (western Mediterranean), the southern Adriatic, the northeast Levantine basin, and the Aegean Sea in the eastern Mediterranean (Lacombe et al. 1970; Roether et al. 1996). The basin's circulation is characterized by the presence of subbasin 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. To explicitly resolve with high spatial resolution the two-way interactions at the atmosphere–ocean interface, fully coupled high-resolution atmosphere–ocean RCMs (see the appendix for a complete list of acronyms and definitions) are needed (Somot et al. 2008; Artale et al. 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 "hotspots" of the twenty-first 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

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temperature has increased more than the global average, mean annual precipitation has decreased since the mid-twentieth century, and trends toward 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 5 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).

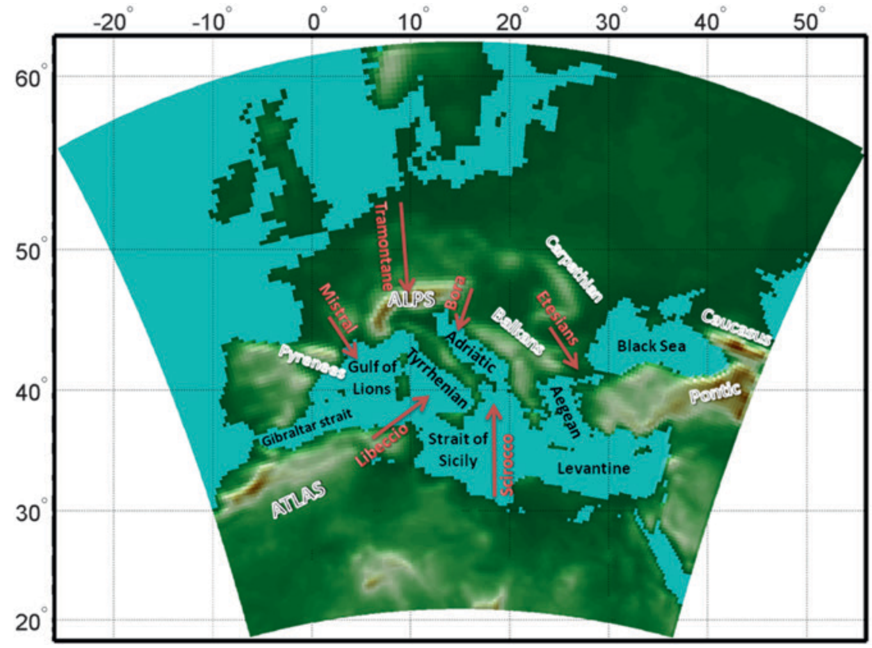

Fig. 1. Maximum model integration area for coupled systems.

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 1990s, a number of research and intercomparison projects have focused on downscaling global climate simulations (reanalysis or GCMs) over the Euro-Mediterranean region (RACCS, Machenhauer et al. 1996; Christensen et al. 1997; MERCURE, Hagemann et al. 2002; STARDEX, Goodess et al. 2005; PRUDENCE, Christensen et al. 2007; ENSEMBLES, Van der Linden and Mitchell 2009; CIRCE, Gualdi et al. 2013). Building on these programs, and as part of the CORDEX 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 finescale climate information for the region. Med-CORDEX aims at addressing a number of key scientific challenges, including the following:

- to develop fully coupled RCSMs for the Mediterranean basin (Fig. 1), considering and improving all relevant components of the system: that is, 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, finescale 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; and
- to strengthen the link with the VIA research community through the provision of tailored climate information datasets 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 a 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 at 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 approximately 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 reanalyses (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 twentieth and full twenty-first century (1950–2100 or 1970–2100) with the RCMs driven at the lateral boundaries by fields from different GCMs from CMIP5 (http://cmip-pcmdi.llnl.gov/cmip5/). (More detail on the CORDEX experimental protocol can be found in http://wcrp-cordex.ipsl.jussieu.fr/.)

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 RCSMs including fully interactive atmosphere–land–river–ocean components, covering the whole Mediterranean basin and its catchment basin at an intermediate grid spacing of about 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; and
- advancement of regional reanalyses to serve as reference datasets and ocean initial conditions.

The Med-CORDEX phase 1 gathers 22 different modeling groups from nine countries (France, Italy, Spain, Serbia, Greece, Turkey, Tunisia, Germany, and Hungary) in Europe, the Middle East, and North Africa and more than 75 active members of the modeling 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, and Mykonos in September 2015) have been organized thanks to the MISTRALS meta program that supports HyMeX.

There are 12 coupled RCSMs covering the whole Mediterranean and its catchment basin that 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 multimodel 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, 50, 25, and 12 km) as well as 10 stand-alone ocean models (resolutions from 25 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 (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 period (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 project 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 six 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 noncommercial 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 powerful search tool and online 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 online 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-1 Med-CORDEX activities aimed at illustrating the types of analyses that 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 that 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 on 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 RCSMs (~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 Lion 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 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, and 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-only 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^{-1}) for the period 1989–2008 for ERA-Interim (Fig. 3a) and the COSMO-CLM and ALADIN regional simulations (driven by ERA-Interim fields) at 50- (Figs. 3c,e) and 12-km (Figs. 3d,f) grid spacing over the Med-CORDEX domain. To measure the model performance in reproducing the tail of the distribution with respect to an observation-based finescale dataset, the same results are shown over France in Fig. 4, where they are compared to a high-resolution mesoscale atmospheric analysis for rainfall (SAFRAN; Quintana-Seguí et al. 2008). The results of Figs. 3 and 4 clearly show that ALADIN and COSMO-CLM are able to simulate the tail of the

