Climate Dynamics (2018) 51:771–777
https://doi.org/10.1007/s00382-018-4325-x

EDITORIAL

Editorial for the Med-CORDEX special issue

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Published online: 27 June 2018

Keywords Med-CORDEX · Mediterranean Sea · Mediterranean climate · Regional climate models

1 Introduction

The Mediterranean area has quite a unique character that results both from their complex morphology and socio-economic conditions. It is indeed surrounded by various and complex topography channelling regional winds (Mistral, Tramontane, Bora, Meltem, Sirocco) than defined local climates and from which numerous rivers feed the Mediterranean Sea. Many small-size islands limit the low-level air flow and its coastline is particularly complex. Strong land–sea contrast, land–atmosphere feedback, sea breeze, meso-scale cyclones and medicanes, coastal upwelling, intense air–sea coupling and aerosol–radiation interaction are also among the regional characteristics to take into account when dealing with the Mediterranean climate modeling. In addition, the region features a semi-enclosed sea with an active regional thermohaline circulation. It is connected to the Atlantic Ocean only by Gibraltar strait and surrounded by very urbanized littorals.

This naturally led the climate and ocean modelling community to develop high-resolution stand-alone and fully-coupled climate models to study this specific area. The history of the regional climate models dedicated to the Mediterranean study is now a more than 20-year long story. It started with 50-km resolution Atmosphere stand-alone regional climate models (RCM) also including the land component in the 90s (Jones et al. 1995; Déqué and Piedelievre 1995). Later, two-way coupled atmosphere–ocean regional climate models (AORCM) appeared during the year 2000s in order to take into account the high-resolution and high-frequency coupling between the regional sea and surrounding atmosphere (Somot et al. 2008; Artale et al. 2010). River coupling was the next step in order to connect the land and sea components and to finally close the water cycle of the Mediterranean region (Carillo et al. 2012; Sevault et al. 2014). At that time, coupled RCMs were involving a high-resolution representation and a high-frequency coupling of four components of the Mediterranean regional climate system, that is to say atmosphere, land, river and ocean and were called regional climate system models (RCSM). Coupled regional climate modelling efforts to study the Mediterranean climate and sea were coordinated for the first time in the CIRCE project (Gualdi et al. 2013a) in which six different AORCMs were built and intercompared (Dubois et al. 2012; Gualdi et al. 2013b). Building on this first experience, the Med-CORDEX initiative started in September 2009 (Toulouse meeting, France) under the support of the MISTRALS/HyMeX programme (Drobinski et al. 2014) and it soon became one of the official CORDEX domains (Giorgi et al. 2009). Med-CORDEX (http://www.medcordex.eu, medcordex@hymex.org) is an unique framework where research community makes use of both new very high-resolution regional climate models (RCM, up to 10 km) and new fully coupled regional climate system models (RCSMs) for increasing the reliability of past and future regional climate information and for understanding the processes that are responsible for the Mediterranean climate variability and trends. The Med-CORDEX domain includes the Mediterranean climate zone, the Mediterranean Sea and the river catchment basins of the

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Mediterranean and Black Seas. The initiative was launched by Paolo Ruti, Filippo Giorgi and Samuel Somot and it is currently coordinated by an international steering committee composed by Samuel Somot (CNRM, France), Bodo Ahrens (GUF, Germany), Erika Coppola (ICTP, Italy), Gabriel Jordà? (IMEDEA, Spain), Gianmaria Sannino (ENEA, Italy) and Fabien Solmon (LA, France). A detailed vision of the Med-CORDEX objectives, the modelling approaches and models as well as an overview of the first results obtained can be found in Ruti et al. (2016).

The current Med-CORDEX special issue in *Climate Dynamics* includes most of the Med-CORDEX-related studies since this first overview. It includes articles presenting new reference datasets for regional climate model evaluation, evaluation of the Med-CORDEX models (e.g. atmosphere stand-alone, ocean stand-alone and coupled RCSM), study of the added-value of high resolution and high-frequency coupling and understanding of key regional climate or oceanic phenomena as well as future regional climate change projections.

