Black Sea atmospheric surface forcing function data

Deliverable Nr. 4.2

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CONTENTS

EXECUTIVE SUMMARY / ABSTRACT

The aim of this work is to provide the atmospheric forcing functions for the Black Sea area using the regional climate model (RCM) COSMO-CLM.

Two numerical simulations have been carried out:

- a preliminary simulation driven by ERA40 reanalysis data to assess the model performance using the so-called “perfect” boundary conditions;
- a simulation driven by the global coupled model CMCC-CM, whose atmospheric component is ECHAM5, considering scenario conditions.

The chosen emission scenario is RCP4.5 (Meinshausen et al., 2011). RCPs (Representative Concentration Pathways) specify the expected radiative forcing over the 21st century. In particular, RCP4.5 is a stabilization scenario in which the total radiative forcing is stabilized at 4.5 W/m^2 at 2100. It is important to note that the forcing data used for the Black Sea area are different from those used for the Mediterranean Sea (Deliverable 4.1), in which the considered emission scenario is RCP8.5. However, both scenarios are roughly similar for the period considered in PERSEUS (up to 2020).

The spatial resolution of simulations is 14 km, in order to provide a detailed description of the climate variability on local scale. The ERA40 driven simulation covers the period 1971-2000, and is used to validate the model output over a past period. The CMCC-CM driven simulation, instead, covers the period 1971-2020.

SCOPE

Climate changes have a strong impact on ecosystem health, particularly in semi-enclosed seas such as the Mediterranean and Black Seas (Southern European Seas - SES). Because of their semi-enclosed nature, as well as their smaller thermal inertia compared to large oceans, these seas are more sensitive to variations in atmosphere-ocean interactions.

Climate variability has been identified as one of the dominant factors in triggering some hazards (such as warming of water in seas and its subsequent impact on ecosystem functioning) and generally it contributes to amplify the vulnerability of SES basins to these risks. Due to increased demography and climate change, biodiversity of Mediterranean and Black Seas is declining at an alarming rate. The concern is to understand how the coupled land-ocean and atmosphere-ocean ecosystems will react to these changes. Thus, the need to develop specific adaptation policies to protect and preserve the marine environment is of utmost importance.

It is uncertain how projected climate change will cause further modifications within the marine ecosystem, breaking existing food chains and modifying ecological balances and ocean productivity.

The first step to understand the observed changes in Mediterranean and Black Sea ecosystems is the evaluation of the environmental status of these basins, under current and scenario conditions.

The generation of climate scenarios at high spatial resolution is needed (Giorgi, 2006) to support impact studies and for studies on adaptation strategies to climate change.

The aim of this work is to provide the atmospheric forcing functions on Black Sea needed to evaluate surface boundary conditions for further modeling activities.

The tool used for this goal is the regional climate model (RCM) COSMO-CLM.

ATMOSPHERIC DATA FOR THE BLACK SEA BASIN

The regional climate model COSMO-CLM

At CMCC, the regional climate model COSMO-CLM (Rockel and Geyer, 2008) is currently used to perform climate simulations: it is the climate version of the COSMO LM model (Steppeler et al., 2003), which is the operational non-hydrostatic mesoscale weather forecast model developed initially by the German Weather Service and then by the European Consortium COSMO.

Successively, the model has been updated by the CLM-Community, in order to develop also a version for climate application (COSMO CLM). The development of COSMO CLM has been driven by two main reasons (Rockel et al., 2008): the first was the idea of developing one model able to simulate both weather and climate, and the second was the need of introducing a non-hydrostatic formulation, in order to have a convection resolving weather simulation. This is a very important topic, due to the difficulty in predicting the effects of this phenomenon, such as sudden high intensity rainfall. COSMO-CLM can be used with a spatial resolution between 1 and 50 km even if the non-hydrostatic formulation of the dynamical equations in LM made it eligible especially for the use at horizontal grid resolution lower than 20 km (Bohm et al. 2006). These values of resolution are usually close to the ones requested by the impact modellers; in fact, these resolutions allow describing the terrain orography better than the global models, where there is an over- and underestimation of valley and mountain heights, leading to errors in precipitation estimation, as this is closely related to terrain height. Moreover, the non-hydrostatic modelling provides a good description of the convective phenomena, which are generated by vertical movement (through transport and turbulent mixing) of the properties of the fluid as energy (heat), water vapour and momentum.

Convection can redistribute significant amounts of moisture, heat and mass on small temporal and spatial scales. Furthermore, convection can cause severe precipitation events (as thunderstorm or cluster of thunderstorms). Another advantage related to the usage of COSMO CLM, with respect to other climate regional models available, is that the continuous development of LM allows improvements in the code that are also adopted in the climate version, ensuring that the central code is continuously update.

The mathematical formulation of COSMO-CLM is made up of the Navier-Stokes equations for a compressible flow. The atmosphere is treated as a multicomponent fluid (made up of dry air, water vapour, liquid and solid water) for which the perfect gas equation holds, and subject to the gravity and to the Coriolis forces. The model includes several parameterizations, in order to keep into account, at least in a statistical manner, several phenomena that take place on unresolved scales, but that have significant effects on the meteorological interest scales (for example, interaction with the orography). The main features of the COSMO CLM simulation are:

- non-hydrostatic, full compressible hydro-thermodynamical equations in advection form;
- base state: hydrostatic, at rest;
- prognostic variables: horizontal and vertical Cartesian wind components, pressure perturbation, temperature, specific humidity, cloud water content. Optionally: cloud ice content, turbulent kinetic energy, specific water content of rain, snow and graupel;
- coordinate system: generalized terrain-following height coordinate with rotated geographical coordinates and user-defined grid stretching in the vertical direction. Options for (i) base-state pressure based height coordinate, (ii) Gal-Chen height coordinate and (iii) exponential height coordinate (SLEVE) according to Schar et al. (2002);
- grid structure - Arakawa C-grid, Lorenz vertical grid staggering;
- time integration: time splitting between fast and slow modes (Leapfrog, Runge-Kutta);
- spatial discretization: 2° order accurate Finite Difference technique;
- parallelization: Domain Decomposition (MPI as message passing S/W);
- parameterizations: Subgrid-Scale Turbulence; Surface Layer Parameterization; Grid-Scale Clouds and Precipitation; Subgrid-Scale Clouds; Moist Convection; Shallow Convection; Radiation; Soil Model; Terrain and Surface Data.

