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High resolution climate scenarios on Mediterranean test case areas for the hydro-climate integrated system

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SUMMARY This document is aimed to show the main results of climate projections, under two RCPs, at 2100 obtained in WP A.2.6 “High-resolution climate scenarios” on the geo-hydrological hotspots identified within WP A.2.17 "Analysis of geo-hydrological risk related to climate change" of GEMINA project. The main goal of WP A.2.17 is the analysis of the effect of climate changes on occurrence and magnitude of landslides, floods and low flows hazards on some specific contexts of the Mediterranean area. To reach this objective, climate data at the same horizontal resolution (<10 km) of impacts model are required. Within GEMINA project, the generation of high-resolution climate scenarios is one of the aims of WP A.2.6. Thus, in this research paper, the projected climate changes obtained in WP A.2.6 coupling the GCM CMCC-CM with the RCM COSMO-CLM under RCP4.5 and RCP8.5 scenarios are discussed on the following test case areas identified in WP A.2.17: Po river basin, Cervinara and Orvieto sites. Some details on validation of the climate model on the same areas are also given.

Keywords: Climate scenarios, RCM, GCM, high resolution, landslides, flood, droughts, Po river basin

1. INTRODUCTION AND MOTIVATION

In the last years, the evaluation of the potential effect of climate changes on geo-hydrological hazards became exceptionally debated.

The availability of long time series of weather variables and derived parameters regulating the hazards has sometimes allowed estimating on going variations and their significance [33]; however, for the future period such assessment takes even greater relevance conveying land planning options or, in general, adaptation policies.

To this aim, the general framework reckons on weather variables provided by climate models adopted as input for the specific impact tools; in such contexts, as is well known, GCMs (Global Climate Models) allowing to evaluate at global scale the response to emission scenarios of the climate system, are characterized by horizontal and vertical resolutions compromising a proper assessment at scale needed for impact studies requiring the adoption of downscaling (statistical or dynamical) approaches.

Statistical approaches, preferred for their limited required computational and time effort, are however based on crucial (strong) assumption according which feedback mechanisms between local and global weather pattern, today recognizable, could be suitable also for the future under the effect of climate change; conversely, dynamical downscaling approaches demand huge computational efforts but, as physically based numerical models directly nested for specific region on GCM, do not need to state, under steady-state conditions, relationships between global and local weather patterns.

For example, for Greece characterized by climate features and orographic complexity comparable to Italian one, [44] show how an improved representation of morphology induce a substantial enhancement in reproducing precipitation pattern and, at the same time, entails a strong variation in climate signal detected, on the area, by driving GCM. Gao et al. [16] for South-Eastern Asia, assume that the improvements could be not only due to a better representation of orography but also to more consistent physical parametrizations employed in RCMs.

However, as showed in [38, 39, 45, 51], a further mismatch but achieved horizontal resolutions in RCMs and the usual scale investigated in impact studies subsists; moreover, the validation phase on control period reveal how RCM resolutions and resulting necessary physical parametrizations usually induce errors in proper assessment, for example, of cumulative values of precipitation or wet days preventing the direct use of weather variables provided by RCMs as input for impact tools. For overcoming such issue, usually RCM outputs are subjected to statistical approaches, known as bias correction methods able to correct, at least, the errors associated to mean value (i.e. delta change approach) if not, potentially, those associated to all main statistical moments (i.e. quantile mapping approaches).

It worth noting that the key prerequisite, required to bias correction approaches, regard their attempt to correct only that are recognized as "systematic errors" not affecting the climate signals, physically estimated, by climate models; for these reasons, beyond the possible "quantitative" misrepresentation of climate models, trends and statistical significance revealed by RCMs should be fully preserved also after bias-correction; however, a large debate about the adoption of bias correction approaches, their constraints and advantages, arise in last years [12, 26] but although their "statistical" features produce issues similar to those detected for statistical downscaling approaches, their adoption in impact analysis, on the short term, is almost unanimously acknowledged.

Such findings has led ISC research division, within GEMINA project, to develop the simulation framework widely explained in [49] consisting of GCM (CMCC-CM [35]), RCM (COSMO-CLM [37]), different bias correction approaches depending on investigated impact and its extent and finally, specific impact tools.

So, the aim of this research paper is to display the evolutions and trends of the main weather variables provided by numerical climate models (GCM/RCM) under two RCPs until for the three selected hot-spots deputed, within WP A.2.17 of GEMINA project, as pilot case studies for investigating the potential effect of climate change on geo-hydrological hazards: namely, i) Po river basin for which the assessment of variations, potentially induced by climate change in discharges and then in occurrence of "extreme tails" of it, droughts and floods events, has been carrying out; ii) Orvieto and iii) Cervinara where, instead, at the slope scale, the assessment of variations respectively in magnitude of slope reaccelerations and occurrence of flowslide triggering have been performing. In such context, the target variables assumed regulating geo-hydrological hazards (namely, discharge for Po river basin and soil water pressures for landslide case studies), could be assumed main function of the soil surface balance for which precipitation and temperature play a significant role, the first controlling the ingoing fluxes, the latter as proxy variable of evapotranspiration (outgoing fluxes).

In the following, first a brief review on climate modelling chain (Section 2) and case studies (Section 3) is carried out; after, for the three cases (Sections 4 and 5), the most meaningful results concerning the trends of precipitation and temperature estimated by climate models for XXI century (under RCP4.5 and RCP8.5 concentration scenarios) are reported; because of the great difference in the extent, the physical dynamics and control variables of the investigated geo-hydrological hazards, different features of weather patterns are taken into account and different results displaying are preferred for Po river basin (flood/low flow hazard) and Cervinara and Orvieto (landslide hazard); however, for each case study, the main findings about validation phases are first briefly recalled and after, according to the aim of this research paper, the displaying of outputs for XXI century is addressed. Those presented here, are only some of the analysis performed on the climate simulations results, e.g. ETCCDI indices [29] and Taylor diagrams [53] are produced for validation purposes on Po river basin; the probability distribution of annual maximum precipitation at 1 and 120 days are studied to support the landslides hazards assessment under climate change [32, 51, 31] for Cervinara test cases.

The high-resolution climate simulations analysed here are generated within the framework of WP A.2.6 "High-resolution climate scenarios" of GEMINA project aimed to study the evolution of climate and the variability of extreme phenomena on the entire Italian territory, Fig.1. Among the climate phenomena of interest we cite, for precipitation: changes in annual maximum precipitation at different temporal scales or duration of dry period; for temperature: frequency and duration of heat waves.

2. CLIMATE MODEL

2.1 REPRESENTATIVE CONCENTRATION PATHWAYS: RCP4.5 AND RCP8.5

Climate projections are the results of numerical simulations performed by climate models driven

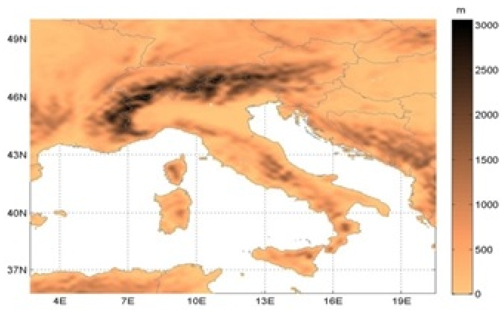

Figure 1:
COSMO-CLM domain and orography for the configuration with horizontal resolution of 8 km

by scenarios hypothesizing, on the basis of different socio-economic assumptions, various concentration pathways for greenhouses gases and pollutants. The most commonly used scenarios are RCP4.5 and RCP8.5. The RCP4.5 is a stabilization scenario where the radiative forcing will assess at about 4.5 W/m^2 before 2100, while RCP8.5 is a more extreme scenario where radiative forcing will increase up to 8.5 W/m^2 in 2100 compared to pre-industrial era [27]. Such scenarios are used to drive global climate models, that are characterised by a coarse horizontal resolution that makes their outputs not suitable for application in geo-hydrological studies. Thus GCMs outputs are dynamically downscaled by regional climate models obtaining climate variables at higher horizontal resolution comparable with the one requested by geo-hydrological impact models.