2 New reference datasets for Med-CORDEX model evaluation

Evaluating high-resolution and multi-component regional climate models requires to re-think the notion of reference datasets. Indeed, the reference datasets commonly used for climate model evaluation are often not suitable in this case for various reasons: (1) they do not address the right spatial and temporal scales, (2) they do not allow the evaluation of the fluxes at the interfaces between the climate system components, (3) they do not take into account carefully the complex land–sea mask of the region, or (iv) their temporal consistency is not good enough to study long-term variability. Besides, the evaluation of the ocean component of the RCSMs at climate scale is a real challenge as ocean data are often sparse and not homogeneous in time. Developing and validating new reference datasets is therefore part of the Med-CORDEX work.

As an illustration, Chakroun et al. (2016) and Rysman et al. (2016) test new satellite products for regional model evaluation using respectively lidar-based and microwave-based spatial products to evaluate the vertical structure of cloud and rainfall over the sea. Adloff et al. (2017) use for the first time the new ESA-CCI product for the Mediterranean Sea level.

Somot et al. (2016) perform a thorough reanalysis of past observations over the north-western Mediterranean Sea to derive the most complete ever time series characterizing the deep water mass formation interannual variability in this zone. Dunić et al. (2016) also aggregate a very long time series of recurrent CTD transects allowing to qualify for the first time climate-scale ocean models for the Adriatic Sea.

Fantini et al. (2016) aggregate all the recently-available high-resolution (about 10-km) gridded reference datasets for daily precipitation in Europe to evaluate precipitation statistics in Med-CORDEX and Euro-CORDEX simulations. Froidurot et al. (2016) develop a new 10 km and 3 h gridded product for Mediterranean France based on all available station data and specifically adapted for RCM sub-daily evaluation.

Thanks to long-term and homogenized datasets, Blanchet et al. (2016) and Somot et al. (2016) are able to derive trend estimates for respectively the heavy precipitations over Mediterranean France and the bottom water masses of the north-western Mediterranean Sea.

Attempts to evaluate the fluxes at the interfaces of the RCSM components and to understand their biases are done using land–atmosphere and air–sea super-sites for which long-term and multi-variate datasets are available (Bastin et al. 2016; Somot et al. 2016).

3 Model evaluation

This special issue is the first opportunity to coordinate multi-model evaluation for the Med-CORDEX RCMs at the Mediterranean basin scale. This is done for a large number of parameters including extreme-related indices for the atmosphere. Dell'Aquila et al. (2016) evaluate temperature and precipitation over land comparing the RCMs of the ENSEMBLES project with the new Med-CORDEX RCMs. They focus on the decadal variability and show an overall good model behaviour for both parameters and no clear difference between both ensembles. Fantini et al. (2016), Cavicchia et al. (2016) and Panthou et al. (2016) extend this first analysis by focusing on multiple indices concerning the mean behaviour and the extremes of the models for temperature and precipitation. They generally conclude that Med-CORDEX RCMs are at the state-of-the-art for the mean behaviour and represent adequately the extremes, especially the 12 km resolution models. It is worth noting that RCMs show an excessive production of low precipitation events leading to underestimate the dry day frequency and the dry spell length. However, note that the obtained conclusions depend on the reference datasets used for evaluation.

More specific evaluations of the extreme precipitations are conducted by Drobinski et al. (2016b) focusing on the scaling with local temperature on stations, by Khodayar et al. (2016) focusing on one of the HyMeX case study in Fall 2012 and by Rysman et al. (2016) using satellite-derived extreme precipitation indices over sea.

Concerning the ocean, Harzallah et al. (2016) evaluate the various terms of the Mediterranean Sea heat budget for both the Ocean RCMs and RCSMs whereas Llasses et al. (2016) look at the heat and salt redistribution among layers and subbasins inside the Mediterranean in a similar ensemble. They conclude that the model spread is large for the mean value of the various components of the heat and salt budgets, for the vertical heat and salt transfers, and for the trends in the heat and salt contents. Besides the models agree well on the interannual heat variability, in this case, being close to the observations. Those model intercomparison studies have helped to elucidate deficiencies in model configurations and to improve the design of the new ocean simulations. Finally, Adloff et al. (2017) assess the realism of sea level variability in modelling systems with different configurations, point out the limitations of certain configurations and propose a new approach that solve them.

Evaluation of the interfaces are tackled in Bastin et al. (2016) for the land–atmosphere feedbacks using the WRF model and in Macias et al. (2016) using an indirect way to determine the Atmosphere-RCM air–sea flux biases in order to propose ad hoc corrections to improve them.

