Performance evaluation of high temporal and spatial resolution regional climate simulations for CLIMAERA Project

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Introduction

This report documents the assessment of results of climate data provided in the framework of the ALCOTRA 2014-2020 CLIMAERA Project. It contains a technical and scientific documentation about the high-resolution regional climate simulations with the COSMO-CLM model (CCLM), the evaluation of climate data with respect to the available observational datasets and with respect to other similar state of the art simulated data.

The Regional Climate Simulations and the Observations

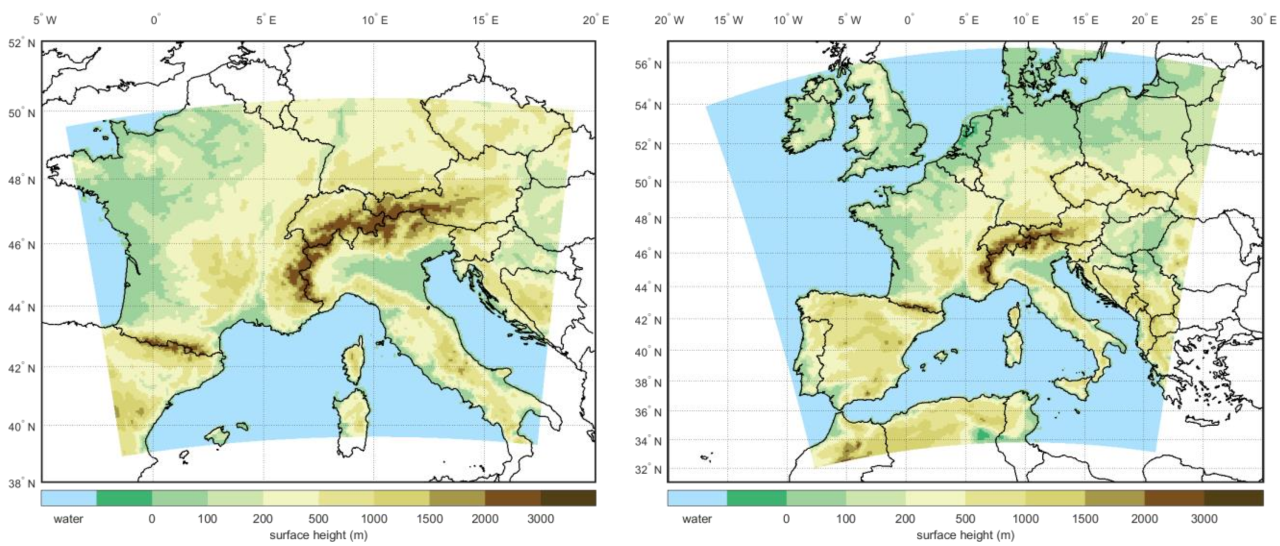
COSMO-CLM (Rockel et al., 2008) is the climate version of the operational, non-hydrostatic mesoscale weather forecast model COSMO-LM (Steppeler et al., 2003; Doms et al., 2002), developed initially by the German Weather Service (Deutscher Wetterdienst) and currently by the European COSMO consortium. The CCLM instead is develop also by CMCC within the European Consortium CLM Assembly.

Simulation setup

In the frame of CLIMAERA Project, two simulation setups with the regional climate model (RCM) CCLM have been designed:

1. The first configuration considers the ALCOTRA-CLIMAERA domain, Figure 1a, at the horizontal resolution of 0.0715° (about 8 km).
2. The second one considers the EUROPEAN domain, Figure 1b, at the horizontal resolution of 0.125° (about 14 km).

The main features of simulation setups and model version of RCM are summarized in Table 1.



(a) (b)

Figure 1.Orography of the computational domains respectively named (a) ALCOTRA-CLIMAERA and (b) EUROPEAN.

	EXPERIMENTS	
	ALCOTRA-CLIMAERA	EUROPEAN
COSMO-CLM model version	5.00 clm9	5.00 clm9
INT2LM model version	2.04	2.04
Horizontal resolution	0.0715°	0.125°
Time step	40 s	100 s
Number of vertical levels	46	41
Number of soil levels	7	7

Table 1. Main Features of COSMO-CLM Model Formulation and COSMO-CLM Simulation Setup

For both configurations, three experiments have been carried out, with initial and boundary conditions provided by the General Circulation Model (GCM) EC-EARTH, under the scenario IPCC RCP4.5:

- Historical experiment, over the period 2010-2015, one year spin-up (2010);
- Near Future Scenario, over the period 2027-2032, one year spin-up (2027);
- Medium Future Scenario, over the period 2047-2052, one year spin-up (2047).

The observations

The COSMO-CLM simulations have been validated using gridded datasets:

- The E-OBS dataset (Haylock et al., 2008) has been adopted to evaluate the model response in terms of 2m temperature and precipitation. It is a European daily gridded dataset (resolution 0.25°, about 28 km).
- NWIOI dataset (Ronchi et al. 2008; AAVV, 2011) provided by ARPA Piemonte. It is a gridded dataset for daily maximum and minimum air temperature and precipitation.
-

Observational dataset	Resolution	Period
NWIOI v2.1	0.125° x 0.125° (~14 km)	1957 - 2018
E-OBS v 17.0	0.25° x 0.25° (~28 km)	1950 – 2017

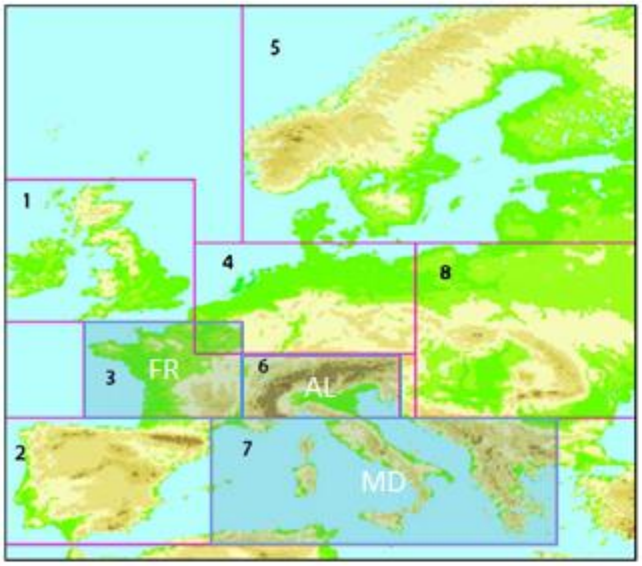
Table 2. Information about the observational data

Analysis of results

In this section, the validation of historical simulations in terms of air temperature and total precipitation is shown, considering E-OBS and NWIOI datasets as observations. Furthermore, model results are compared with data available from the EURO-CORDEX project at the highest resolution available (about 12 km).