2.2 GLOBAL CLIMATE MODEL: CMCC-CM

The global climate model CMCC-CM is a coupled atmosphere-ocean general circulation model, which has been implemented and developed in the framework of the European project CIRCE [18]: the atmospheric model component is ECHAM5 [34] with a T159 horizontal resolution (0.75°), while the global ocean component is OPA 8.2, in its ORCA2 global configuration, at a horizontal resolution of 2°. ORCA2 also includes the Louvain-La-Neuve (LIM) model for the dynamics and thermodynamics of sea-ice. A performance assessment of CMCC-CM in simulating the observed Sea Surface Temperature and precipitation is reported in [35], while a comparison with other state-of-art GCMs available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) is presented in different other works e.g. [13].

2.3 REGIONAL CLIMATE MODEL: COSMO-CLM

A detailed description of the regional climate model COSMO-CLM and is reported in [49, 28]. COSMO-CLM is the climate version of COSMO-LM weather model [37], developed by the CLM Community. It is a high resolution (less than 50 km) non-hydrostatic RCM able to explicitly capture small scale severe weather events and an improved representation of subgrid scale physical processes, such as clouds, aerosols, orography, land and vegetation properties. It has been already used in the framework of several European projects, such as PRUDENCE [8] and CORDEX [17], highlighting its good capability in reproducing the mean climate features of the areas under study, with a similar range of accuracy with respect to the other RCMs adopted. More details concerning the description of the main characteristics of COSMO-CLM and the configuration used to perform the simulations presented in this work are reported in [50, 29]. Climate simulations have been carried out at 0.0715° (about 8 km) of horizontal resolution using as initial and boundary conditions: (a) ERA Interim Reanalysis [11] over the 1981-2010 period, characterized by a horizontal resolution of about 0.70°, about 79 km, to assess the performances of the regional climate model when driven by "perfect" boundary conditions; (b) the global climate model CMCC-CM (0.75°, about 85 km) to assess the uncertainties of the GCM/RCM couple before use it to climate change studies,in this case the simulation period covers 1971-2005, an extension to 2010 of the simulation is obtained forcing the GCM with the RCP4.5 scenario.

Numerical simulations over the whole Italian domain are performed on a cluster of 30 IBM P575 nodes, installed at CMCC (Italy); each node has 32 Power6 (4.7 GHz) cores, amounting to a total of 960 cores and an aggregate peak power of 18 TFlops. The elapsed time to simulate one climatological year using 512 cores is about 24 hours.

3. TEST CASES

3.1 ORVIETO AND CERVINARA

The test cases sites of Cervinara (Southern Italy) and Orvieto (Central Italy), Fig.2, are of interest to investigate the impacts of climate change on different types of landslides phenomena. Orvieto is an historical town located 100 km North to Rome. It rises on top of a 50 m thick tuff slab delimited by subvertical lateral cliffs overlying overconsolidated clays. In the deeper part, these are stiff and intact, but the shallowest part of the deposit is jointed and fissured. The clayey slopes are blanketed by an irregular cover of talus and slide debris [32]. Since prehistoric times, failures and slow movements have been affected the Orvieto slopes : the two historically failures events (Porta Cassia, on northern slope, 1900 and Cannicella, on southern slope, 1979) were induced by man-made changes to slope geometry or hydraulic conditions; ongoing slow movements (translational) are directly related to soil-atmosphere interaction. Deep movements occur along pre-existing slip surfaces located within the softened part of clay formation (displacement rates from 2 to 6 mm/years) while, shallow movements, superimposed to the deep ones, involve the debris cover and show higher displacement rate (displacements between 7 and 12 mm/month) [42].

Cervinara slope is located 50 km North-East to Naples; on December, 16, 1999, it has been affected by a rapid flowslide triggered by a total precipitation of 320 mm in about 50 h, causing huge damage and five casualties in surrounding areas. In the area, highly fractured calcareous mountains are maintained by loose unsaturated pyroclastic covers hardly thicker than 2-3 m. These morphological configurations are widespread in the Campania Region, as result of the activity of some volcanoes including Somma-Vesuvius.

3.2 PO RIVER BASIN

Po river is the longest river in Italy with a length of 652 km from its source in Cottian Alps (at Pian del Re) to its mouth in the Adriatic Sea, in the north of Ravenna and it is the largest Italian river with an average discharge of 1540 m^3/s. The area covered by Po river basin is about 71000 km^2 in Italy and about about 3000 km^2 in Switzerland and France. The orography of the basin is quite complex since it is bounded by Alps, Apennines with the Po valley between them, Fig.3. In the context of the Italian Law 183/1989, the Po river basin is classified as being of national relevance. During the last centuries, flooding events, due to extreme meteorological conditions, of the Po river or of its tributaries have caused numerous natural catastrophes, two of them, characterized by extraordinary large scale, occurred in the last 10 years, [48] and signal of changes in precipitation and temperature are present in climate

Figure 2:
a) geographical location of the two case-histories; b) Orvieto slope; c) Cervinara landslide

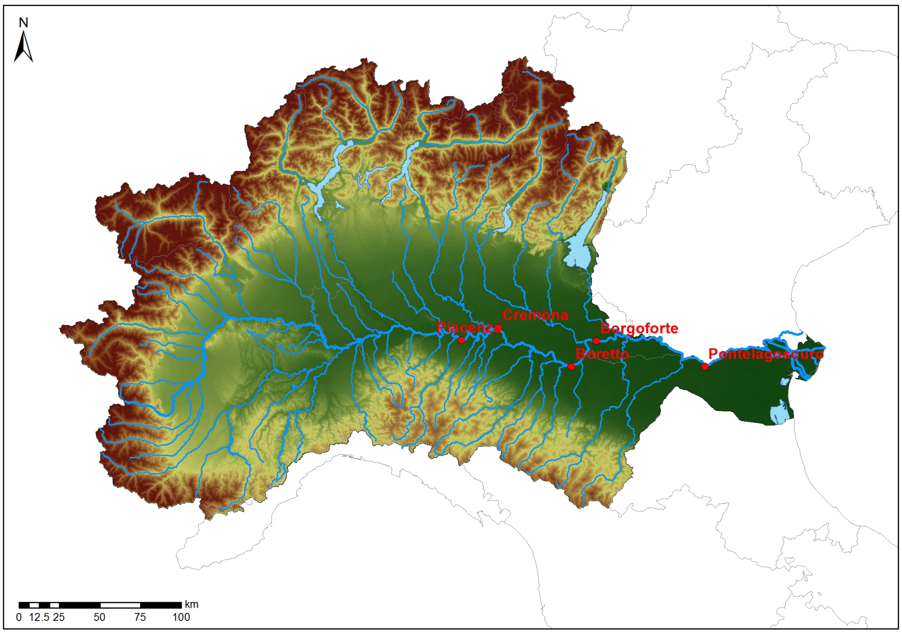

Figure 3:
Po basin: hydrological network and main closure sections

observations [43, 9, 40]. Climate data analysis show, on Po river basin, an increase in annual maximum precipitation with a trend of about 0.5°C/decade since 1960. The signal is detectable in all the seasons [43], in particular, in Summer where maximum temperature are higher than the reference climate [40]. Change in precipitation, since 1980, are less evident than those in temperature, in average, there the precipitation event are more intense but less frequent, as results the annual total precipitation is reduced of 20%. At seasonal scale, the highest reduction rate are found in Spring and Summer (up to 50%) while autumnal precipitation are almost unvaried; in Winter, snowfalls reduces as well [40]. [9] analyse time series of daily cumulated precipitation and of daily minimum and maximum temperatures in the period 1952-2002 from Piemonte and in the Valle d'Aosta regions (north-western Italy) finding a significant increase of about 1°C on average temperatures, in particular, for maximum daily temperatures in winter and summer months; while for precipitation any significant trend is identified.