Other studies of the special issue focus on the evaluation of specific climate phenomena of the region such as the cyclones (Flaounas et al. 2016; Sanchez-Gomez and Somot 2016), the medicanes (Gaertner et al. 2016), the cloud cover (Chakroun et al. 2016), the ocean deep water formation (Somot et al. 2016; Dunić et al. 2016), the regional winds (Obermann et al. 2016) and the sea breeze (Drobinski et al. 2017).

4 High-resolution and coupled RCM added-value

Proving the added-value of the new RCM tools is a long-term effort of the community. In Med-CORDEX, models at different spatial resolutions allow to study the added-value related to the increase in resolution. Gaertner et al. (2016) find that 12 km RCMs improve the medicane frequency but not their intensity with respect to 50 km models. In a similar comparison, Obermann et al. (2016) demonstrate that 12 km model improve the Mistral and Tramontane representation despite some model-dependency. Akhtar et al. (2017), using twin coupled runs, confirm that high resolution models improve the representation of sea wind and the related turbulent heat flux, especially close to the coast, but no improvement is found for the radiation fluxes. Fantini et al. (2016) show that 12 km models improve the spatial patterns and seasonal cycle of the mean precipitation as well as the daily probability density functions and the daily precipitation intensity. In addition Fantini et al. (2016) show that this added-value is true at fine scale but also when upscaling the model outputs at coarse scales typically of GCM. Note, however, that Panthou et al. (2016) do not obtain added-value of 12 km models for the heavy precipitations. This discrepancy is probably due to the use of different reference datasets. Besides, the added-value concerning drought related indices (dry day frequency, dry spell length) is less clear as contradictory results are obtained in Fantini et al. (2016) and Panthou et al. (2016). Finally, Coppola et al. (2016) show that resolution plays a critical role in improving the model representation of snow-melt driven runoff.

The added-value of coupled RCSMs versus atmosphere stand-alone RCMs is also studied by various authors. The added-value of the air–sea coupling is more difficult to show because (1) the SST bias that can develop in RCSMs often hides the potential added value (Akhtar et al. 2017), (2) coupled/non-coupled differences over land are often limited to the coastal zone (Panthou et al. 2016) and (3) adequate reference datasets over the sea are often lacking. Dell'Aquila et al. (2016) and Flaounas et al. (2016) show that coupled and non-coupled RCMs have similar behaviours respectively for temperature and precipitation decadal variability over land and for Mediterranean cyclone climatology and intensity. Concerning medicanes however, Gaertner et al. (2016) show a realistic seasonal shift from autumn to winter in the RCSM ensemble despite no clear improvements in terms of intensity or frequency. Akhtar et al. (2017) illustrate that coupled model can improve their non-coupled counterpart for sea wind and related turbulent heat flux and that only their coupled high-resolution RCSM can reproduce the observed net outgoing total heat flux over the Mediterranean Sea.

Besides, the special issue studies also confirm that the performance of the Med-CORDEX and Euro-CORDEX ensembles are of similar quality (Dell'Aquila et al. 2016; Fantini et al. 2016; Gaertner et al. 2016) and that the Med-CORDEX evaluation simulations only show limited improvements with respect to the ENSEMBLES project simulations (Dell'Aquila et al. 2016).

5 Processes and phenomena understanding

Besides model evaluation, Med-CORDEX regional climate models can also support studies oriented to better understand regional climate phenomena and in particular their climate variability. This is especially true for complex, fast, oceanic, extreme or coupled phenomena that are not well captured by observation-based datasets especially when looking for long and temporally homogeneous datasets.

Contrary to expectations, Flaounas et al. (2016) suggest, in a multi-model study, that high-frequency coupled ocean–atmosphere processes only play a weak role in shaping the climatology and intensity of Mediterranean cyclones. They also warn that cyclone characteristics detected in a model are strongly dependent on the detection algorithm used. Another warning concerning the study of cyclones using RCMs is given by Sanchez-Gomez and Somot (2016) who illustrate the strong impact of the regional climate model internal variability on the cyclone tracks at various spatio-temporal scales.

Regarding the quality of medicanes representation, Gaertner et al. (2016) suggest that the model physics (e.g. parameterizations) is probably more important than the spatial resolution or the high-frequency ocean–atmosphere coupling. They also conclude that the 12 km resolution is still probably too weak to capture the observed medicane intensity. Concerning the effects of air–sea coupling on the medicanes, they show that the ocean mixed layer depth is a key factor in some cases. Concerning numerical experiment setting to study medicanes, Gaertner et al. (2016) also warn that, generally, medicanes do not occur with the right timing in RCMs or RCSMs, therefore limiting the study of specific cases with these tools.