In order to evaluate the model performances with respect to the E-OBS dataset, the simulated domain has been split in different sub-regions, according to the PRUDENCE Project (Christensen et al. 2008). In particular, taking into account the limits of ALCOTRA-CLIMAERA and EUROPEAN domains, the sub-regions considered for the current analysis are Alps (AL), France (FR) and Mediterranean (MD), as highlighted by the filled boxes shown in Figure 2.

For what concerns the comparison with respect to the NWIOI dataset, the validation is performed considering the Piedmont region, Figure 3.



Area	West	East	South	North
1 (BI) British Isles	-10	2	50	59
2 (IP) Iberian Peninsula	-10	3	36	44
3 (FR) France	-5	5	44	50
4 (ME) Mid-Europe	2	16	48	55
5 (SC) Scandinavia	5	30	55	70
6 (AL) Alps	5	15	44	48
7 (MD) Mediterranean	3	25	36	44
8 (EA) Eastern Europe	16	30	44	55

Figure 2. European sub-regions in the frame of PRUDENCE project. Colored sub-regions represent the validation domains: Alps (AL), France (FR) and Mediterranean (MD). The table provides information about the sub-regions, the name of area and the limits of the domains.

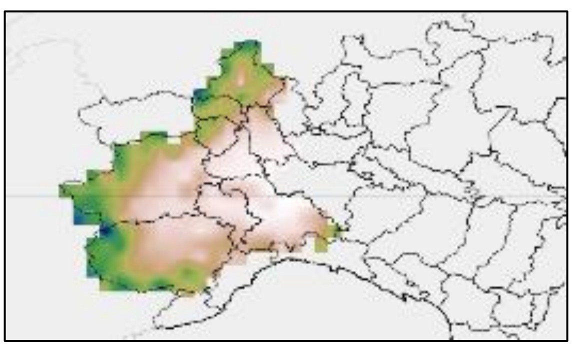


Figure 3. Orography of NWIOI domain (Piedmont region).

Temperature

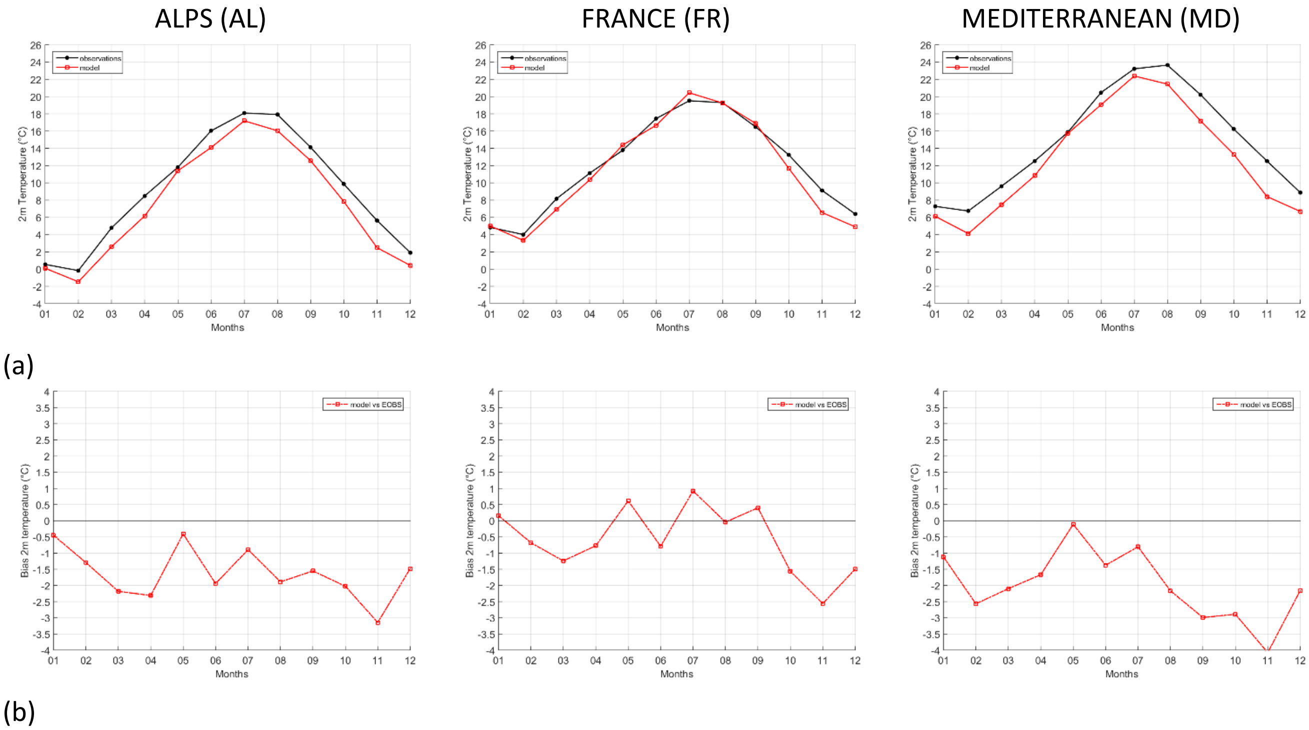


Figure 4. Annual cycle of 2m temperature (a) and bias (b) of COSMO-CLM (red line) versus E-OBS (black line) observations, over the period 2011-2015 for Alps (AL), France (FR) and Mediterranean (MD) regions for ALCOTRA-CLIMAERA experiment.