4. CLIMATE PROJECTIONS FOR ORVIETO AND CERVINARA TEST CASES

For the landslide case studies, Orvieto and Cervinara, the trends concerning the main features of temperature and precipitation, for XXI century under RCP4.5 and RCP8.5 scenarios, are presented; in particular, firstly, a comprehensive characterization of seasonal weather patterns is carried out displaying: the evolution of seasonal cumulative rainfall values for the control period 1981-2100 and, through Mann-Kendall test, evaluation of statistical significance of trends estimated through Thiel-Sen approach (see Appendix); in the same way, trends and statistical significance are computed for seasonal maximum and minimum temperature. In addition, for 1981-2010 and three future projection periods: 2021-2050, 2041-2070 and 2071-2100 are shown: (i) mean monthly cumulative values; (ii) wet days (daily rainfall>1 mm); (iii) mean monthly maximum daily precipitation; (iv) mean monthly rainfall value for event; (v) mean monthly maximum and minimum temperature, moreover, the climate signal, computed as ratio for rainfall and difference for temperature, is reported.

Finally, the trend of proxy variables that more specifically influence the slope stability for the two case studies are considered. The reference variables for slow (very slow movements) affecting clayey slopes of Orvieto are: maximum yearly precipitation values cumulated over 30 and 60 days (of particular interest, for shallow movements in debris covers) and over 120 and 180 days (associated to deep movements in clayey formations); for flowslide triggering in pyroclastic covers, Cervinara case, back-analysis of case histories [30, 14] in similar geomorphological contexts have recognized as significant the effect of a main precipitation event on 1-2d scale coupled to antecedent precipitations on time span directly linked to hydraulic behaviour of pyroclastic cover and slope features, i.e. pyroclastic mantle thickness or slope angle: thus the proxy variables considered for trend analysis are: maximum yearly 2 days precipitation, cumulative values over 30 and 60 days, and the trends in cumulative value of rainfall over 58 days before the 2d for which the maximum 2d rainfall value is estimated for every year. For each variable, trend slopes detected by Thiel-Sen approach and statistical significance through Mann-Kendall approach are also computed.

At the beginning, for completeness, on the control period 1981-2010, for both test cases, the performances of climate models in terms of (i), (ii), (iii) and (iv) indicators are compared with observed data to briefly recall which are the skills of adopted climate modelling in reproducing observed weather patterns on investigated areas; however, a wider discussion about such issue is reported in [32, 33, 31].

4.1 SUMMARY OF PERFORMANCES OF CLIMATE MODELS ON CONTROL PERIOD

Figure 4 reports observed (black lines) and simulated (red lines) values of cumulative monthly rainfall (first row), monthly wet days (second row), monthly maximum daily precipitation (third row) and monthly average maximum and minimum temperature (forth row) on the control period 1981-2010 for both Orvieto (left column) and Cervinara (right column) case studies. First of all, two remarks are relevant: for allowing the comparison between climate conditions, on current period, between the two case studies, the trends are reported adopting the same intervals; and, since both Orvieto and Cervinara cases are essentially investigated at point scale (represented by the investigated slopes) while the effective resolution of climate models can be assumed about equal to 3-7Δx the nominal resolution, in this case about 8 km, according the weather variable of interest and the specific features of used RCM [36, 3, 21]. For Orvieto, an assessment on the effective resolution (respectively equal to 3-, 5- and 7-times the nominal resolution) is shown in Fig.4(a) finding very slight variations in performances both in terms of precipitation that of temperature as function of the resolution, thus, for all the further elaborations shown in the following only the intermediate value 5Δx of effective resolution is displayed.

Coming back to the analysis of performances of climate models, concerning Orvieto, seasonal cumulative values show an annual cycle characterized by two peaks the first one located in late winter season and the second one, more prominent, during the Autumn; the climate simulation is able to properly reproduce the first one while larger underestimations are returned during the Autumn and the entire dry season (Fig.4(a)); as displayed, in wet days, Fig.4(c), although the cumulative values are well reproduced during the first part of the year, they are the result of an excessive number of estimated wet days while, in the second part, a better correspondence is returned but in the face of the above shown substantial underestimation. Regarding monthly average maximum daily precipitation, Fig.4(e), observed values return seasonal patterns similar to those shown for cumulative values but also, in this case, climate simulations partially fail to reproduce the autumnal peak estimating values about equal to 20 mm/d vs 35 mm/d observed during the wet season and lower than 10 mm vs about 20 mm/d from observations in the dry season. Finally, for temperature Fig.4(g), observed values provide the usual annual cycle detected in Mediterranean area with winter values ranging between 1°C and 10°C and summer ones in the interval 15-30°C; however, climate simulation show very different performances for maximum (where biases are about equal to 3°C during the entire year) and minimum temperature (with biases often lower than 1°C); such difference could be partly due to various current weaknesses of climate simulations to properly reproduce temperature dynamics during the daytime [6, 7]. For what concern Cervinara case study, despite its position (300 km south of Orvieto), its location on Apennines of Campania Region entails rainfall amounts substantially higher than those recorded for Orvieto town; again, a seasonal pattern with two peaks is detected but, for this one, the rainfall heights during late Winter and Autumn reach respectively, on average, values higher than 150 mm/month and 250 mm/month,

Fig.4(b). In this respect, climate simulation fails to properly reproduce cumulative values with highly lower rainfall heights (maximum values about equal to 100 mm/month); despite this significant underestimation (which affects in comparable way also the daily maximum precipitation values), an higher number of wet days is estimated during the first part of the year while the subsequent underestimation is however directly associated to strong underestimation of cumulative values, Fig.4(d) and (f). Finally, concerning temperature **trends**, the foregoing considerations about Orvieto case can be verbatim reiterated, Fig.4(h). Therefore, in general terms, the performances of climate simulation for landslide hot spots substantially follow the average results on the entire Italian domain [6, 7]; in the same way, the main recognizable weaknesses are essentially associated to generalized underestimation of cumulative values and maximum daily precipitation but with a concurrent overestimation of wet days; in term of temperature values, climate simulations show very high skills in reproducing minimum temperature values while higher biases affect maximum temperature evolutions.

4.2 CLIMATE SCENARIOS FOR ORVIETO CASE STUDY

In order to frame, in broad terms, the expected variations in key variables, precipitation and temperature, while taking into account the differences in the seasonal dynamics, in Fig.5 the trends of seasonal cumulative precipitations covering 1981-2100 period under both RCP4.5 and RCP8.5 concentration scenarios are displayed (trend lines, evaluated through Theil-Sen method, and indication about statistical significance, assessed through Mann-Kendall approach, are also marked); while, for seasonal temperature, the trend slope and the indication of statistical significance are reported in Tab.1.