Berthou et al. (2016b) confirm with two model pairs the results obtained in Berthou et al. (2016a) concerning the influence of sub-monthly SST variations on Mediterranean heavy precipitation events in particular in situations where a Mistral wind event precedes a heavy precipitation event in the Valencia region. Similarly to Gaertner et al. (2016) but for extreme precipitations, Cavicchia et al. (2016) obtain that the model physics and in particular the convective parameterization is more important for their representation in models than the spatial resolution or the air–sea coupling. The key role of the physical parameterizations is also underlined by Fantini et al. (2016) concerning the model representation of the number of dry days.

Comparing Med-CORDEX RCM and NWP (numerical weather prediction) models with or without explicit convection for an HyMeX heavy precipitation case study, Khodayar et al. (2016) show that RCMs are able to capture the occurrence and location of the events if the large-scale conditions are well imposed. RCMs however produce too wide, too long-lasting and too weak events with respect to the convection-permitting NWP models. High-intensity short-duration convective events are not well reproduced by RCMs. The authors suggest that main drawbacks of the RCMs is not the representation of the mean moisture or of the CAPE (Convective Available Potential Energy) but rather in the vertical distribution of moisture and in the triggering of deep convection.

Drobinski et al. (2017) show that a standard RCM at 20 km resolution is able to reproduce the intensity, direction and inland penetration of the sea breeze in the north-western Mediterranean Sea. The authors suggest that high-frequency air–sea coupled effects and the related SST anomalies are only weakly influencing this phenomena. They also use the RCM to determine the inland limit of the SST anomaly effect on the sea breeze.

Concerning the ocean component, Llasses et al. (2016) show, in a multi-model study, that heat and salt transfers between the surface and intermediate water layers are upwards in the Western basin and downwards in the Eastern basin. They are also stronger in winter than in summer. Heat and salt transfers to the deeper layers strongly depend on the model. Initial model stratification, model resolution and data assimilation in ocean stand-alone RCMs seem to be the explaining factors of the model differences.

Somot et al. (2016) show that a state-of-the-art RCSM is able to simulate accurately the spatial and temporal climate variability of the deep water formation phenomena in the north-western Mediterranean Sea. They explore the atmospheric and oceanic factors explaining the interannual variability of the phenomena as well as its observed long-term trend. On the contrary, Dunić et al. (2016) find that a state-of-the-art Ocean RCM shows large deficiencies in reproducing the deep water formation in the Adriatic Sea as well as the bimodal oscillation in the Ionian Sea (the so called BiOS phenomenon). This currently limits the possibility to use such a model to help understanding the ocean variability of the Central Mediterranean Sea.

6 Future regional climate change projections for the Mediterranean

Models are the only tools allowing to foreseen the possible evolution of regional climates and associated phenomena. Currently, studies focusing on future climate projections are still rare in Med-CORDEX but their number will probably increase in coming years. In the special issue, Coppola et al. (2016) investigate the response to climate change of snow-melt driven runoff over the Alpine region in a multi-model framework. They conclude that the snow-melt driven run-off could be anticipated by 1–3 months with respect to the present-day situation.

Also in a multi-model framework, Drobinski et al. (2016a) study how the *hook shape* scaling of precipitation extremes with temperature is changing in future projections over the Mediterranean basin. They show that, in the projections, the hook shifts towards higher temperature implying more intense precipitation extremes in the future.

7 Conclusion and current challenges

This special issue shows the broad range of advances made in the regional climate modelling of the Mediterranean climate and Mediterranean Sea. In particular it illustrates major advances in (1) developing new reference datasets for assessing high-resolution and coupled regional climate models, (2) evaluating this new generation of climate models, (3) demonstrating the added-value of such numerical tools, (4) using them to improve our understanding of key regional climate and oceanic phenomena and finally (5) projecting their likely future evolution. Despite the advances described in this special issue and other Med-CORDEX related articles, many more studies are expected using the large amount of simulations currently available in Med-CORDEX and specifically in the Med-CORDEX database (http://www.medcordex.eu).

In addition, we would like to underline that the Mediterranean regional climate modelling community is still facing big challenges. For example, the RCSMs are still under-used within the climate science community with a clear preference for GCMs for example in IPCC reports but also for Ocean stand-alone and Atmosphere stand-alone RCMs.