Simulation set-up

The main features of the two numerical simulations are briefly summarized. The preliminary simulation has been carried out with boundary conditions provided by the global reanalysis data ECMWF ERA40 (Uppala et al., 2006), characterized by a horizontal resolution of 1.125° (about 128 km). The horizontal resolution used for the regional simulation is 0.125° (about 14 km). The period considered for the validation analyses in the present work is 1971-2000, but the first year of the simulation (1971) was not considered to neglect the spin-up effects. The simulation under scenario conditions has been carried out with the same setup features but using boundary conditions provided by the global model CMCC-CM, whose atmospheric component is ECHAM5 (horizontal resolution of about 80 km). The period considered for this simulation is 1971-2020. In Table 1, the main features of the configurations are summarized.

Table 1. Main features of the COSMOCLM setup.

Driving data	ERA40 / CMCC-CM
Horizontal resolution	14 km
Num. of Grid points	385 x 265
Num. of vertical levels in the atm.	40
Num. of soil levels	7
Soil scheme	TERRA_ML
Time step	150 s
Melting processes	yes
Convection scheme	TIEDTKE
Frequency of radiation computation	1 hour
Time integration	Runge-Kutta (3rd ord.)
Frequency update boundary cond.	6 hours

The domain considered for the simulation is the Black Sea drainage basin (Figure 1).

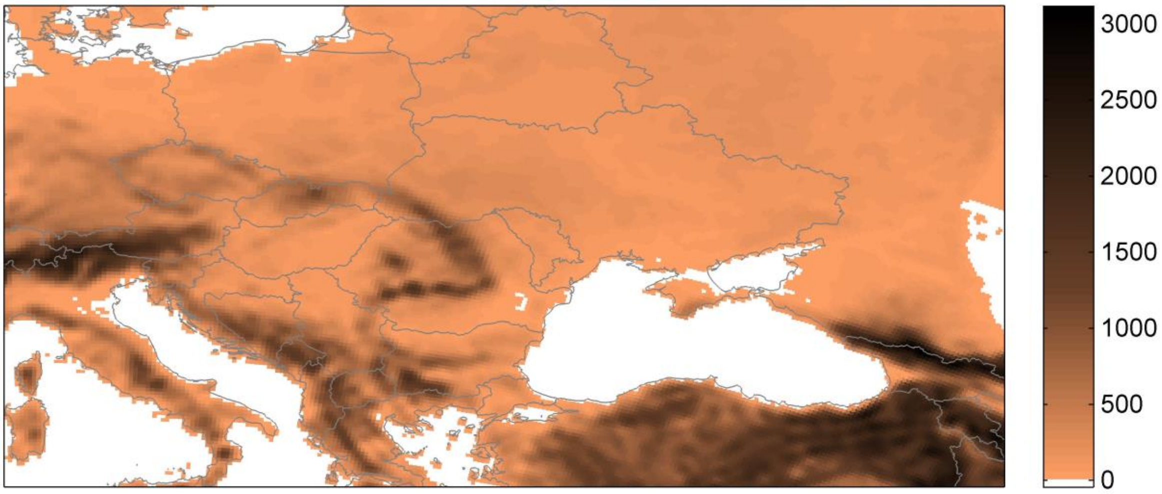

Figure 1. Topography of the simulated domain.

Table 2 contains the list of the main parameters provided by the COSMO-CLM model that will be distributed for the Black Sea basin for the period 1980-2020. The output of the model is provided with temporal resolution of 6 hours.

Table 2. Atmospheric forcing data available for the Black Sea region.

Meaning	Field	Units
Surface pressure	PS	Pa
Total precipitation (accumulated over 6 hours)	TOT_PREC	kg/m^2
Sensible heat flux (surface)	SHFL_S	W/m^2
Latent heat flux (surface)	LHFL_S	W/m^2
Relative humidity	RELHUM	%
Total cloud cover	CLCT	%
Zonal wind in 10m	U_10M	m/s
Meridional wind in 10m	V_10M	m/s
Temperature in 2m	T_2M	K
Dew-point temperature in 2m	TD_2M	K
Temperature of surface	T_S	K
Surface albedo (shortwave radiation)	ALB_RAD	%
Average solar radiation budget (surface)	ASOB_S	W/m^2
Average thermal radiation budget (surface)	ATHB_S	W/m^2
Accumulated flux of surface moisture	AEVAP_S	kg/m^2

Dataset organization

The atmospheric forcing data have a spatial resolution of 14 km and a daily temporal resolution.

Data are organized in files (one file for year); each file contains daily values.

The data are available at the CMCC supercomputing center, Italy. For data requests please contact Dr. Edoardo Bucchignani (e.bucchignani@cira.it).

COSMO-CLM validation

The evaluation of the accuracy of the simulation is performed considering the daily values of 2-metre mean temperature (T_2M) and total precipitation (TOT_PREC) for the past period 1972-2000.

The results of the simulation are compared with the last available version (v. 7.0) of EOBS observational dataset (Haylock et al., 2008). It is a European daily high-resolution (0.25° x 0.25°) gridded data set for precipitation, minimum, maximum, mean surface temperature and sea level pressure covering the period 1950-2011. This dataset has been designed to provide the best estimate of grid box averages rather than point values in order to enable direct comparison with RCM output.

The daily values of the variables of interest (spatially averaged over the whole domain) have been statistically analysed, calculating the Probability Density Functions (PDF).