In term of precipitation, a sharp difference in behaviour is revealed between fundamentally dry (MAM and JJA) and wet (SON and DJF) seasons; the first ones display a substantial reduction particularly marked for the summer season (statistical significant at 0.1% for both RCPs) and for the spring season under RCP8.5 scenario (statistical significant at 1%) while, for the second ones, values remain almost unchanged (DJF under RCP4.5) or characterized by not significant increase (i.e. DJF under RCP8.5 and SON under RCP4.5) or slight decrease (SON under RCP8.5). In term of temperature, the trends are instead completely unambiguous: for all seasons and under both RCPs an increase, statistical significant at 0.1%, is assessed for minimum and maximum temperature; under RCP8.5, the increases attain 7-8°C/century in summer season while they remain, on average, at 4-5°C in other seasons; under the intermediate RCP4.5, the increase stands instead, averagely, on 3°C.

Moreover, in Fig.6, on monthly scale, for control period 1981-2010 (for which 2006-2010 RCP4.5 is adopted) and 2021-2050, 2041-2070 and 2071-2100 projection periods, the variations in different features of precipitation patterns (and associated climate signals) are investigated. In this regard, the strong assumption according which the deficiencies of the climate model simulations affect, in the same way, the projections regardless of the considered period or the influence of radiative forcing, allows to consider reliable the absolute signal climate detected between two different simulated periods. The cumulative values show roughly what seen in Fig.5; decreases in dry seasons result main function of time horizon and "severity" of RCP scenarios (attaining reduction until 80% for 2071-2100) while, during the wet season, the increases generally do not exceed 20%; against these cumulative values, reduc-

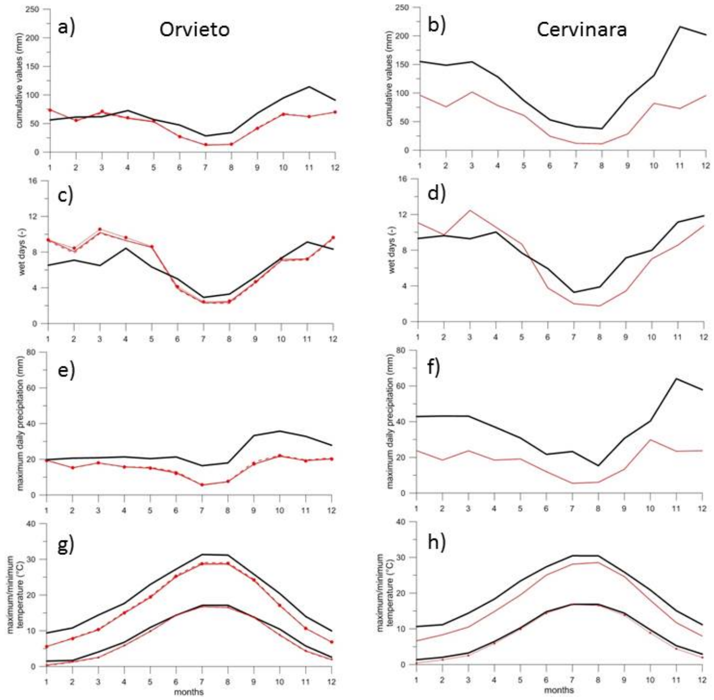

Figure 4:
Orvieto case study: a) monthly cumulative values observed (black line) and simulated by climate models adopting an effective resolution equal to 3Δx (red dashed line), 5Δx (red continuous line), 7Δx (red line with filled red dots); c) wet days for observed and simulated values; e) monthly maximum daily precipitation for observed and simulated values; g) maximum and minimum temperature for observed and simulated values. Cervinara case study: b) monthly cumulative values observed (black line) and simulated by climate models adopting an effective resolution equal 5Δx (red continuous line); d) wet days for observed and simulated values; f) monthly maximum daily precipitation for observed and simulated values; h) maximum and minimum temperature for observed and simulated values

Table 1

Orvieto case study slopes of trend lines detected, through Theil-Sen approach, in evolutions of seasonal maximum and minimum temperature for RCP4.5 (upper part) and RCP8.5 (bottom part); statistical significance, assessed through Mann-Kendall approach, is also reported (+ at 10%, * at 5%, ** at 1%, *** at 0.1%)

		Max T2m		Min T2m	
		Statistical significance	°C/year	Statistical significance	°C/year
RCP4.5	DJF	***	0.02	***	0.03
	MAM	***	0.03	***	0.03
	JJA	***	0.04	***	0.04
	SON	***	0.03	***	0.03
RCP8.5	DJF	***	0.05	***	0.05
	MAM	***	0.05	***	0.04
	JJA	***	0.08	***	0.07
	SON	***	0.06	***	0.05

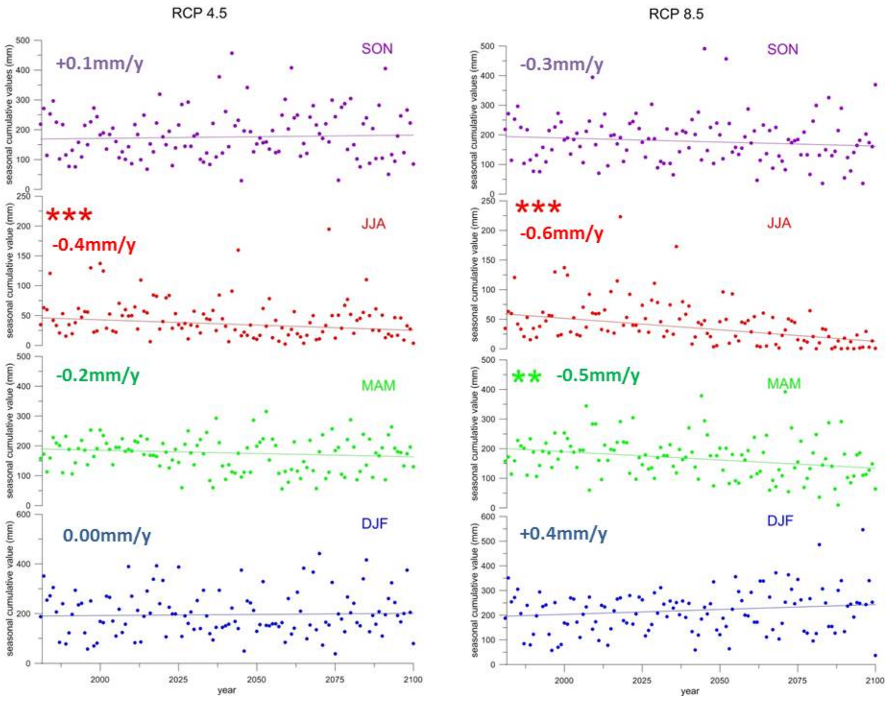

Figure 5:
Orvieto case study: trends of seasonal precipitation on time periods 1981-2100 for RCP4.5 (left column) and RCP8.5 (right column)scenarios; are also reported trend line estimated through Theil-Sen and indications about statistical significance (+ at 10%, * at 5%, **at 1%, *** at 0.1%) estimated through Mann-Kendall approach

tions (with rare exceptions) of rainy days generalized are estimated during the entire year. The coupled effect of the two behaviours is therefore revealed in Fig.6(d) where, on monthly scale, average precipitation heights for event are shown (trivially given as the ratio between the two previous quantities): of course, an increase in climate signal is returned for months characterized by an increase in cumulative values; however, also in other periods during the year where a reduction of total values is estimated, the amount for event is expected increasing (average growing about equal to 20-30%) or, at least, nearly steady. In this regard, the summer season under the RCP8.5 scenario constitutes an exception due to the reduction in cumulative values so substantial to represent, probably, the main reason of reduction in wet days. However, concerning maximum daily precipitations, the main displayed trends are confirmed; the increase in maximum values during the wet season, exceed 30% during the Autumn while lower in late Winter; however, during dry season, again a reduction is estimated; in this regard, however, it is well recalling also the weaknesses of the current regional climate models in reproducing convective dynamics essentially governing precipitation events during the dry season partially affecting the shown trends.