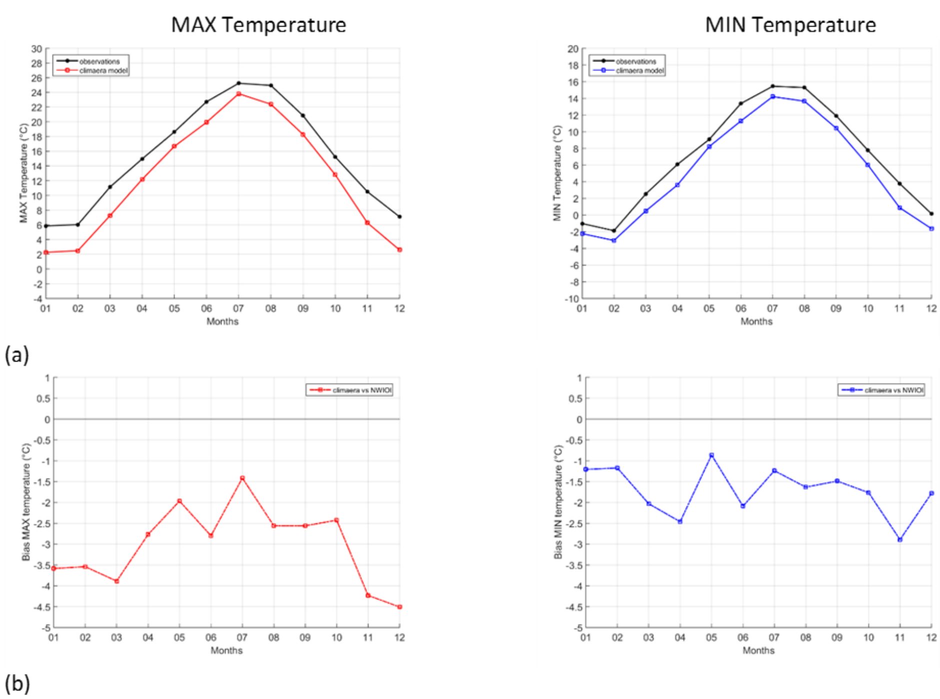


Figure 5. Annual cycle of maximum and minimum temperature (a) and bias (b) of COSMO-CLM versus NWIOI observations, over the period 2011-2015 for ALCOTRA-CLIMAERA experiment.

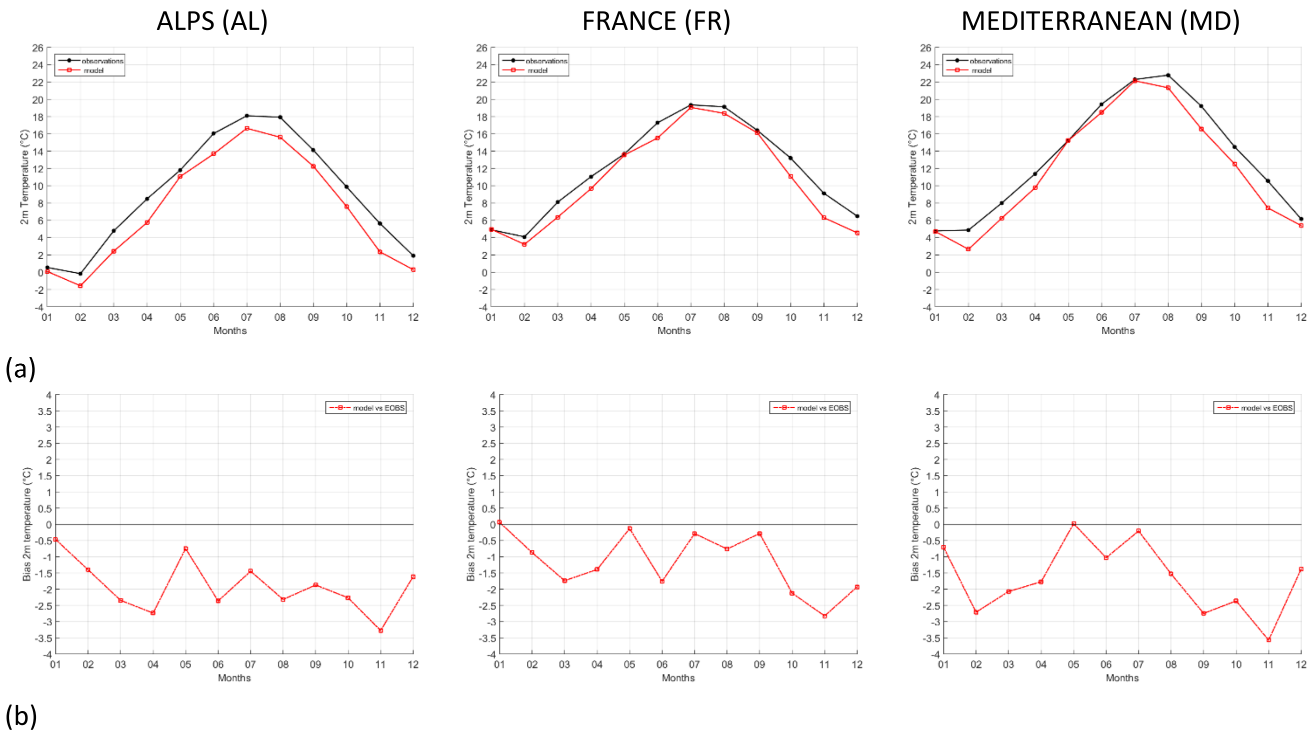


Figure 6. Annual cycle of 2m temperature (a) and bias (b) of COSMO-CLM (red line) versus E-OBS (black line) observations over the period 2011-2015 for Alps (AL), France (FR) and Mediterranean (MD) regions for EUROPEAN experiment.