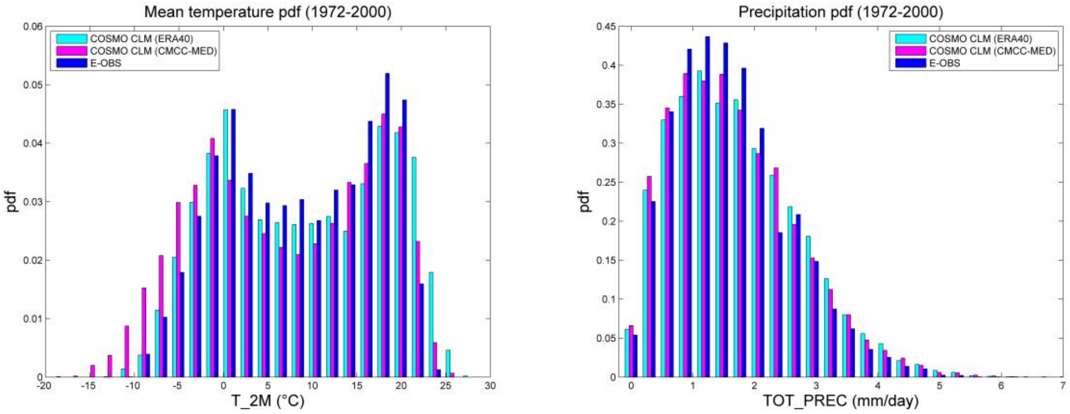

Figure 2. Empirical probability distribution functions for mean temperature (left) and total precipitation (right): COSMO-CLM output (cyan for ERA40 driven simulation and magenta for CMCC-CM driven one) and EOBS data (blue)

The analysis of the distribution functions (Figure 2) shows a quite good agreement between data obtained with COSMO-CLM model and EOBS observations.

The bimodal distribution of temperature is well captured; the main difference between simulated data and observations is in the left tail of distribution, indeed both the simulations intensify extreme values of minimum temperatures.

Concerning the precipitation, instead, PDFs of the simulated data, with respect to the observations, have a lower probability for central values and a more gradual decay of the tails of the distribution.

The seasonal cycle of T_2M and TOT_PREC have also been calculated (Figure 3). Concerning the temperature, the seasonal cycle is well captured by the model in both the simulations. With regard to the total precipitation, instead, the seasonal cycle of COSMO-CLM is quite different from the observed one. The analysis of seasonal maps of the bias of precipitation of the two simulations with respect to EOBS data (Figure 6 and Figure 7) allows to a better understanding of this result. This figure shows a general tendency to an overestimation of precipitation in winter and spring and an underestimation in summer and autumn (except for the Alpine region and on higher mountains). The south-east Black Sea area is characterized by the highest bias, however in this area EOBS is less reliable because the number of stations used to produce the gridded dataset is rather low (see Figure 4).

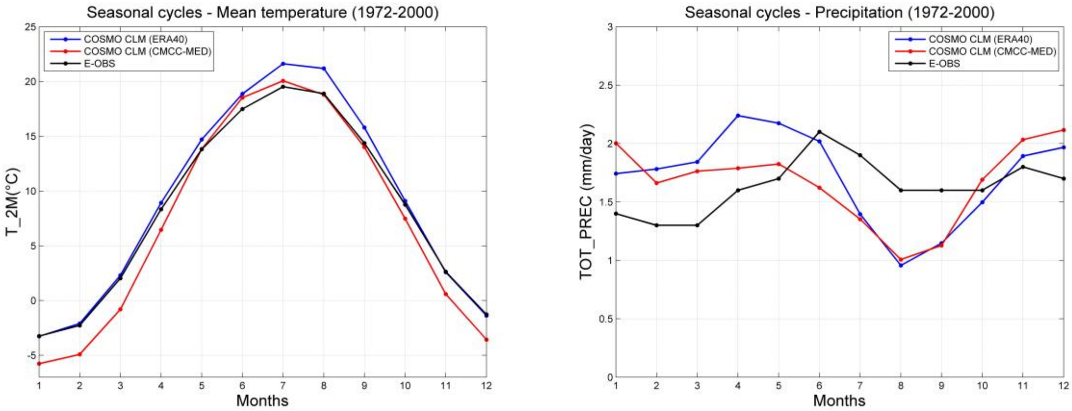

Figure 3. Seasonal cycle of mean temperature (left) and total precipitation (right): COSMO-CLM output (blue for ERA40 driven simulation and red for CMCC-CM driven one) and EOBS data (black)

Finally, the annual time series of T_2M and TOT_PREC, averaged over the entire domain, have been calculated (Figure 5). All the three datasets are characterized by a rising trend in temperatures.

The trend of the annual time series of precipitation, instead, does not highlight significant changes in the total precipitation expected in the near future.

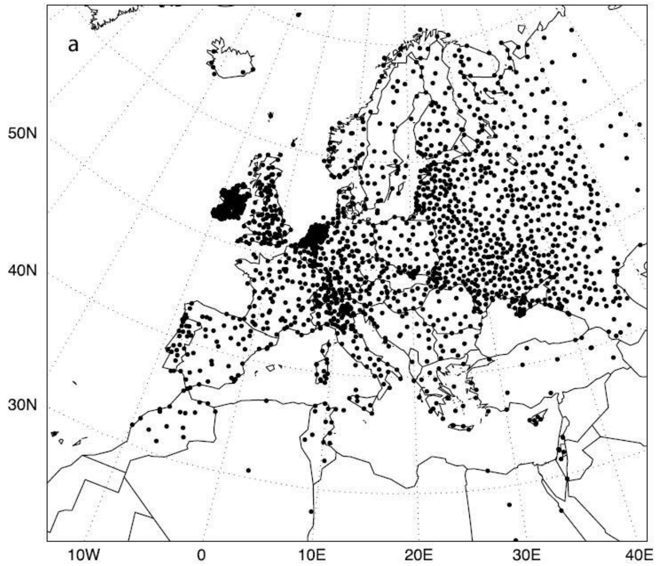

Figure 4. Precipitation station network of the EOBS dataset.

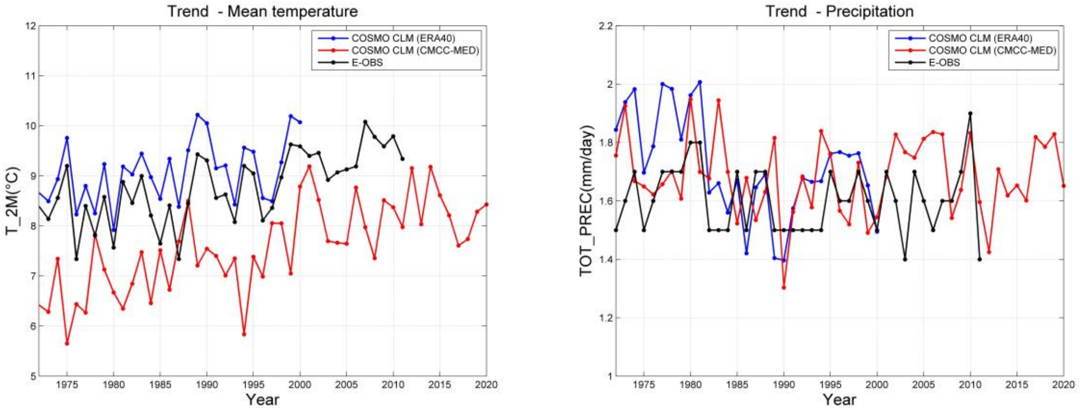

Figure 5. Annual time series of mean temperature (left) and total precipitation (right): ERA40 driven simulation (blue), CMCC-CM driven simulation (red) and EOBS (black)