Displayed results are quite consistent with those found by other studies on the Mediterranean area (i.e. PRUDENCE and ENSEMBLE project); in the specific, the atmospheric warming especially tends to affect the precipitation patterns (dry days and precipitation for event) because of higher atmospheric moisture retention capacity; in term of precipitation values, at the same time, soil moisture depletion induced by warming during the dry season, entail a sharp reduction of precipitation amounts mainly under the RCP8.5 scenario.

The last issue deals, in greater detail, the trend of “proxy” variables that, through the back analysis of the slope movements and field monitoring [42, 41, 5], have been assumed as directly related to the movements of the landslide bodies: in Fig.7, for both RCPs, are then displayed the trends on 1981-2100 period of maximum yearly value of cumulative precipitations on 30, 60, 120 and 180 days.

Indeed, the low permeability characterizing the soils in situ (10^{-7} m/s for debris cover until 10^{-9} m/s for intact deep clays) induce a “time lag” between rainfall events and the arrival of the corresponding infiltrated rate at the soil depth in which the sliding surfaces arise; the increase of water content, producing the growth of water pressures, induce a reduction of frictional resistances and then the potential reacceleration of landslide bodies; moreover, the temporal shift is main function of soil depth and inversely proportional to permeability of involved soils; then, the cumulative values on 30 and 60 days are essentially correlated to shallower movements while 120 and 180 days to the deepest ones. However, considering for each year as proxy variable only the maximum value could provide a generic information on possible occurrence of the movements but not about their duration. In Fig.7, for both RCPs and for the four reference time span, the trends show an increase but only for the shorter durations it is assumed statistical significant (at 5% for RCP4.5 and 1% for RCP8.5). This findings might suggest an almost invariance of the existing rate movement for deep landslide bodies and a presumable worsening of slope stability conditions for shallower movements; on the other hand, on such reference time periods, also the effect of evaporation removing water from the soil before it arrives in depth could play a remarkable role in the special way, investigating future scenarios, characterized as shown in Tab.1, by a strong ex-

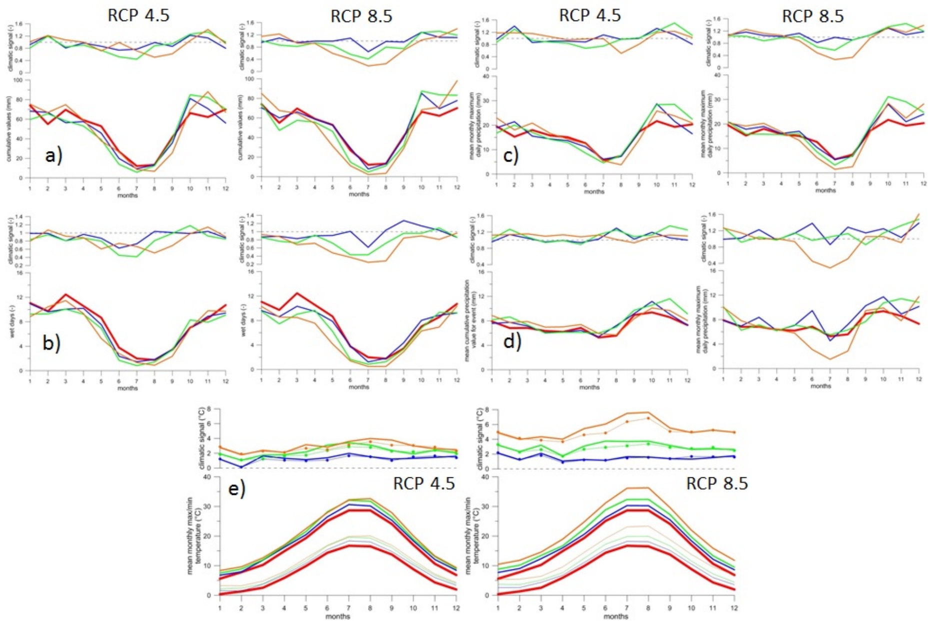

Figure 6:
Orvieto case study: bottom part: values on 1981-2010 (red line), 2021-2050 (blue line), 2041-2070 (green line), 2071-2100 (orange line); upper part: associated climatic signal: 2021-2050 vs 1981-2010 (blue line), 2041-2070 (green line), 2071-2100 (orange line) for mean cumulative precipitation values (a), wet days (b), mean monthly maximum precipitation value (c), mean monthly precipitation for event (d), average monthly maximum and minimum temperature (e)

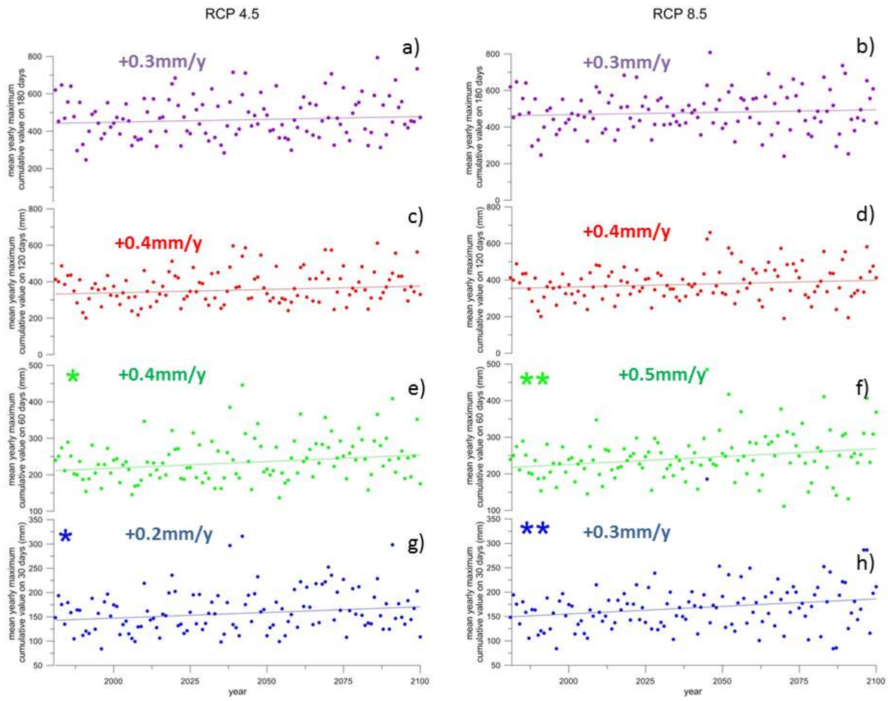

Figure 7:
For Orvieto case study: trends on time periods 1981-2100 for RCP4.5 (left column) and RCP8.5 (right column)scenarios of: (a) and (b) maximum yearly precipitation value over 180 days; (c) and (d) maximum yearly precipitation value over 120 days; (e) and (f) maximum yearly precipitation value over 60 days; (g) and (h) maximum yearly precipitation value over 30 days

pected increase in the temperature values. For these reasons, more refined analysis (through, for example, physically-based models adopted in [31]) are required to better understand if climate changes could affect in different ways shallow and deep movements (as conceivable from Fig.7) or the increase of temperature could be such to induce a substantial soil moisture depletion and subsequent improvements of average slope stability conditions.