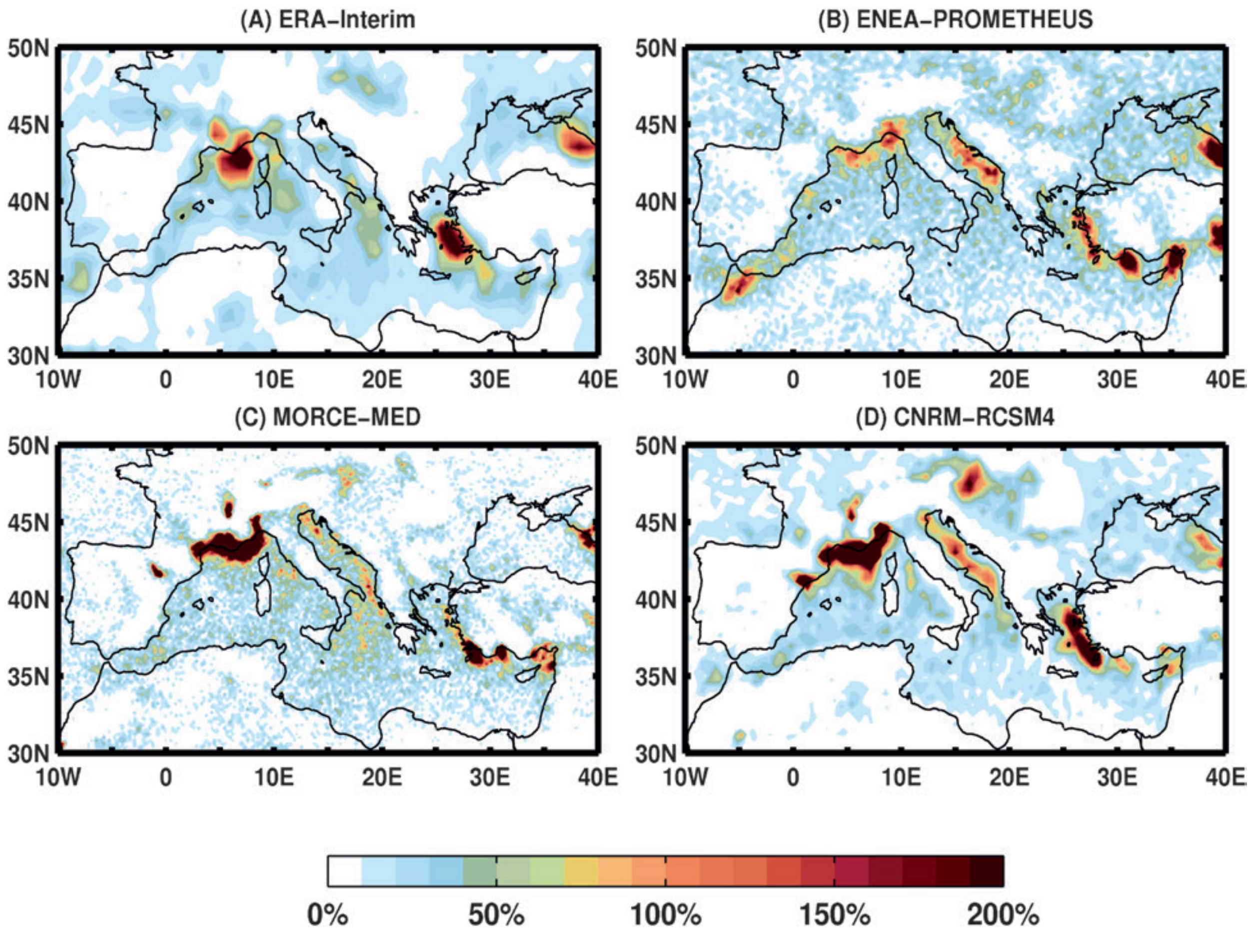

Fig. 2. Frequency of cyclone occurrence [(1000 km^2)$^{-1}$ (25 days)$^{-1}$] for autumns and winters of the period 1989–2008. For example, a 10% value suggests the occurrence of 10 cyclones in a 1000-km^2 area in 25 days. Values exceeding 100% suggest the occurrence of more than one cyclone: (a) ERA-Interim, (b) ENEA-PROTHEUS coupled run, (c) MORCE-Med coupled run, (d) CNRM-RCSM4 coupled run.

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, ERA-Interim and the coarse-resolution ALADIN model strongly underestimate the magnitudes of these precipitation extremes (Figs. 3a,b, 4a). The results shown in Figs. 3 and 4 were also confirmed by the study of E. Harader et al. (2015, unpublished manuscript) based on different quantitative metrics of model performance.

The added value highlighted over France in Fig. 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) that can lead to ocean deep convection in various sites of the Mediterranean