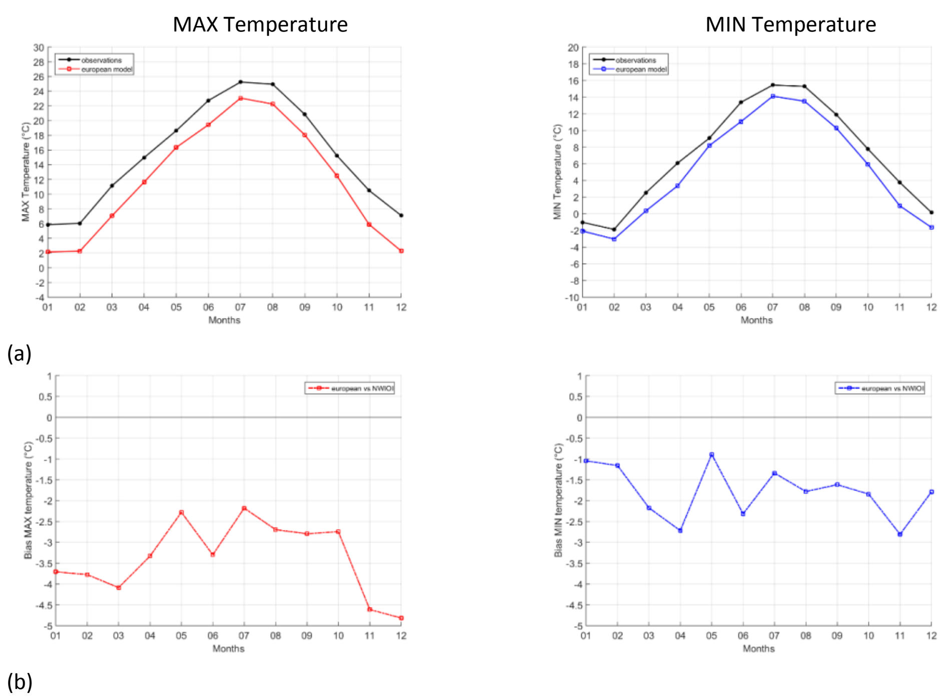


Figure 7. Annual cycle of maximum and minimum temperature (a) and bias (b) of COSMO-CLM versus NWIOI observations, over the period 2011-2015 for EUROPEAN experiment.

Figure 4 and Figure 6 show the annual cycle of 2m temperature for ALCOTRA-CLIMAERA and EUROPEAN experiments compared to the E-OBS observations, averaged over three European sub-regions, Alps (AL), France

(FR) and Mediterranean (MD). Over AL and MD the mean 2m temperature is generally underestimated, more pronounced over MD area and especially for autumn months. Over FR instead, a very good agreement between model and observation is found, with a general bias never exceeding 1.5°C in absolute value, except for November, when a large cold bias is found over all the sub-regions considered.

For what concerns the evaluation of maximum and minimum temperature, the evaluation is performed over the Piedmont region, considering NWIOI dataset as reference. Figure 5 and Figure 7 display the annual cycle of 2m maximum and minimum temperature for ALCOTRA-CLIMAERA and EUROPEAN experiments, averaged over NWIOI domain, along with the relative biases. Both experiments show that the RCM is not able to well reproduce the maximum temperature, with a peak of underestimation up to 4.5 °C in December. It is worth noting that the minimum temperature is properly reproduced and the mean bias is about 1.5°C.

The shortcoming of COSMO-CLM, leading to underestimation of winter temperature at high altitudes, could be due to inadequate representation of complex orographic areas. These results are consistent with Kotlarski et al., 2014 - Bucchignani et al., 2016. Part of this bias is inherited by the GCM since, in general, most atmosphere-ocean GCMs tend to underestimate the temperatures. (Macadam et al., 2010).

Precipitation

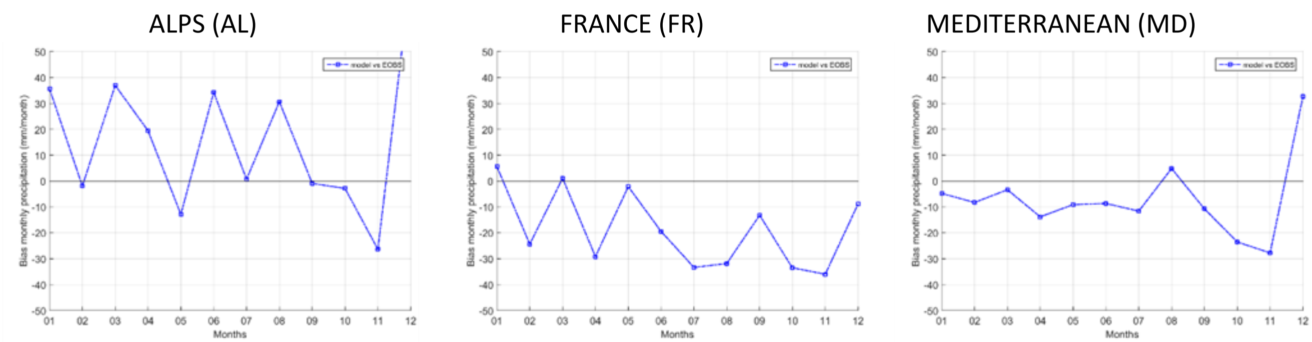


Figure 8. The total precipitation annual cycle bias of COSMO-CLM versus E-OBS observations, over the period 2011-2015 for Alps (AL), France (FR) and Mediterranean (MD) regions for ALCOTRA-CLIMAERA experiment.