4.3 CLIMATE SCENARIOS FOR CERVINARA CASE STUDY

The framework carried out for the other case study, constituted by flowslides affecting Cervinara (Avellino, Southern Italy), is fully similar to that, above described, for slow movements of Orvieto. Also in this case, Fig.8, under both RCPs, a dramatic decrease in cumulative values is estimated during the dry season (statistically significant for Summer and Spring at 0.01% under RCP8.5 and at 1% for Summer under RCP4.5); for winter season, for the two scenarios, remarkable variations in cumulative values are not assessed while, finally, for Spring season, the behaviour substantially differ with the “stabilization” scenario (RCP4.5) returning a slight (not significant) increase and the more “extreme” RCP8.5, confirming, also, in this case a significant (at 5%) decrease in cumulative values.

Against these differences, the projections about the temperature, Tab.2, are totally in agreement in estimating a substantial increase in minimum and maximum temperatures (statistically significant at 0.1% for all seasons and both RCPs); the magnitude of such increases is roughly equivalent to that estimated for Orvieto (Central Italy).

Refining the representation showing the data, for the 30 years periods considered, on monthly scale, Fig.9, a further confirmation of these results through the ratio defining the climatic signal between future and current time intervals constantly below the unit value (with reductions attaining 60% in dry seasons under RCP8.5); the coupled effect of decreases of cumulative values and increase in atmospheric moisture retention capacity (induced by warming) strongly affect the number of wet days, estimated decreasing, with rare exceptions, for all reference future time spans, Fig.9(b). Also in this case, the combined effect of evolutions of monthly cumulative values and wet days is assessed through average “Precipitation for Event” index, Fig.9(d); for this one, under RCP4.5, the climatic signal, for all the time intervals, is kept almost unchanged in the first part of the year (approximately Winter and Spring) while it is evaluated experiencing increases up to 30% in late Summer and Autumn partially proving that in such periods, the effect of increased atmospheric retention capacity could play a greater role compared to reduction in cumulative values in reduction of wet days; as regards the RCP8.5 scenario, the trend seems more fluctuating but mainly for the period 2071-2100, the decrease in cumulative values could regulate the estimated future precipitation patterns. Finally, concerning average values of maximum daily precipitation, under RCP4.5 scenario, for a large part of the year, increases attaining, on average, 30% are estimated while for RCP8.5, the high reduction in total amounts involve a reduction also in average maximum values, mainly in dry seasons, while in wet seasons increases up, on average, 20% are estimated mainly for farther 2071-2100. In this regard, it is worth remembering, however, again the possible weaknesses of the climate modelling in reproducing convective dynamics, especially significant, in the warmer seasons. With slight differences between maximum and minimum values, also climate signals

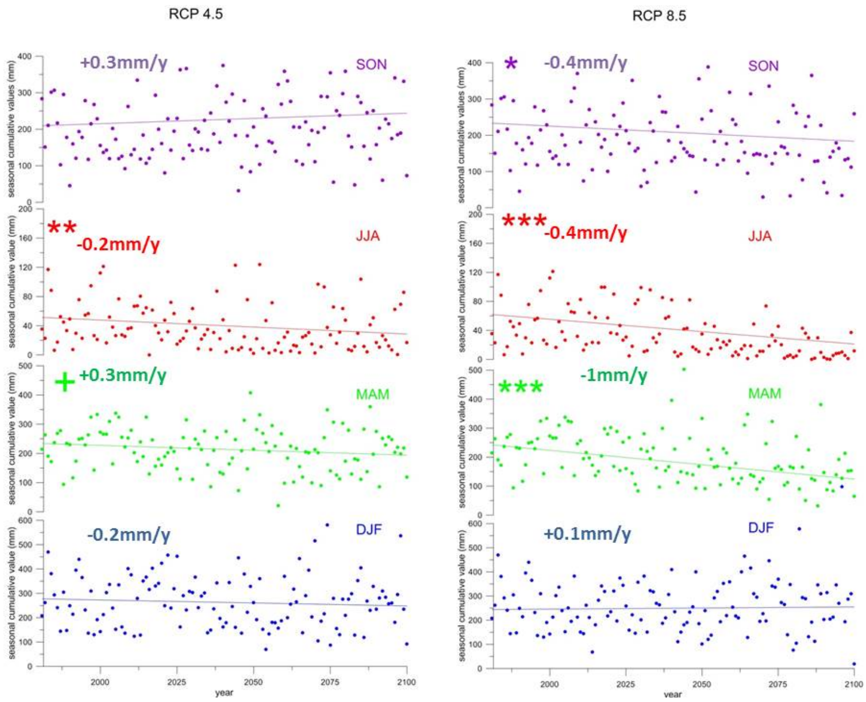

Figure 8:
for Cervinara case study; trends of seasonal precipitation on time periods 1981-2100 for RCP4.5 (left column) and RCP8.5 (right column)scenarios; are also reported trend line estimated through Theil-Sen and indications about statistical significance (+ at 10%, * at 5%, ** at 1%, *** at 0.1%) estimated through Mann-Kendall approach

Table 2

For Cervinara case study slopes of trend lines detected, through Theil-Sen approach, in evolutions of seasonal maximum and minimum temperature for RCP4.5 (upper part) and RCP8.5 (bottom part); statistical significance, assessed through Mann-Kendall approach, is also reported (+ at 10%, * at 5%, ** at 1%, *** at 0.1%)

		Max T2m		Min T2m	
		Statistical significance	°C/year	Statistical significance	°C/year
RCP4.5	DJF	***	0.03	***	0.03
	MAM	***	0.03	***	0.03
	JJA	***	0.04	***	0.03
	SON	***	0.03	***	0.03
RCP8.5	DJF	***	0.05	***	0.05
	MAM	***	0.05	***	0.04
	JJA	***	0.08	***	0.06
	SON	***	0.06	***	0.05

provided for temperature increases, are substantially equivalent to that detected for Orvieto.

Finally, the last part of discussion is aimed to discuss the trends estimated for those variables that can be assumed as "proxy" in triggering of flowslide events in Cervinara area. According what is above recalled, trends of maximum yearly values of cumulative precipitation on 30 and 60 days (1981-2100) are assumed to be relevant to assess the tendencies in potential "antecedent precipitation" while maximum yearly precipitation on 2 days is considered as reference for "main" triggering event, Fig.10.

Moreover, as, for flowslides in pyroclastic soils, the trigger is regulated by concomitant presence of a particularly wet period followed by an intense precipitation event, in order to assess future trends only of the main events in the periods of potential interest, also the trends in the maximum yearly precipitation values on 2 days occurring only during wet season, October-March, and the corresponding antecedent precipitation on 58 days are considered. For what concern the trends on 30 and 60 days, slight increases (almost unchanging and not statistically significant) are evaluated under both RCPs while, for the main event on 2 days, a more remarkable increase is assessed both considering the entire year that the only wet seasons; moreover, for RCP4.5 scenario, it is associated to a significant increase (although at 10%) of the corresponding antecedent precipitations on 58 days. Under the strong assumption of assuming all the others factors, currently, governing the phenomena as steady, such findings might suggest a not-negligible worsening of average slope stability conditions resulting in a possible increase in the number of occurrences of flowslides events. On the other hand, this preliminary estimate, mostly qualitative, carried out in "isothermal conditions", neglects the potential beneficial effect of the increased evapotranspiration on the slope stability; for these reasons, also in this case, clearer indications about the possible trends require the adoption of more physically based tools allowing, for example, to estimate soil surface water balances and the linked variations in soil suction regulating the triggering of landslide events.