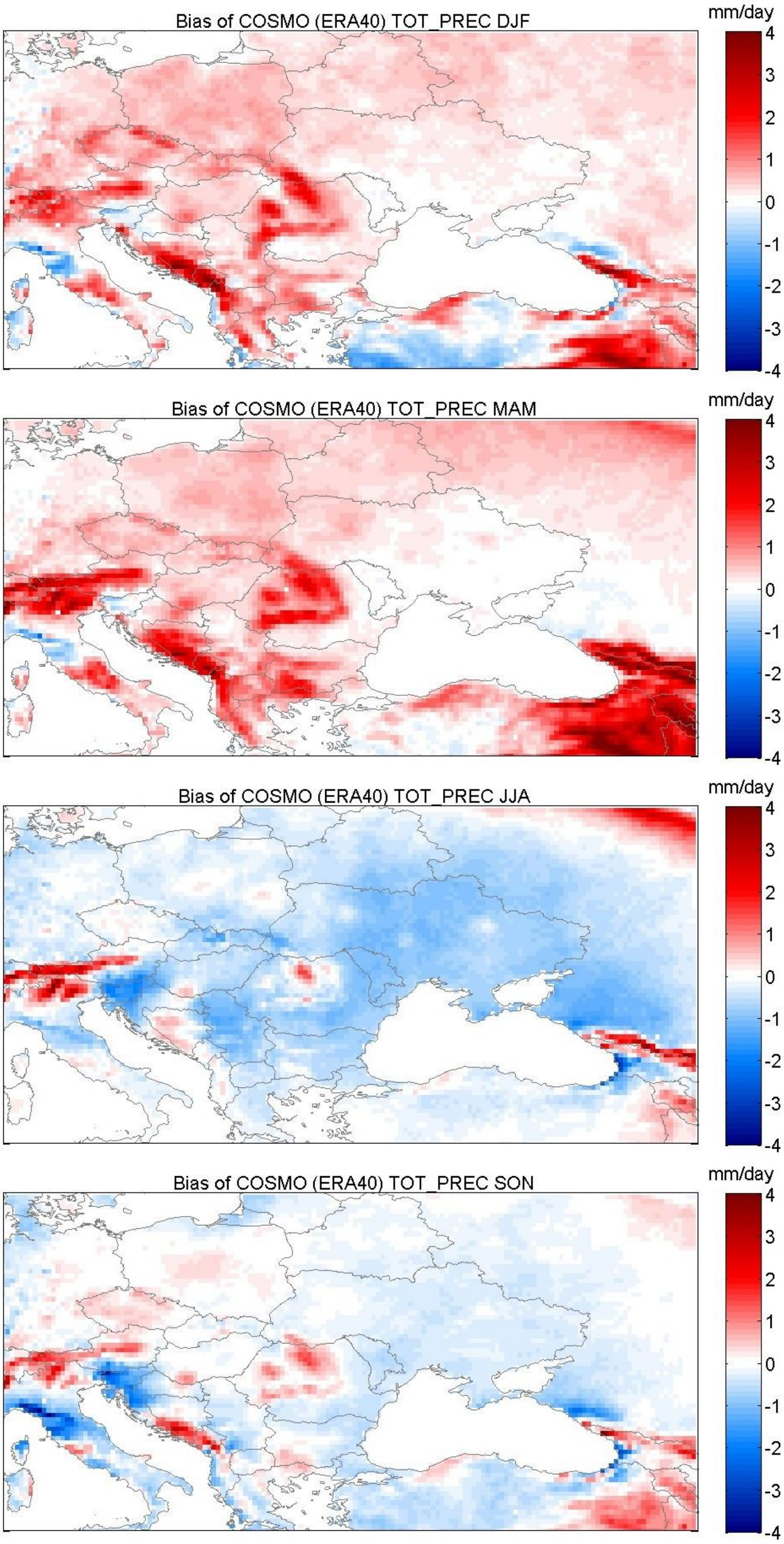

Figure 6. Bias of total precipitation of ERA40 driven simulation with respect to EOBS dataset for (top to bottom) winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