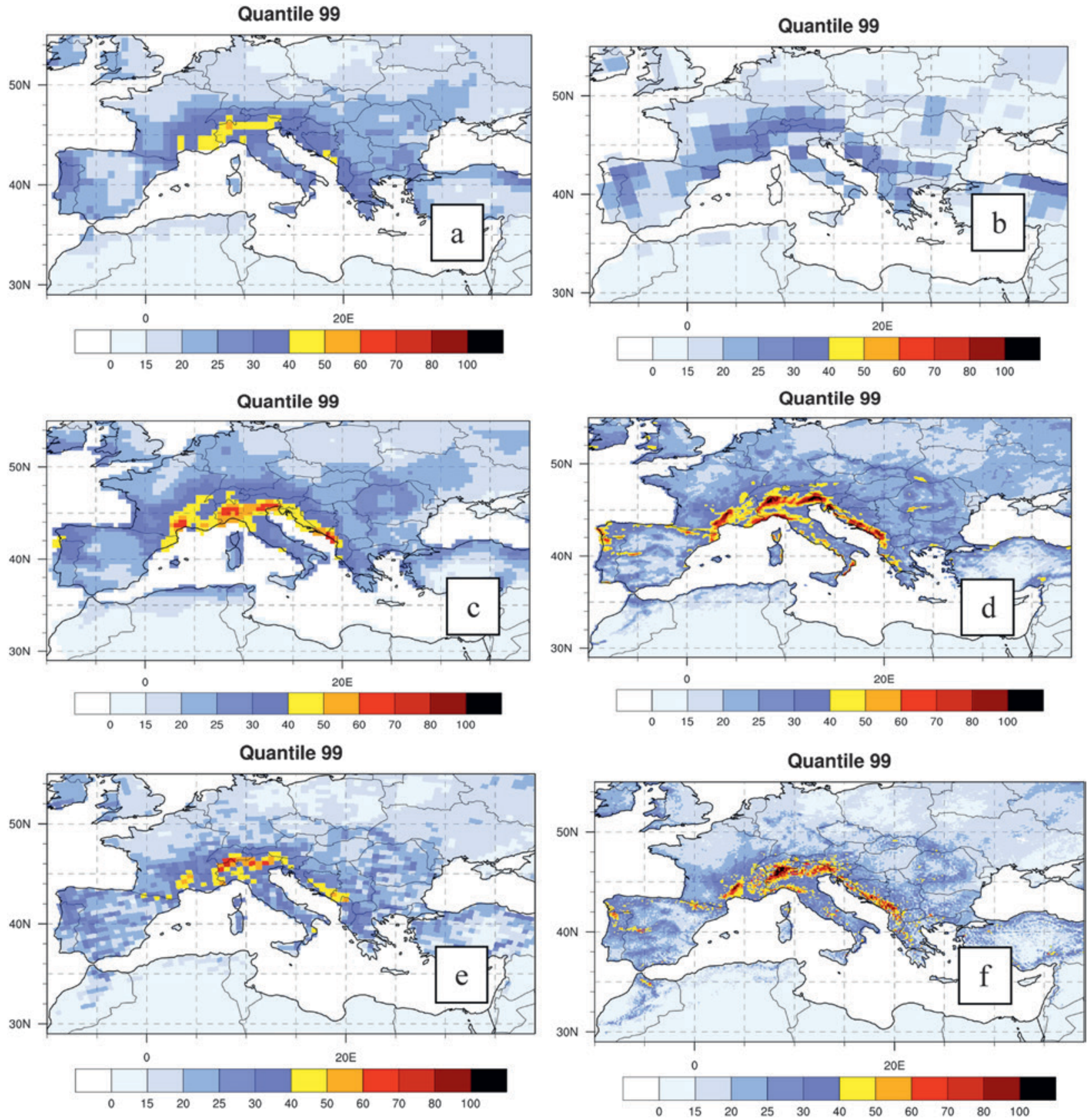

Fig. 3. The 99% quantile of daily precipitation (mm day^{-1}) in SON for the period 1989–2008: (a) ERA-Interim; (b) ALADIN-Climate model, 150 km; (c) COSMO-CLM model, 50 km, forced by ERA-Interim; (d) COSMO-CLM model, 12 km; (e) ALADIN-Climate model, 50 km; and (f) ALADIN-Climate model, 12 km.

Sea (Herrmann and Somot 2008; Herrmann et al. 2010). In such phenomena, the wind strength and direction are fundamental parameters that 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. 2011), from an analysis of Med-CORDEX experiments with the regional model ALADIN at various resolutions (grid spacings of 125, 50, 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).