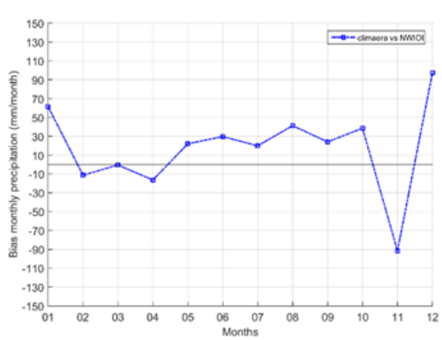


Figure 9. The total precipitation annual cycle bias of COSMO-CLM versus NWIOI observations, over the period 2011-2015 for ALCOTRA-CLIMAERA experiment.

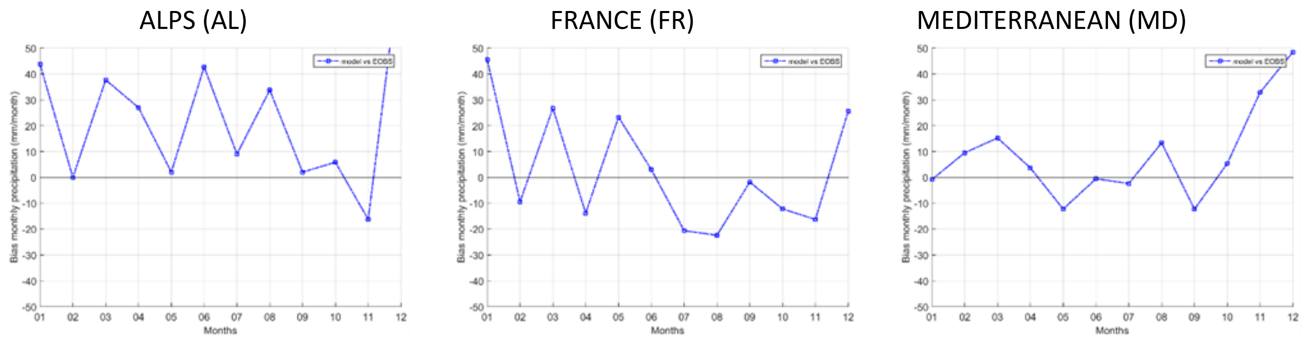


Figure 10.The total precipitation annual cycle bias of COSMO-CLM versus E-OBS observations, over the period 2011-2015 for Alps (AL), France (FR) and Mediterranean (MD) regions for EUROPEAN experiment.

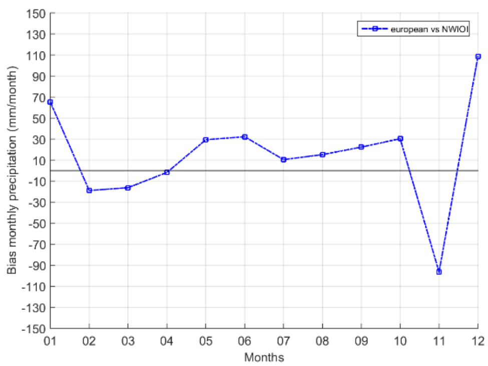


Figure 11.The total precipitation annual cycle bias of COSMO-CLM versus NWIOI observations, over the period 2011-2015 for EUROPEAN experiment.

Concerning the evaluation of precipitations, simulated and observed values have been also averaged over the period 2011–2015, and split over three European sub-areas and Piedmont region. Figure 8 and Figure 10 show the total precipitation annual cycle bias of ALCOTRA and EUROPEAN simulations versus E-OBS. Over the Alps, both experiments exhibit a wet bias over the whole cycle, with a peak of about 50 mm/month and a negligible bias in February, May and September. Over France, the total precipitation is generally overestimated with dry bias during the summer months. The model exhibits a good agreement with the observations over the Mediterranean area, except for November and December.

The evaluation of total precipitation has been performed also considering the NWIOI dataset (Figure 9 and Figure 11). Over the Piedmont region, a wet bias is found especially during summer months being the absolute bias lower than 30 mm/month. The peak of rainfall in November is not captured, both at 8 km and 14 km of resolution; the experiments exhibit a dry bias up to -90 mm/month.

It is important to highlight that the representation of precipitation benefits from the increase in resolution, indeed the experiment at higher resolution (0.0715°) is able to keep a bias lower with respect to the other one (0.125°).

CCLM vs EURO-CORDEX 11

In order to quantify the effectiveness of the CCLM simulations, bias values have been compared with values affecting 'state-of-the-art' regional climate simulations (i.e. EURO-CORDEX data at 0.11° resolution). EURO-CORDEX is the European branch of the international CORDEX initiative, which is a program sponsored by WRCP to organize an internationally coordinated framework aimed to produce improved regional climate change projections for all land regions worldwide. A wide range of RCM simulations is available over the European domain (EURO-CORDEX) with resolution 0.11° (about 12 km) forced by different GCMs, according to the IPCC scenarios. In Table 3, it is reported the list of GCMs/ RCMs and the variables simulated by the Research Institutes in the CORDEX Project and used in this analysis to compare the performances with respect to the CCLM experiments.

#	Driving GCM	GCM Member	RCM
1	CNRM-CM5	r1i1p1	ALADIN53
2	CNRM-CM5	r1i1p1	RCA4
3	CNRM-CM5	r1i1p1	CCLM4-8-17
4	EC-EARTH	r12i1p1	CCLM4-8-17
5	EC-EARTH	r12i1p1	RACMO22E
6	EC-EARTH	r12i1p1	RCA4
7	EC-EARTH	r1i1p1	RACMO22E
8	EC-EARTH	r3i1p1	HIRHAM5
9	IPSL-CM5A-MR	r1i1p1	WRF331F
10	IPSL-CM5A-MR	r1i1p1	RCA4
11	HadGEM2-ES	r1i1p1	CCLM4-8-17
12	HadGEM2-ES	r1i1p1	RACMO22E
13	HadGEM2-ES	r1i1p1	RCA4
14	MPI-ESM-LR	r1i1p1	CCLM4-8-17
15	MPI-ESM-LR	r1i1p1	REMO2009
16	MPI-ESM-LR	r1i1p1	RCA4
17	MPI-ESM-LR	r2i1p1	REMO2009
18	NorESM1-M	r1i1p1	HIRHAM5

Table 3. List of the EURO-CORDEX simulations (GCMs/RCMs matrix) used in this work.