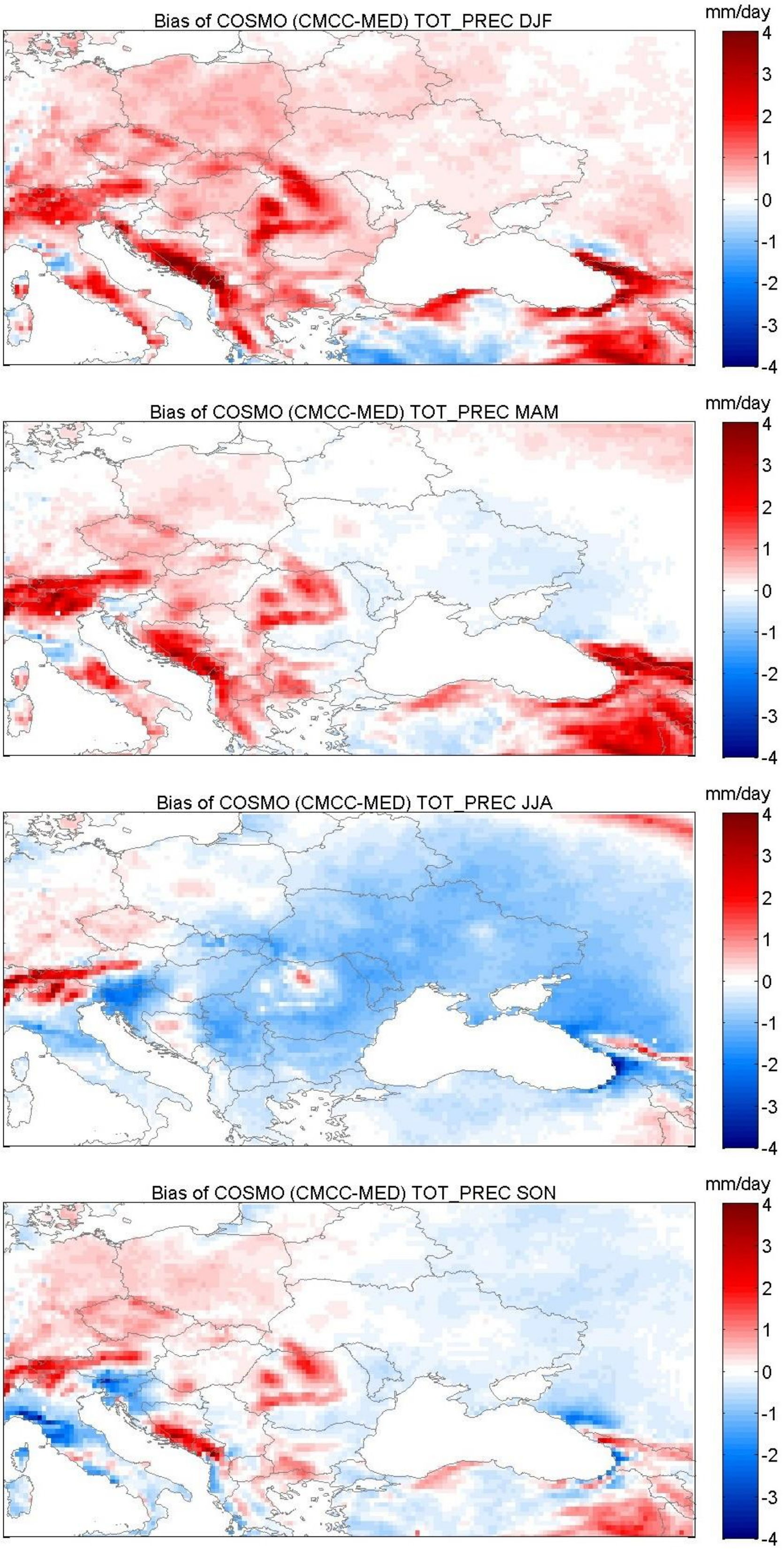

Figure 7. Bias of total precipitation of CMCC-CM driven simulation with respect to EOBS dataset for (top to bottom) winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

CONCLUSIONS

The analysis presented in this document shows a quite good capacity of the Regional Climate Model COSMO-CLM in simulating the main features of the observed climate over the wide area of the Black Sea drainage basin. The seasonal cycle of temperature is well captured, while the precipitation is characterized by an overestimation in the first part of the year and an underestimation in the second part.

The simulation driven by CMCC CM (RCP4.5 scenario) provides the atmospheric forcing functions needed, such as surface boundary conditions for further modeling activities over Southern European Sea basin.

The atmospheric forcing data for the period 1980-2020 are available at CMCC.

Appendix

A.1 Bias correction of atmospheric boundary conditions

As described in the Summary, the present deliverable focuses on the current and future atmospheric boundary conditions for further modeling activities in the framework of PERSEUS project.

The atmospheric fields made available for the modeling activities within PERSEUS were produced by the high-resolution coupled atmospheric and oceanic general circulation model CMCC-CM (Scoccimarro et al., 2011). In particular, the future climate variability of the CMCC-CM simulations account for both RCP4.5 and RCP8.5 scenarios (details in Moss et al., 2010).

An error analysis of the CMCC-CM atmospheric data was performed against the ERA-Interim reanalyses fields (Dee et al., 2011) to assess the presence of systematic errors. In fact, a known limitation of the global atmospheric and oceanic general circulation models (AOGCM) is the occurrence of strong biases when focusing on specific regional domains (see Berg et al., 2012; Cattiaux et al., 2013; Lafon et al., 2013).

The overall comparison of the monthly climatologies computed for two dataset over the period 1980-2010 indicates that remarkable differences affect the air and dew point temperature fields of the Southern European Seas area (see Figure A.1.1). So, in order to reduce the spatiotemporal biases of the air temperature data, a correction technique was selected to adjust the CMCC-CM data or the atmospheric fields produced by regional climate models, which make use of this dataset (e.g., COSMO CLM).

The monthly bias correction of the temperature fields was achieved through the linear scaling approach (see, e.g., Teutschbein and Seibert 2012). It consists in subtracting a corrective factor, calculated as the difference between simulated and observed monthly mean temperature, to the model data. The corrected temperature values are obtained as follows:

$$T_{corr}^{m}(d) = T_{sim}^{m}(d) - \left(\overline{T}_{sim}^{m} - \overline{T}_{obs}^{m}\right) \tag{A.1}$$

where, for the day d of the month m, $T_{corr}^{m}(d)$ is the corrected value, $T_{sim}^{m}(d)$ is the originally simulated daily temperature, $\overline{T}_{obs}^{m}$ and $\overline{T}_{sim}^{m}$ are respectively the observed and simulated monthly mean temperature, averaged over a reference period, for the month m. The procedure has to be performed on each grid node of the original atmospheric fields.

A description of the estimated biases and the validation of the corrected fields are given in section A.3.