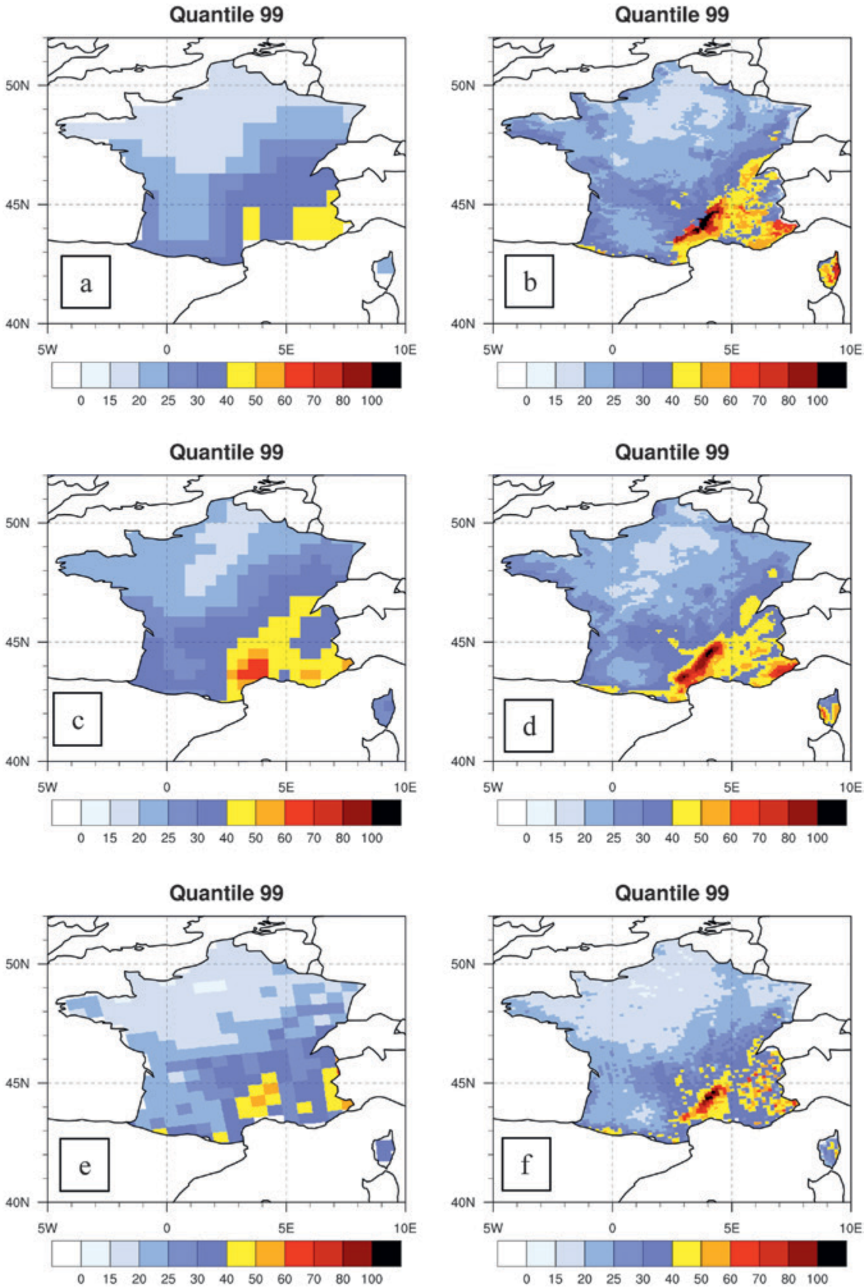

Fig. 4. The 99% quantile of daily precipitation (mm day^{-1}) in SON for the period 1989–2008: (a) ERA-Interim; (b) SAFRAN, 9 km; (c) COSMO-CLM model, 50 km; (d) COSMO-CLM model, 12 km; (e) ALADIN-Climate model, 50 km; and (f) ALADIN-Climate model, 12 km.

Figure 5 generalizes this result in a multimodel 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- 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 with the tramontane and mistral strong northwesterly winds that blow through the Garonne and Rhone valleys driven by large-scale pressure patterns. Over the Côte d'Azur site, two main regimes are present—that is, from the northeast (associated with the mistral) and from the southwest—because of 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, Fig. 5 shows that the 12-km RCMs (COSMO-CLM and ALADIN-Climate) improve the representation of the wind probability density function at both locations with respect to the corresponding 50-km versions and the coarse-resolution ERA-Interim. 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

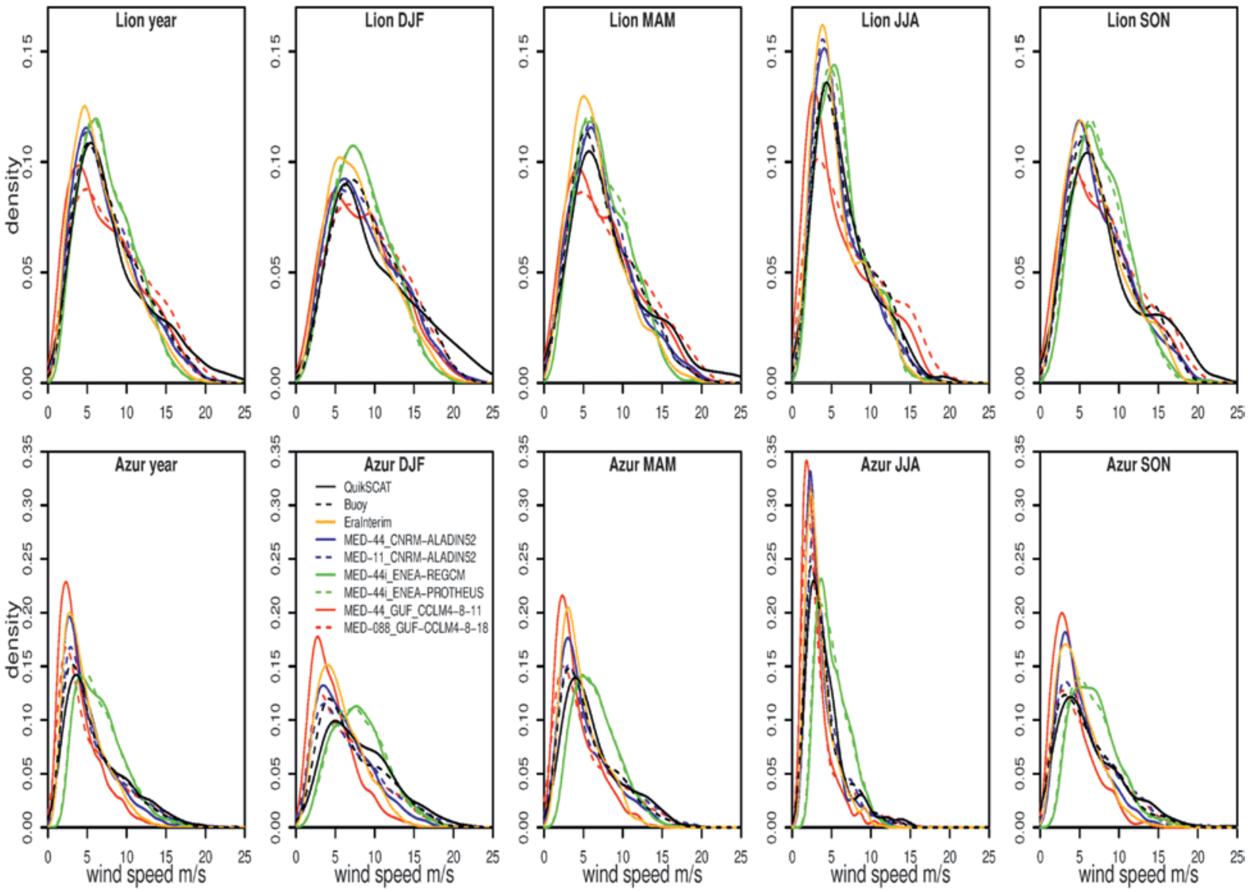

Fig. 5. Plots of wind speed distribution at Lion and Azur buoy locations for several models in comparison with QuikSCAT, ERA-Interim, and buoy wind speed for the whole time period (2000–08) and the seasons.