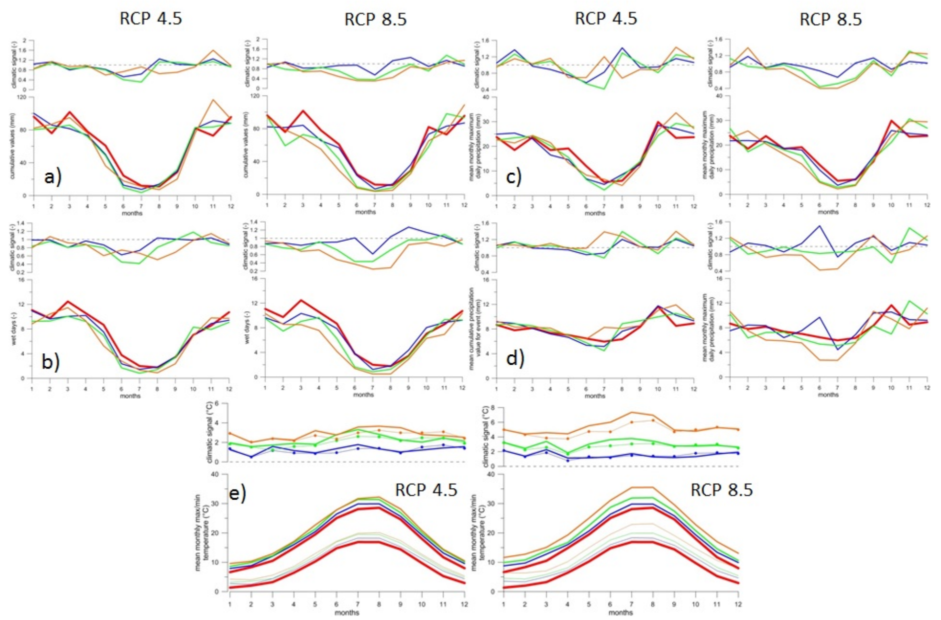

Figure 9:
Cervinara case study: bottom part: values on 1981-2010 (red line), 2021-2050 (blue line), 2041-2070 (green line), 2071-2100 (orange line); upper part: associated climatic signal: 2021-2050 vs 1981-2010 (blue line), 2041-2070 (green line), 2071-2100 (orange line) for mean cumulative precipitation values (a), wet days (b), mean monthly maximum precipitation value (c), mean monthly precipitation for event (d), average monthly maximum and minimum temperature (e)

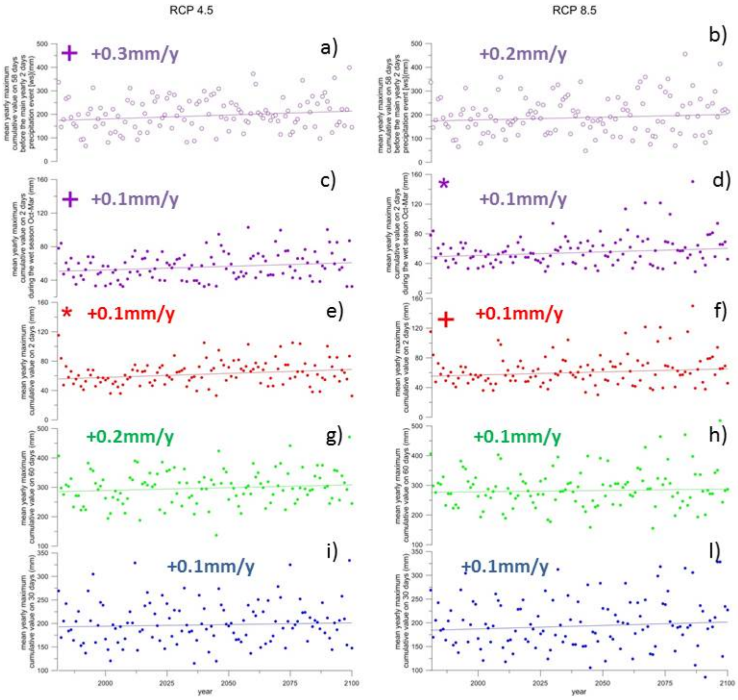

Figure 10:
for Cervinara case study: trends on time periods 1981-2100 for RCP4.5 (left column) and RCP8.5 (right column) scenarios of: (a) and (b) maximum yearly precipitation value over 58 days before the corresponding maximum 2 days event simulated in wet season; (c) and (d) maximum yearly precipitation value over 2 days simulated in wet season; (e) and (f) maximum yearly precipitation value over 2 days considering the entire year; (g) and (h) maximum yearly precipitation value over 60 days; (i) and (l) maximum yearly precipitation value over 30 days

5. CLIMATE PROJECTIONS FOR PO RIVER BASIN TEST CASE

For the flood and drought case study area, i.e. Po river basin, the main features of temperature and precipitation, for XXI century under RCP4.5 and RCP8.5, are investigated in terms of anomalies with respect to the control period 1982-2011 of seasonal weather pattern and of annual cycle; moreover trend and distribution probability are analysed at seasonal scale. The statistical significance of trends is tested using Mann-Kendall test. The capability of the GCM/RCM couple to reproduce the observed climate in terms of seasonal patterns and annual cycle is presented before discuss the climate projections. Differently to landslide phenomena, to deal with floods/droughts phenomena on Po river daily precipitation and temperature data are sufficient due to the basin extension, in a smaller basin the study of floods will require sub-daily time series.

5.1 SUMMARY OF PERFORMANCES OF CLIMATE MODELS ON CONTROL PERIOD

This section presents the validation of the climate outputs, precipitation and 2 meter mean temperature, simulated by COSMO-CLM driven by ERA-Interim reanalysis [11] and by the GCM CMCC-CM [35] with respect to a gridded climate dataset provided by the Hydro-Meteo-Climate Service of the Regional Agency for Prevention and Environment (ARPA SIMC) of the Emilia-Romagna Region. The dataset is based on the meteorological data published in the Hydrological Yearbooks and integrated with observations, validated and quality checked, collected by the stations network in Po river catchment. The interpolation method used to generate the dataset is the inverse of the distance; for temperature the orographic effect is considered using a fixed gradient. The precipitation data span from 1971 to 2010 and those of temperature cover the period 1990-2010 due to the low density of the temperature measurements network before 1990. The validation period is 1991-2010, Fig.11, alternatively, the validation over a 30 year long period of the RCM outputs both driven by climate reanalysis and by the GCM, is available in [6, 7]. Figure 11 shows the seasonal bias maps of COSMO-CLM driven by ERA-Interim Reanalysis and CMCC-CM global model against observations. Concerning temperature (Fig.11(a)), ERA-Interim driven simulation shows a very good agreement with the observations in Spring and Autumn, with a bias close to 0°C in most of the domain under study. In Winter, a general cold bias is registered (with peaks of -3°C), probably ascribed to an underestimation of the real orography, whereas in Summer a general temperature overestimation occurs (with the exception of the Alpine arc). The summer warm bias can be caused by a tendency of COSMO-CLM to underestimate latent heat fluxes (with a consequent overestimation of sensible heat fluxes) [2], along with an underestimation of cloud cover. It is worth noting that a general tendency of RCMs to underestimate winter temperature, in particular over mountainous chains and Alps, e.g. [10], and overestimate the summer ones, e.g. [4], especially in semi-arid regions and south Europe is reported in literature. However, with respect to other studies at coarser resolution, the bias found in this work is lower, highlighting the role of the horizontal resolution [29]: for example, some RCMs driven by ERA-Interim reanalysis involved in EURO-CORDEX project [23] at horizontal resolution of 0.11° exhibit even -5°C of difference with respect to observations in Winter, whereas in Summer, overestimation over Italian domain generally ranges between +2 and +3°C. The CMCC-CM driven simulation