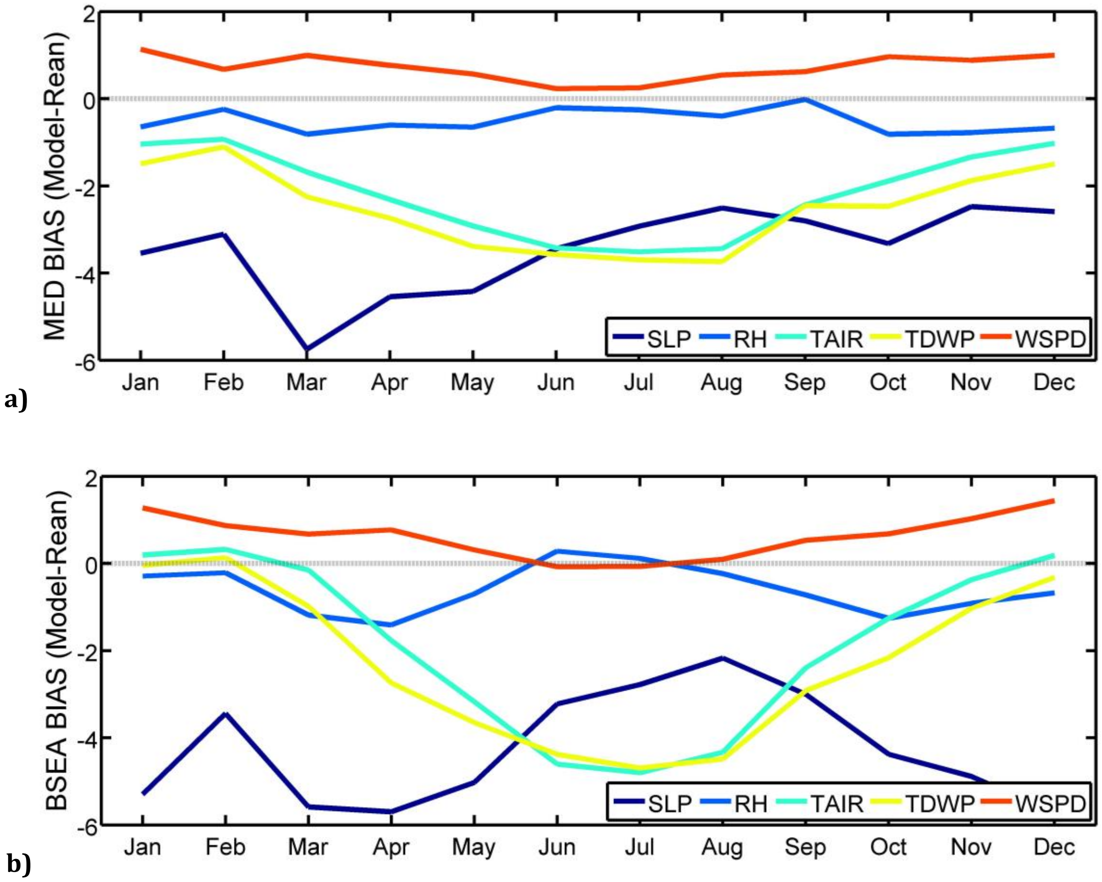

Figure A.1.1. Time series of the difference between the CMCC-CM and ERA-Interim monthly climatologies over the Mediterranean Sea (a) and the Black Sea (b) for the period 1979-2010. Variables in the plot: SLP - sea level pressure (hPa); RH – relative humidity (%); TAIR – Air temperature at 2 m (°C); TDWP – Dew Point temperature at 2m (°C); WSPD – Wind speed module (m/s). Positive values indicate an overestimation of the CMCC-CM data with respect to ERA-Interim Reanalyses.

A.2 How to apply the correction fields

The monthly correction fields are provided in a separate file, as they represent an *a posteriori* revision of the originally data made available to all PERSEUS partners.

Partners are strongly suggested to use the available correction fields that are distributed in a single NetCDF file.

The file contains a 12 months climatology of the biases computed at each grid node of the climate model for the reference period 1980-2011. In agreement with the methodology illustrated in section A.1, the bias represents a systematic error of the climate model and, thus, the correction has to be applied to the air temperature fields produced by the COSMO-CLM model for both current climate and scenario data.

Partners should apply the correction field by subtracting the monthly air temperature bias from the fields of the respective month for all the user-selected years of the original dataset. For example, in order to correct the data of the air temperature at 2m (T_2M) for a specific month, the following CDO commands (www.mpimet.mpg.de/fileadmin/software/cdo) can be used:

```
cdo -monsub \
     -selname, T_2M -selmon,mm Data_yyyymm.nc \
     -setdate,yyyy-mm-01 -selname, T_2M -selmon,mm  biasfile.nc \
     yyyymm _out.nc
```

where *mm* is the month, *yyyy* the year, -monsub is the subtraction operator from monthly values, -selname is used to select a specific variable, -selmon allows to select a specific month as a number, -setdate reset the time to a specific value. *Data_yyyymm.nc* contains the daily simulated data, *biasfile.nc* contains the correction monthly fields, and *out.nc* contains the corrected fields for the user-selected variable.

Note that, the bias correction of the present deliverable addresses only to the air temperature fields, but it can be extended also to the dew point air temperature through the methodology described in the Appendix of Deliverable 4.1 for the Mediterranean Sea.

A.3 Estimation and validation of the correction fields

The tool used in the PERSEUS project to investigate the climate variability of the Black Sea is the regional climate model (RCM) COSMO CLM.

The validation of the COSMO CLM simulation driven by the global model CMCC-CM has shown a significant cold bias in 2-meter temperature, an important driver for ocean models. This bias, therefore, is a limit to use the data as input for further models, because it could alter their dynamics. Indeed several studies demonstrated that the direct use of RCM outputs as input for impact models is not recommended, due to their systematic error (Berg et al. 2012, Lafon et al. 2013). So, in order to reduce bias in climate data, the linear scaling procedure for the bias correction was used (see section A.1).

This method requires a high quality observational dataset over a sufficiently long period, in order to calculate the observed mean temperature, crucial in determining the corrective factor. Unfortunately, over the Black Sea (the area of major interest for further modeling activities) high-resolution observational datasets are not available; the only available data are the ERA-Interim reanalysis (Dee et al., 2011), obtained assimilating historical observational records. ERA-Interim is the latest global atmospheric reanalysis produced by the ECMWF (European Centre for Medium-Range Weather Forecasts) and is characterized by a horizontal resolution of about 0.703° (~ 79 km). The considered calibration period is 1980-2011. Since ERA-Interim data have a coarser resolution than the COSMO CLM simulation, they need to be remapped on the COSMO CLM grid (0.125° - about 14 km). Based on observed and simulated air temperature values, the corrective field $\left(\overline{T}_{sim}^{m} - \overline{T}_{obs}^{m}\right)$, for each grid point and for each month, has been calculated.

The corrected air temperature field has been validated using the E-OBS observational dataset (Haylock et al., 2008), which is a land-only dataset, independent from that used for calibration.