A statistical comparison among EUROCORDEX, the present CCLM model results and observational data is proposed in the following by means of Normalized Taylor diagrams (Figure 12). The diagrams (Taylor, 2001) provide a way of graphically summarizing how closely a set of patterns match observations. The similarity between patterns are quantified in terms of their correlation, their centered root-mean square difference and the amplitude of their variations (standard deviations). In the proposed analyses, the experiments on ALCOTRA-CLIMAERA and EUROPEAN domains are compared with NWIOI dataset over Piedmont region and they are also compared with variables of EURO-CORDEX models.

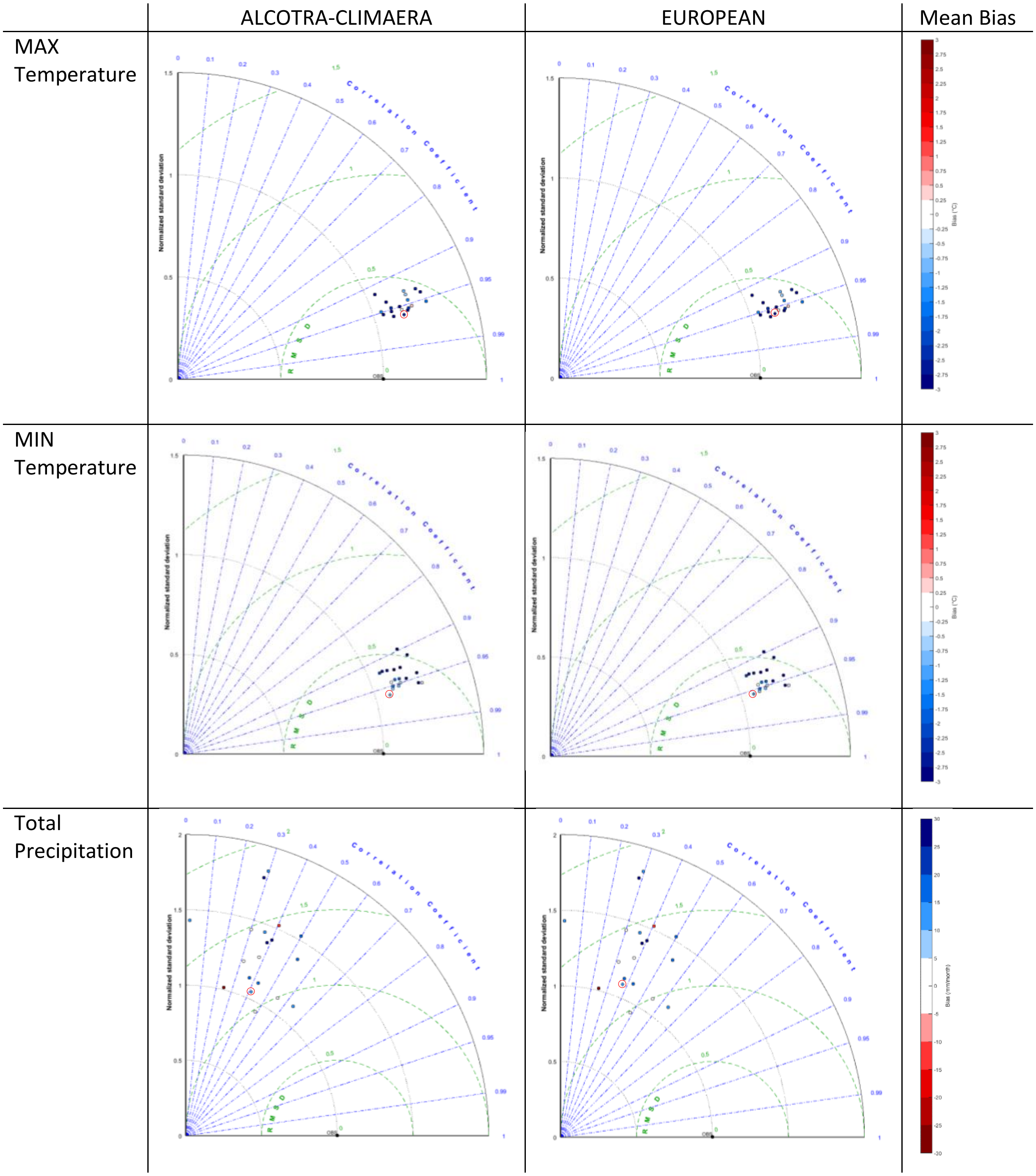


Figure 12. Spatial Taylor diagram exploring the model performance of ALCOTRA-CLIMAERA and EUROPEAN experiments (points circled in red) with respect to the variability of single models of EURO-CORDEX 11, for maximum and minimum temperature and total precipitation. The color of points indicates the mean bias.

The normalized Taylor diagram in Figure 12 shows the performance of CCLM simulations with respect to the 18 models listed in Table 3 for maximum and minimum temperature and total precipitation. The values are averaged over the whole period 2011-2015 and normalized to the NWIOI observations. The points circled in red represent ALCOTRA-CLIMAERA and EUROPEAN experiments. For what concerns the simulation of temperature, the correlation pattern with observation is very high, i.e. 0.95. The centered root-mean-square (RMS) difference between the simulated and observed patterns is proportional to the distance to the point on the x-axis identified as "OBS" The green contours indicate the RMS values and it can be seen that in the case of normalized Taylor diagram the centered RMS error is zero. The standard deviation of the simulated pattern is proportional to the radial distance from the origin.