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 MSWB and MSHB 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; Akhtar 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 multimodel studies within the frame of the ENSEMBLES and CIRCE projects (Sanchez-Gomez et al. 2011; Dubois et al. 2012) demonstrated that 1) the observed references for the MSWB and MSHB terms (evaporation, precipitation, river runoff, Black Sea freshwater inputs, shortwave radiation, longwave radiation, sensible heat flux, and latent heat flux) are far from being accurate and 2) state-of-the-art RCMs still show large deficiencies in reproducing these terms at various scale (mean state, spatial pattern, interannual variability, and trends). Because of 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 challenges in Med-CORDEX. A large number of studies on this topic using Med-CORDEX simulations are still ongoing, 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

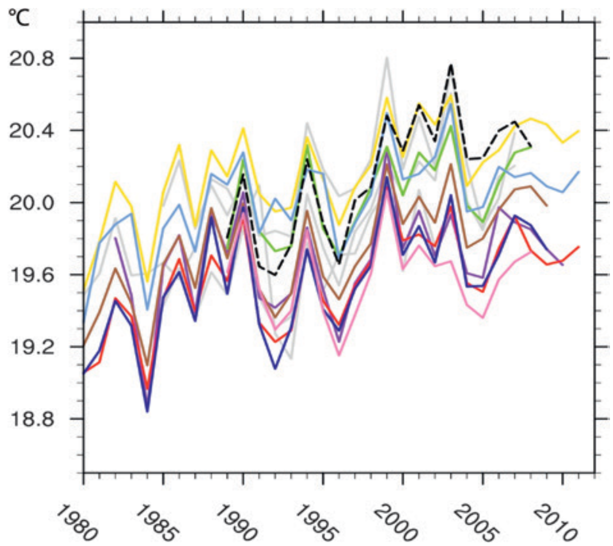

Fig. 6. SST interannual variability time series for the values averaged over the Mediterranean Sea basin. In gray are the observed references (Satellite, Rixen, EN4), in black dashed is ERA-Interim. All coupled simulations are in colors: CNRM (red), LMDZ (blue), INSTM (brown), GUF (yellow), ENEA-PROTHEUS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

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 m 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; northwestern Mediterranean) and four Med-CORDEX coupled RCSMs at the daily temporal scale. The four coupled simulations agree in reproducing the seasonal cycle (Fig. 7a) and the interannual variability of the observed SST (Fig. 7b). The simulated SST distributions are then compared with observed SSTs in daily quantile–quantile (qq) plots for winter (Fig. 7c) and summer (Fig. 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 that is probably due to the misrepresentation of ocean deep convective phenomena. In summer (Fig. 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), and Lebeaupin-Brossier et al. (2015). Despite remaining biases in some terms, these studies consistently demonstrate the added value of the coupled versus 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 Meyssignac 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 (Lacombe et al. 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 behaviors 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 (cf. Sevault et al. 2014).

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 multimodel diagnostic study of stand-alone Med-CORDEX regional ocean models (Fig. 8) by analyzing the heat and salt content of the whole Mediterranean Sea (expressed as average temperature and salinity). The ocean