Figure A.3.1 shows the comparison results in terms of seasonal mean bias for both original and corrected simulation. The original simulation has a significant cold bias, fairly evenly distributed on the entire domain, in almost all seasons, except in summer, when a warm bias occurs in the western part of the domain. Considering the corrected temperature field, this strong cold bias, is removed. However, these corrected data shows a pronounced warm bias over the mountainous chains that fall within the analyzed domain. This problem is sostantially due to the coarse resolution of ERA-Interim data, used to perform the correction, much lower than COSMO CLM resolution. Figure A.3.2 shows a comparison between the orography of COSMO (0.125°) and the orography of ERA-Interim, both the original one (~0.703°) and the remapped one (on the COSMO grid). The difference between the two orographies (Figure A.3.2 (d)) is quite high, especially in correspondence of the mountainous chains, where it reaches peaks higher than 1400 m. This difference lies in the issue that higher elevations are not resolved at the coarse resolution of ERA-Interim (~ 0.7°). Naturally this problem also influences the corresponding temperature field, that has higher values, as they are associated with lower altitudes. Despite this problem, in terms of average temperature over the domain, the corrected version of the RCM data shows good performances.

It is worth noting that PERSEUS partner will use this data as forcings for the ocean model over the Black Sea, so it is important to analyze the effects of bias correction also over the sea. Unfotunately, over the Black Sea the only available data are the ERA-Interim reanalysis, i.e. the same dataset used for the calibration. Figure A.3.3 shows a zoom over the Black Sea of the seasonal mean bias for both the original and corrected simulation with respect to ERA-Interim. The first column of Figure A.3.3 shows that in all the seasons the temperature over the Black Sea is underestimated, and this cold bias of course could influence the ocean model dynamics, when this data are used as forcing. The considered bias correction procedure leads to a significant reduction of this error (second column of Figure A.3.3). It is worth noting the the colorbar ranges of the two sets of plots in Figure A.3.3 are very different each other: the bias of the corrected model is almost null with respect to the ERA-Interim dataset.

The atmospheric dataset represents a crucial element in the definition of surface boundary conditions for ocean modeling activities; however, the RCM output cannot be directly used to this aim, due to their systematic bias. The proposed bias correction technique allows to better represent the simulated 2-meter temperature, reducing the significant cold bias affecting the RCM output.

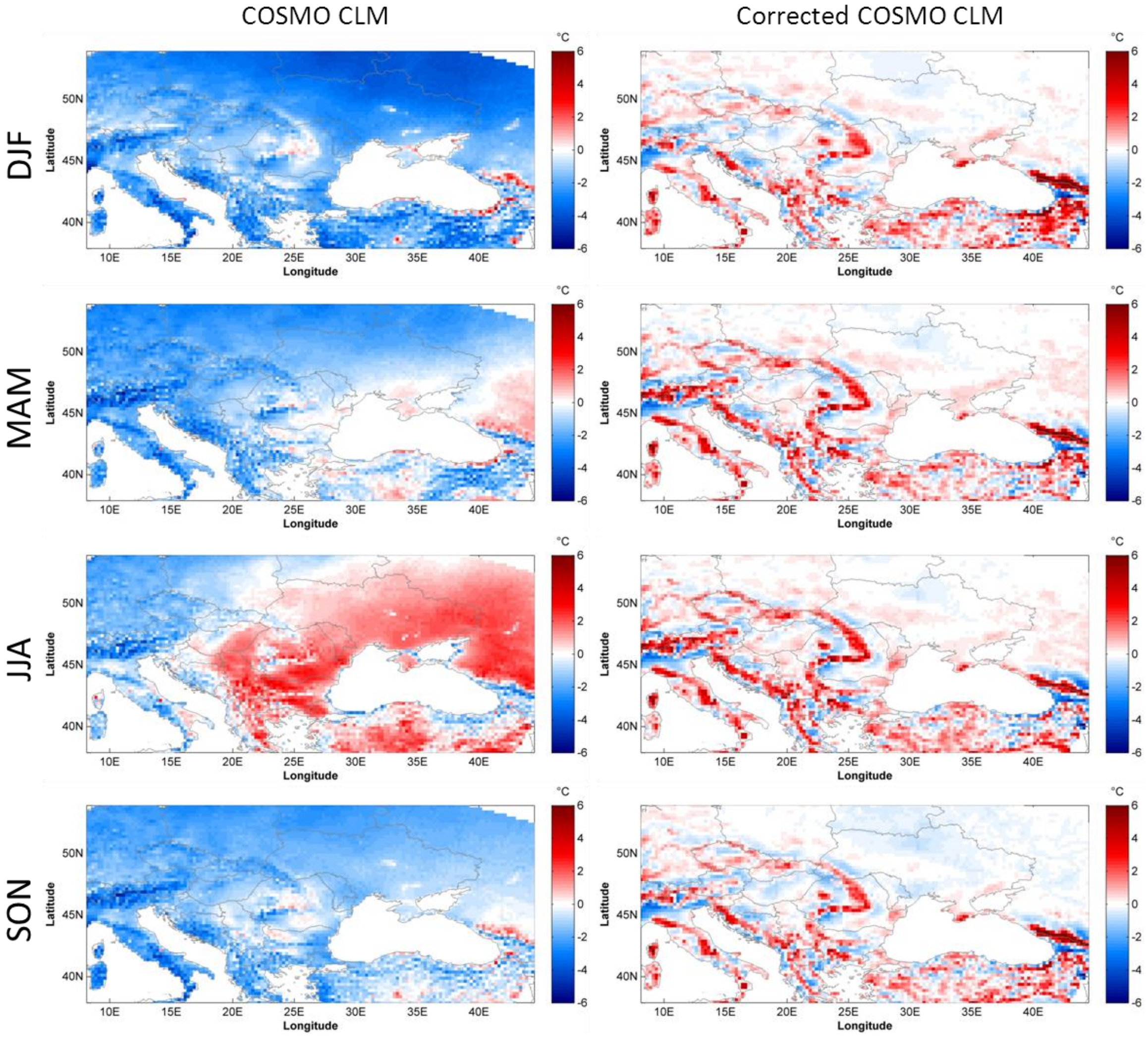

Figure A.3.1 Bias of 2-meter temperature of original (first column) and corrected (second column) COSMO CLM simulation (over the period 1980-2011) with respect to EOBS dataset for (top to bottom) winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