In general, simulated patterns agreeing well with observations will lie nearest the point marked "OBS" on the x-axis. Then, CCLM experiments exhibit very good performances with respect to the available EURO-CORDEX11 models for the temperature variables, with a comparable mean bias.

The performance in the reproduction of spatial pattern of total precipitation are generally lower than temperature for both CCLM experiments and EURO-CORDEX11 models. Most of the models show a correlation of about 0.4, but CCLM experiments exhibit a lower standard deviation.

Figure 13 displays the annual cycle comparison among ALCOTRA-CLIMAERA and EUROPEAN experiments and the ensemble of 18 EURO-CORDEX11 in the reproduction of maximum, minimum temperature and precipitation over Piedmont region.

About the temperature, comparison with EURO-CORDEX shows that the bias magnitude is of the same order of magnitude. The representation of minimum temperature is improved, while CCLM shows deficiencies in the representing the maximum. Comparison between different resolutions reveals that the resolution increase produces a fair reduction in error in all months.

About the evaluation of total precipitation (Figure 14), the performances of the ensemble EURO-CORDEX11 and CCLM simulation are similar. Overestimation at high altitudes affects all the models involved in EURO-CORDEX 11 and the worst behavior is evident in November.

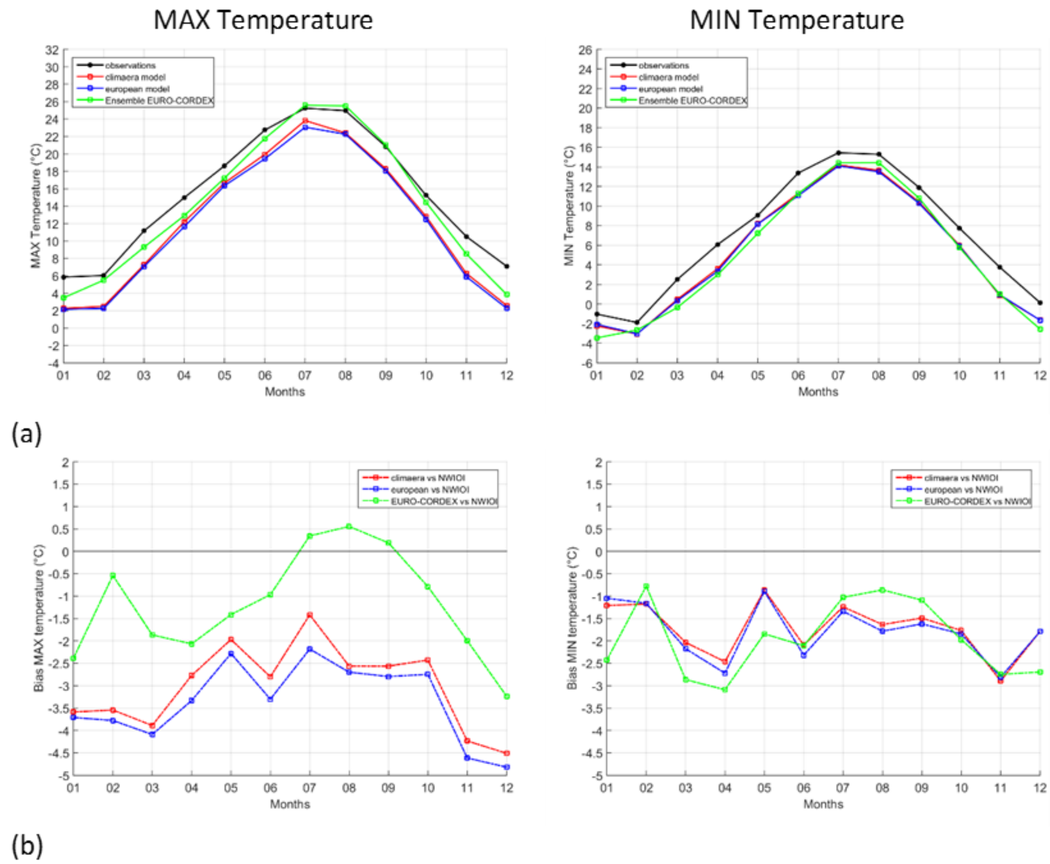


Figure 13. Annual cycle of maximum and minimum temperature (a) and bias (b) of COSMO-CLM and ensemble EURO-CORDEX 11 versus NWIOI observations, over the period 2011-2015.

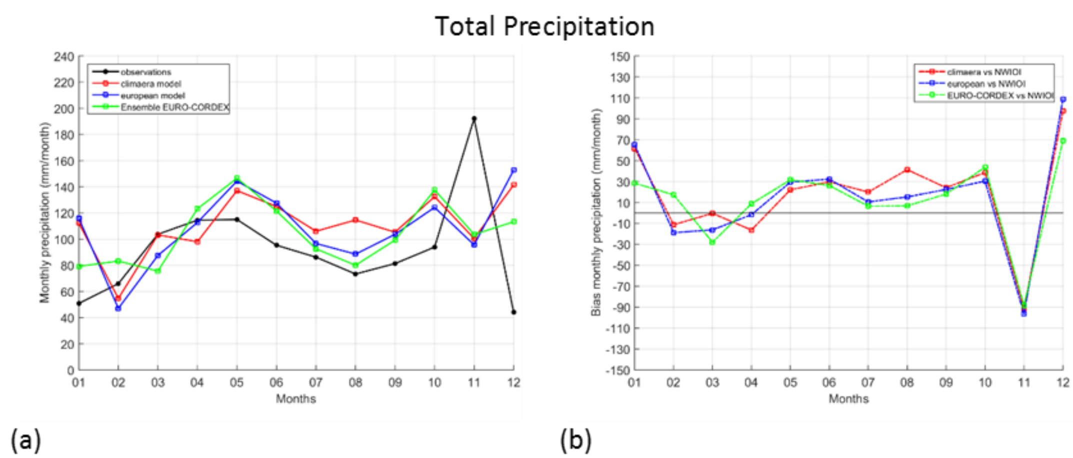


Figure 14. Annual cycle of total precipitation (a) and bias (b) of COSMO-CLM and ensemble EURO-CORDEX 11 versus NWIOI observations, over the period 2011-2015.