This is probably due to three main weaknesses: (1) the complexity to set-up, maintain, share and improve such a complex modelling tools, (2) the small number of multi-model studies using RCSM-based future projections probably due to the still limited number of available simulations and (3) the lack of clear proofs of the added-value of coupled tools to represent climate over land. In future climate change projections however, Somot et al. (2008) showed that a coupled AORCM can significantly modify the SST climate change signal of its driving GCM with implications for the climate change signal over sea and over land. This result, if confirmed in a multi-model framework, may change the paradigm of regional climate modelling.

Concerning RCSM future developments, we believe that key challenges should be addressed in the coming years:

- increase the spatial resolution of the models to reach convection-permitting resolution for the atmosphere and eddy-resolving resolution for the sea,
- add new components in the regional climate system models following recent works for the marine biogeochemistry (Sein et al. 2015), ocean waves, interactive vegetation, natural aerosols (Nabat et al. 2015), lakes or aquifers (Voldoire et al. 2017),
- improve continuously the physics of the individual components of the RCSMs and of their interfaces as increased resolution and complexity is not the only path towards improvement,
- add the human component within the system through the anthropogenic aerosols, the water reservoirs (dams), the land and water use (irrigation) or the cities to finally reach the status of Regional Earth System Models (RESM),
- sustain the improvement of the model quality and the large diversity of the current RCSM ensemble,
- develop space and time higher-resolution reference dataset to improve the model evaluation, also targeting the evaluation of the interfaces between the components and the evaluation of the coupled phenomena,
- make model outputs and expertise easily accessible outside the modelling community using standardized file formats, open forum, user-friendly databases and easy-to-handle RCSMs.

Those challenges are at the heart of the second phase of Med-CORDEX. This Phase 2 is based on five main scientific pillars. Those scientific pillars are completed by the will to enhance interactions with the climate data users and the stakeholders through contributions to the ESGF network, the coming IPCC assessments and the regional MedECC reports. Shortly the five pillars can be described as:

- The Med-CORDEX baseline runs, which are targeting to increase the coordination, the standardization and the number of available evaluation and scenario simulations using improved RCSMs dedicated to the Mediterranean climate and sea study,
- The joint Med-CORDEX/Euro-CORDEX Flagship Pilot Study on convection (FPS-convection), targeting to improve knowledge on phenomena related to atmospheric convective activity, using in particular convection-permitting regional climate models (CPRCM). This FPS also targets to improve convection parameterizations in climate models and to explore the possibility to mimic complex CPRCM by model emulators,
- The Med-CORDEX Flagship Pilot Study on air–sea interactions (FPS-airsea), targeting to understand how improved sea representation and air–sea interaction representation may influence the regional climate under past, present and future conditions. This FPS also targets to improve the physical schemes coupling the planetary boundary layer and the ocean mixed layer in order to help improving global GCM and ESM,
- The Med-CORDEX Flagship Pilot Study on aerosol–climate interactions (FPS-aerosol), targeting to characterize the past and future aerosol spatio-temporal variability within the region and to understand the role of regionally-born aerosols on the regional climate at multiple scale,
- The so-called Med-CORDEX Free Modelling Zone (FMZ), targeting to assess the modelling protocols of the four above-mentioned actions by testing new ideas and preparing the next phases of Med-CORDEX.

Solving the above-listed current limitations and achieving the new goals of the Med-CORDEX Phase 2, will likely improve our understanding of the Mediterranean climate and related phenomena, allow to better quantify their past variability and trends, to develop more robust estimates of their future evolution and to establish the regional impacts of climate change including, in particular, for the first time marine ecosystems and maritime activities to finally hope to foster climate-aware adaptation measures.

Acknowledgements We acknowledge that the Med-CORDEX initiative (http://www.medcordex.eu) would have not been possible without the initial support by the MISTRALS/HyMeX programme and by CORDEX. It is currently endorsed and financially supported by many funding agencies, international organisations and institutions, in particular WCRP CORDEX programme, the French MISTRALS programme and the Med-CLIVAR network. A special thank to Paolo Ruti and Filippo Giorgi for their contributions to the birth of Med-CORDEX, to Emanuele Lombardi from ENEA for his long-term and efficient work for setting and running the web site and the database (http://www.medcordex.eu). We would like to thank also S. Corti as contact editor for this special issue, the *Climate Dynamics* editorial staff as well as all the anonymous reviewers that have contributed to the scientific quality of the articles and the completion of this special issue.

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