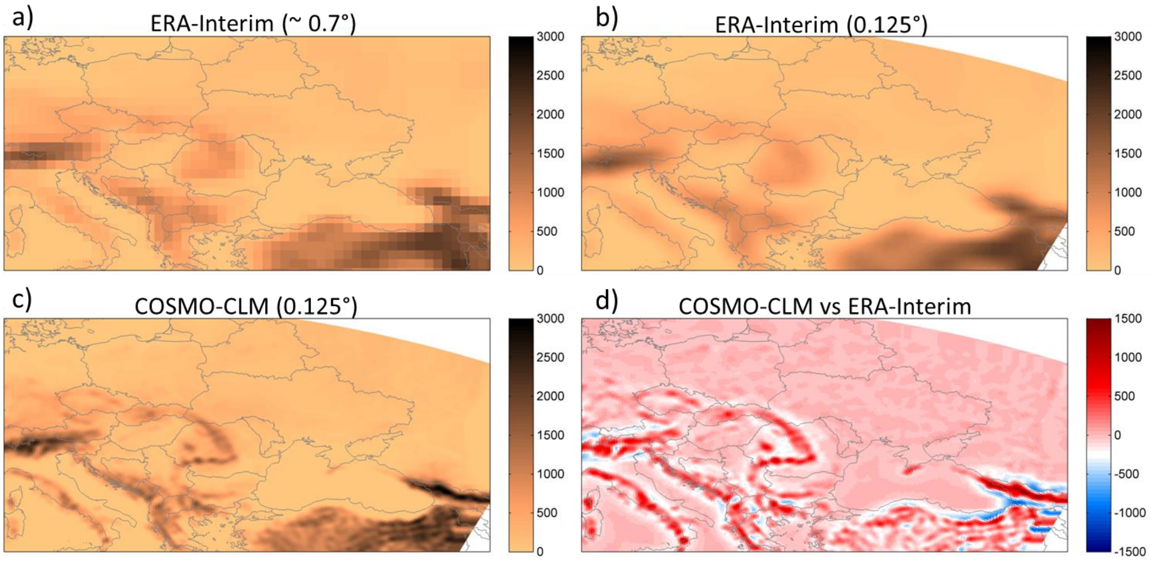

Figure A.3.2 Comparison between the orography of ERA-Interim, both the original one (a) and the remapped one (b), and the orography of COSMO CLM model (c). (d) shows the difference between the two orographies at 0.125°.

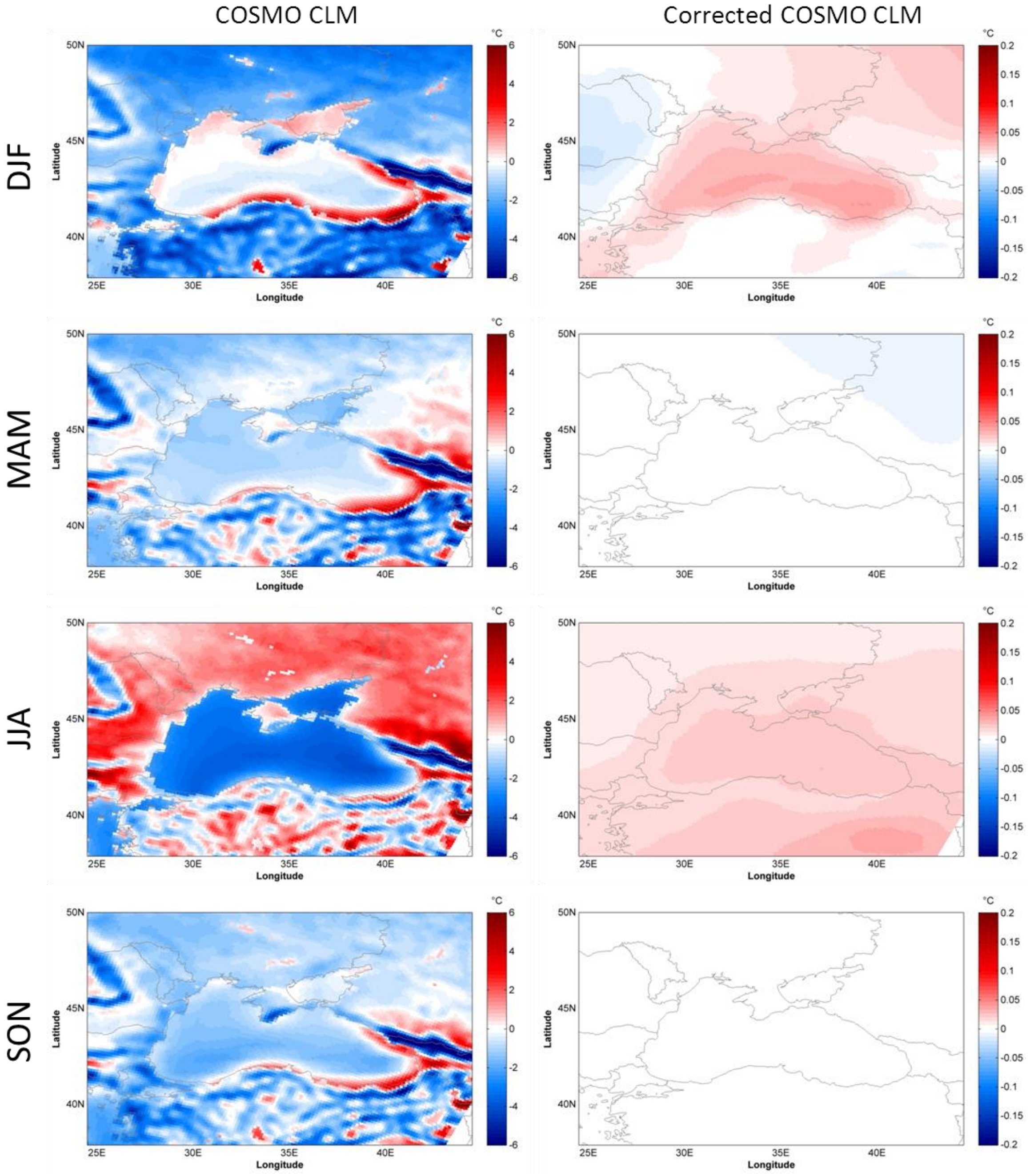

Figure A.3.3 Zoom over the Black Sea of the bias of 2-meter temperature of original (first column) and corrected (second column) COSMO CLM simulation (over the period 1980-2011) with respect to ERA-Interim dataset for (top to bottom) winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

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