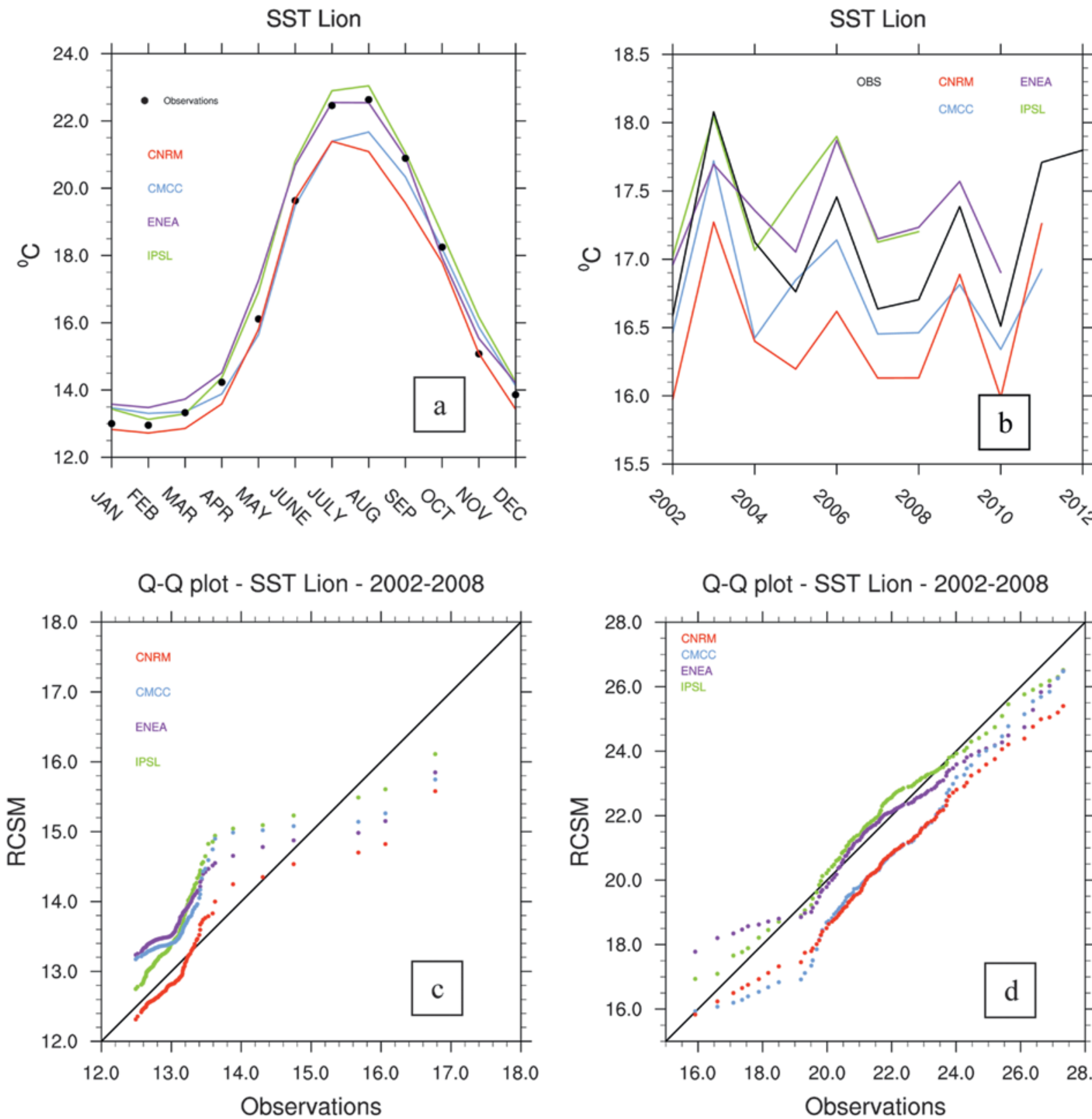

Fig. 7. SST validation of the SST at the Lion buoy location (42.10°N, 4.70°E) for different coupled models over the ERA-Interim period: (a) the time series, (b) the annual cycle, (c) Dec–Feb qq plot, and (d) Jun–Aug qq plot. CNRM coupled model, coupling the limited-area model ALADIN-Climate with the ocean model NEMO-MED8 (red); CMCC and COSMO atmospheric model coupled with OPA ocean model (green), ENEA, RegCM4 regional atmospheric model coupled with MIT ocean model (blue); and LATMOS and atmospheric WRF Model coupled with NEMO-MED8 ocean model (orange).

models are driven by different atmospheric forcings produced by dynamical downscaling of ERA-40 or ERA-Interim. Two quality-controlled subsurface ocean temperature and salinity observational datasets are used for evaluation purposes (MedAtlas-II, Rixen et al. 2005; EN3, Ingleby and Huddleston 2007). The models represent quite well the interannual 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. 2014), and in particular the representation of clouds and turbulent fluxes, as well as the choice of system components (aerosols, ocean coupling, and 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 interannual