Post-processing and dissemination data

The data are saved in NetCDF format and aggregated in daily files: YYYYMMDD.nc. Each file contains all the variables listed in Table 4, at hourly temporal frequency and compliant with the standard CF, Climate and Forecast (http://cfconventions.org).

The results of the simulations (original output variables of the COSMO model) have been post-processed to get all the variables required by the technical specifications of the ALCOTRA project and to make them compliant with the CF Standard. Furthermore, the variables were cut out on the analysis domain, deleting 15 frame points at each side from the computational domain.

Dataset specific information

The daily files, both single year YYYYMMDD.nc and average year avg_MMDD.nc, are compressed and archived in monthly files, YYYYMM.tar and avg_MM.tar.

- YYYYMMDD.nc

	Variables (standard_name)	ID	Unit	CCLM variable
1	eastward_wind	ua	m/s	U
2	northward_wind	va	m/s	V
3	upward_air_velocity	wa	m/s	W
4	air_temperature	ta	K	T
5	air_pressure	plev	Pa	P
6	relative_humidity	hur	%	RELHUM
7	mass_fraction_of_cloud_condensed_water_in air	qc	1	QC
8	geopotential_height[1]	zg	m	HHL
9	humidity_mixing_ratio	qv	1	QV
10	soil_moisture_content	mrso	kg/m^2	sum(W_SO(i=1:8))
11	mass_fraction_of_ice_in_air	cli	1	QI
12	pressure perturbation	pdev	Pa	PP
13	pressure_reference	pref	Pa	P-PP
14	geopotential_height Perturbation*			
15	surface_air_pressure	ps	Pa	PS
16	cloud_area_fraction	clt	1	CLCT
17	precipitation_amount	pr	kg/m^2	TOT_PREC
18	snowfall_amount	prsn	kg/m^2	SNOW_CON + SNOW_GSP
19	freezing_level_altitude	hzerocl	m	HZEROCL
20	air_temperature (2m)	tas	K	T_2M
21	eastward_wind (10m)	uas	m/s	U_10M
22	northward_wind (10m)	vas	m/s	V_10M
23	surface_downwelling_shortwave_flux_in_air	rsds	W/m^2	ASWDIR_S + ASWDIFD_S
24	surface_downwelling_longwave_flux_in_air	rlds	W/m^2	ALWD_S
25	convective_precipitation_amount	prc	kg/m^2	RAIN_CON + SNOW_CON
26	large_scale_precipitation_amount	prl	kg/m^2	RAIN_GSP + SNOW_GSP
27	surface_upward_latent_heat_flux	hfls	W/m^2	-ALHFL_S

[1] COSMO-CLM is a non-hydrostatic model, and then the geopotential height on the levels of the model (zg) corresponds with the geometric height of the levels (zh). The height of the levels (zh) is included in the file fix.nc.

28	surface_snow_thickness	snd	m	H_SNOW
29	surface_upward_sensible_heat_flux	hfss	W/m^2	-ASHFL_S
30	atmosphere_boundary_layer_thickness	zmla	m	HPBL

Table 4. Variables list of single file YYYYMMDD.nc

- fix.nc

	Variables (standard_name)	**ID**	**Unit**	**CCLM variable**
1	surface_altitude	orog	m	HSURF
2	geopotential_surface	fis	m^2/s^2	FIS
3	Height	zh	m	HHL

Table 5. Variables list of constant file fix.nc

- avg_MMDD.nc

This file contains the average year of all variables listed in Table 4, over the reference period and aggregated in daily file.

Data delivery

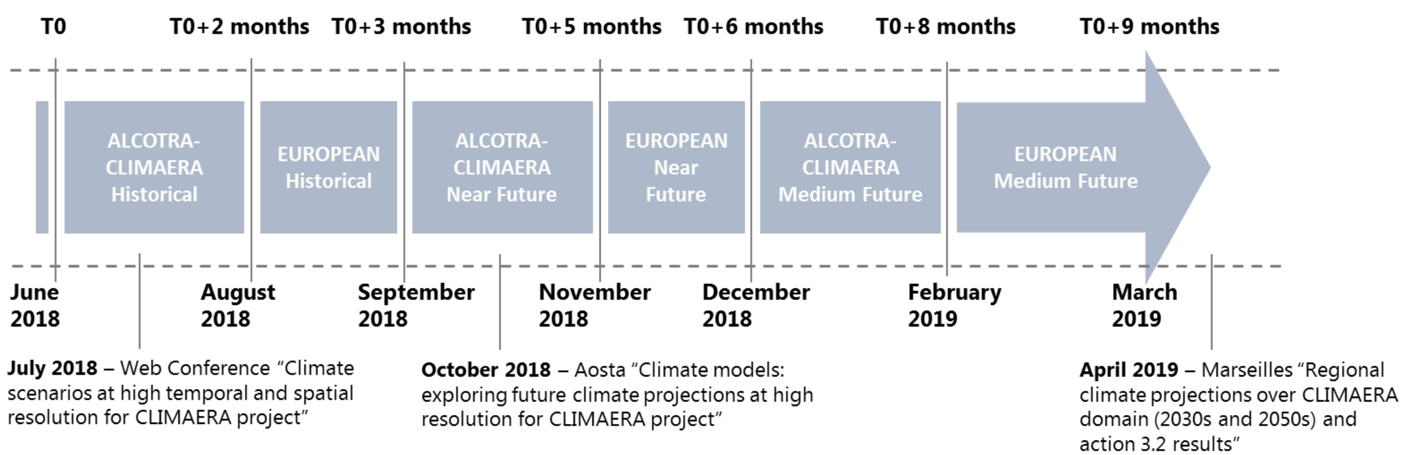


Figure 15. Timeline of data delivery.