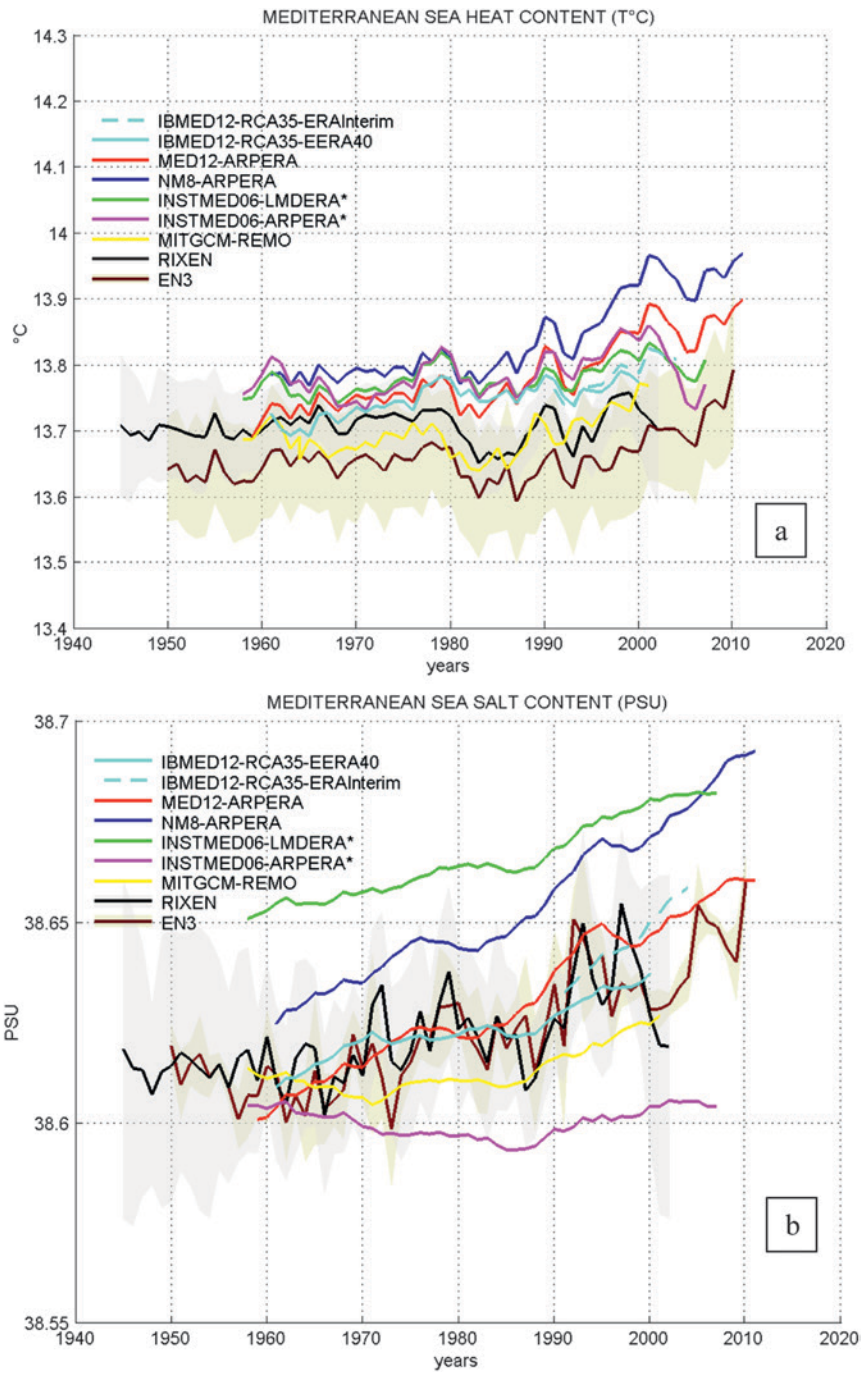

Fig. 8. Time series of Mediterranean heat and salt content, defined as volume average of (a) temperature and (b) salinity for ocean stand-alone simulations using different atmospheric forcing produced by downscaling global reanalysis.

variability and long-term trends, also probably due to deficiencies in the observation sampling. In fact, the number, spatiotemporal 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, Fig. 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

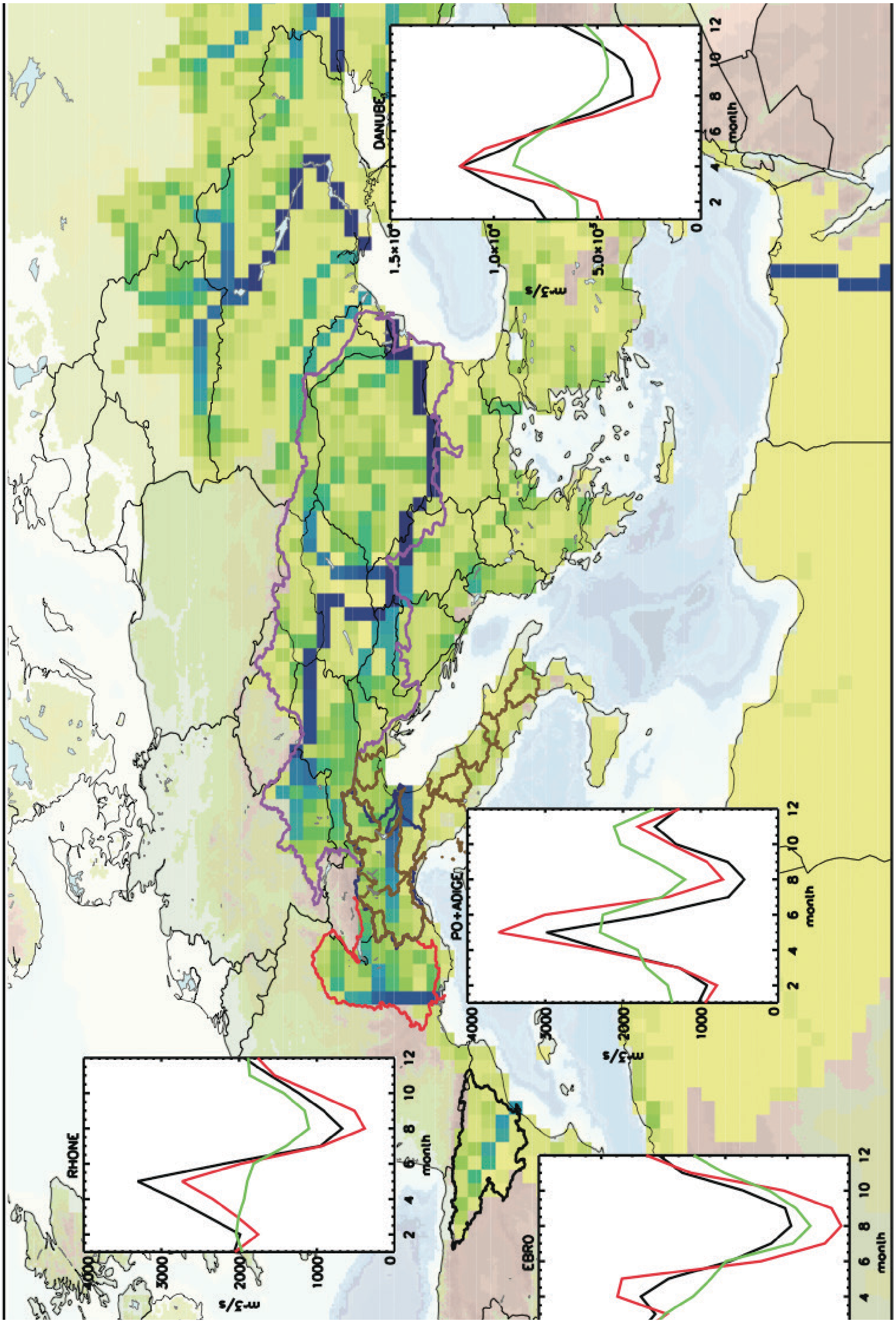

Fig. 9. Seasonal cycle of runoff for the most important Mediterranean rivers. ENEA coupled system (black), CNRM (red), and observations (green). Average for the reference period 1970–2000. The four catchments are the Ebro in Spain, the Rhone in France and Switzerland, the Po plus Adige in Northern Italy, and the Danube.

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 toward 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, and 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 CO_2 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 interannual variability of Mediterranean plankton dynamics using a high-resolution coupled hydrodynamic–biogeochemical model. They demonstrated how winter mixing–induced interannual variability of winter nutrient contents controls spring primary production. Going from subregional 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.

1) Understand the past variability of the Mediterranean regional climate system and characterize its possible future evolution, with emphasis on an integrated multicomponent approach and on the study and attribution of the relative role of different regional/local climate drivers (natural and anthropogenic aerosols, high-resolution SST, and land use) with respect to the large-scale forcings (climate natural variability and 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 Palmiéri 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 versus 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?

Modeling 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 RESMs in which the various components of the climate system are fully coupled (as in RCSMs) and the human component is adequately considered. This new generation of RESMs will allow the Med-CORDEX community to explore the complex interactions and regional feedbacks that 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, irrigation, and air quality.

Model evaluation. Evaluating RCSMs (or RESMs) is a new open challenge for the climate modeling community. Indeed, high-resolution and multicomponent 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 programs, model evaluation against long-term multicomponent in situ super sites, and evaluation using multicomponent gridded products coming from satellite products or model data regional reanalyses.

2) 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, and 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, and the 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 day^{-1})? 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 and bora)? Can we improve the characterization of changes in storm surges as affected by regional sea level rise and the occurrence of intense storms?

Modeling 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 toward 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., toward 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, finescale 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.

3) Improve the characterization of the impacts of the Mediterranean climate variability and climate change on human activities and natural ecosystems toward 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 toward providing climate information, and evaluation of related uncertainties, for areas that are specific to the Mediterranean: for example, maritime activities (ocean biodiversity and marine protected areas, maritime transport, ocean pollution, fish and fisheries, and aquaculture), coastal activities such as tourism (coastal-, islands-, and sea-related tourism), sustainable energy (solar energy, wave energy, wind farm, and so on), water resources and agriculture (combining human and climate influence), regional/local geoengineering, and biodiversity conservation planning.

Modeling framework. Targeted experiments will be designed to explore the importance of specific forcings (e.g., aerosols, land use, and wave) in shaping the future of the Mediterranean climate. This will complement the completion of a large coordinated multimodel 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 a user-friendly format and with associated metadata. Postprocessing 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, and 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 IPCC report or of a possible forthcoming 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); and 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; 4) regional sea level rise is highly relevant for Mediterranean coastal activities and ecosystems; and 5) 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, working toward 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, and 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, 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 is currently under way and will be finalized during the next Pan-CORDEX conference to take place in Stockholm in May 2016.

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APPENDIX: ACRONYM LIST.

ALADIN	Aire Limitée Adaptation Dynamique Développement International (www.cnrm.meteo.fr/aladin/?lang=en)
ALADIN-Climate	ALADIN model version used for regional climate modeling
ALPEX	Alpine Experiment
ChArMEx	Chemistry–Aerosol Mediterranean Experiment
CIRCE	Climate Change and Impact Research: The Mediterranean Environment (www.cmcc.it/projects/circe-climate-change-and-impact-research-the-mediterranean-environment)
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CMIP	Coupled Model Intercomparison Project
CMIP5	Phase 5 of the Coupled Model Intercomparison Project
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	Coordinated Regional Downscaling Experiment
COSMO-CLM or CCLM	Consortium for Small-Scale Modeling model in Climate Mode (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-40	40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis
ERA-Interim	ECMWF interim reanalysis
GCM	Global circulation models
GEWEX	Global Energy and Water Cycle Experiment
GPCP	Global Precipitation Climatological Project
GUF	Goethe University Frankfurt coupled model
HyMeX	Hydrological Cycle in Mediterranean Experiment (www.hymex.org)
LATMOS	Laboratoire Atmosphères, Milieux, Observations Spatiales

LMD	Laboratoire de Meteorologie Dynamique (France)
LMDZ	Stretched model of the Laboratoire de Meteorologie Dynamique zoom model, 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)
Med-CLIVAR	Mediterranean Climate Variability and Predictability
MENA	Middle Eastern North Africa
MORCE-MED	Mediterranean Regional Coupled Model (Ecole Polytechnique, Paris, France), WRF coupled with NEMO-MED12
MSWB	Mediterranean Sea water budget
MSHB	Mediterranean Sea heat budget
MERCURE	Modeling European Regional Climate, Understanding and Reducing Errors
MerMeX	Marine Ecosystems Response in the Mediterranean Experiment
MISTRALS	Mediterranean Integrated Studies at Regional and Local Scales (www.mistrals-home.org/spip/?lang=en)
MITGCM–REMO	Massachusetts Institute of Technology General Circulation Model–Max Planck Institute for Meteorology Regional Model
NAO	North Atlantic Oscillation
NEMO	Nucleus for European Modelling of the Ocean Mediterranean Ocean Model at different resolutions (MED8 at 1/8° horizontal resolution, MED12 at 1/12° horizontal resolution)
NM8–ARPERA	NEMO Mediterranean Ocean Model at 1/8° horizontal resolution–ARPEGE Atmospheric model downscaling ERA dataset
OPA	Océan Parallélisé
PRUDENCE	Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (http://prudence.dmi.dk/)
QuikSCAT	Quick Scatterometer
RACCM	Regional Assessment of Climate Change in the Mediterranean
RACCS	Regionalization of Anthropogenic Climate Change Simulations
RCSM	Regional climate system models
RCM	Regional coupled model
RCP	Representative concentration pathway
REMS	Regional Earth system model
RIXEN	Observed hydrological (temperature and salinity) data
SST	Sea surface temperature
SAFRAN	Système d'Analyze Fournissant des Renseignements Atmosphériques à la Neige
STARDEX	Statistical and Regional Dynamical Downscaling of Extremes for European Regions (www.cru.uea.ac.uk/projects/stardex/)
UniBel	University of Belgrade coupled model
VIA	Vulnerability, impacts, and adaptation
WATCH	Water and Global Change
WCRP	World Climate Research Program
WMDW	West Mediterranean Deep Water

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