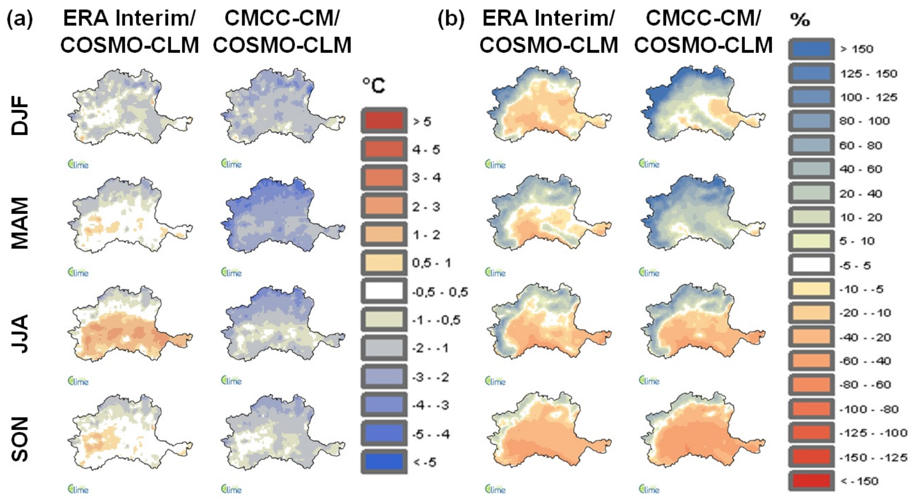

Figure 11:
Bias of (a) 2-meter mean temperature (°C) and (b) precipitation (%) of ERA-Interim/COSMO-CLM and CMCC-CM/COSMO-CLM simulations for all the seasons

Table 3
Average value of 2 meter mean temperature (°C) and precipitation (mm/day) of observation (OBS) and synthetic errors (BIAS, MAE, RMSE) of the same fields from COSMO-CLM driven by ERA-Interim and CMCC-CM with respect to observation for the four seasons.

		T2m (°C)			P (mm/day)		
Season	Index	ERA-Interim/ COSMO-CLM	CMCC-CM/ COSMO-CLM	OBS COSMO-CLM	ERA-Interim/ COSMO-CLM	CMCC-CM/ COSMO-CLM	OBS COSMO-CLM
	Average	0.14	-0.63	1.02	2.08	2.89	1.97
DJF	BIAS	-0.89	-166	-	0.10	0.91	-
	MAE	0.91	2.30	-	0.39	1.79	-
	RMSE	1.01	2.85	-	0.50	2.13	-
	Average	9.12	6.86	9.51	3.42	4.53	2.86
MAM	BIAS	-0.38	-2.64	-	0.56	1.67	-
	MAE	0.49	2.82	-	0.68	2.28	-
	RMSE	0.63	3.30	-	0.89	2.79	-
	Average	19.82	17.51	19.13	2.72	2.86	2.58
JJA	BIAS	0.69	-1.62	-	0.14	0.27	-
	MAE	0.81	2.10	-	0.66	1.39	-
	RMSE	0.98	2.50	-	0.89	1.87	-
	Average	9.96	8.92	10.12	3.31	3.07	4.13
SON	BIAS	-0.16	-1.20	-	-0.82	-1.06	-
	MAE	0.50	1.87	-	1.02	2.29	-
	RMSE	0.59	2.30	-	1.40	3.02	-

is affected by a general cold bias in all seasons (higher than the simulation driven by "perfect" boundary conditions), more pronounced in Spring, where peaks of -5°C are reached; it is partially due to the general tendency of the Atmosphere-Ocean General Circulation Models to underestimate the temperature [24]; in particular, [18] has verified that CMCC-CM is generally affected by a cold bias up to -2°C over the Mediterranean area. For precipitation, Fig.11(b), both simulations are affected by an overestimation over Alps. It is more evident in Spring, when the simulation forced by CMCC-CM shows the highest bias. Over the plain area, instead, an underestimation occurs, stronger in Autumn. The error occurring over mountainous areas has already been reported in other works, e.g. [19], and it can be caused by the joint underestimation of the orographic effects joint and of precipitations, the latter caused by the hydrometeor deflection due to wind, that lead to an undercatchment of the observed rainfall [1, 15]. Table 3 reports the values of three objective quantities for performance evaluation, namely BIAS (Model minus Observation), MAE (Mean Absolute Error) and RMSE (Centered Root Mean Square Error); they have been computed for both ERA-Interim and CMCC-CM driven climate simulations spatially averaged over the whole Po river basin.

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(S_i - O_i) \quad (1)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|(S_i - O_i)| \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2} \quad (3)$$

where N is the size of the sample, S_i and O_i are, respectively, simulated and observed value at the i-th time step. The index BIAS provides estimate of the average error, but it is affected by a possible error compensations, whereas MAE and RMSE yield the average magnitude error without indicating the direction of the deviation (in addition, the latter tends to emphasize large errors than smaller ones). Results show a very good agreement between ERA-Interim forced simulation and observations, both for 2 meter mean temperature and precipitation (mean BIAS never exceeds 1°C and 1 mm/day in absolute value). Spring and Autumn are characterized by the lowest T2m BIAS (-0.38°C and -0.16°C, respectively), but they are characterized by the highest precipitation error, with a general Spring overestimation and Autumn underestimation (however smaller than 40%). CMCC-CM driven simulation is characterized by a more pronounced error, in all seasons and for both the variables under study. BIAS is higher than 100% in winter season, both for temperature and precipitation; that is strongly overestimated also in Spring (more than 1.67 mm/day on average).

5.2 CLIMATE PROJECTIONS

In the next section, we present the outputs of the climate projections at 2021-2050, 2041-2070 and 2071-2100 under RCP4.5 and RCP8.5 scenarios on Po river basin. For each period, the estimated precipitation and temperature are illustrated in terms of spatial and temporal anomalies with respect to 1982-2011, and in terms of trends and probability distribution functions (pdfs). The statistical significance of (linear) trend has been tested through the non parametric Mann-Kendall test.

Period 2021-2050 The first period under analysis is 2021-2050 and within this period, the RCP4.5 and RCP8.5 scenarios agree in projecting a decrease in summer precipitations, (-20% and -15%, respectively) and an increase in the autumnal ones (+2.1% and +8.2%, respectively), in particular, along the main channel of Po river (Fig.12(a)). Under the stabilization scenario RCP4.5, in Winter, the precipitation reduces of about 8.4% mostly on the north-eastern side of basin, while, under RCP8.5, it increases of about 7.4%. In Spring, under RCP4.5 scenario the simulated precipitation is lower than in the control period (-11%) and it is almost unvaried (-1.1%) considering the RCP8.5 projection. Temperature are increasing under both scenarios over the entire basin, considering RCP4.5 emissions, the temperature anomaly ranges between 0.9°C (in Winter) and 1.7°C (in Summer), and it varies between 1.3°C (Spring and Autumn) and 1.7°C (in Winter) under RCP8.5, Fig.12(b).

Figure 13 shows the anomaly in monthly precipitation (a) and 2 meter mean precipitation (b). For precipitation, Fig.13(a), the two scenarios are in agreement, monthly anomalies range between -32% in July and +18% in November (RCP4.5) or between -47% in July and +26% in December, if RCP8.5 emissions are considered. The shape of the monthly temperature anomaly, Fig.13(b), is similar under both emission scenarios but the magnitude is different, 0.7-3.1°C for RCP4.5 and 2.3-4.9°C for RCP8.5.

In 2021-2050, RCP4.5 and RCP8.5 climate projections show a substantial agreement in seasonal trends and variability of average precipitation and 2 meter mean temperature as shown in Fig.14. According to Mann-Kendall test, any of the seasonal precipitation trend is statistically significant at 5%, while, for temperature, the linear trend hypothesis is not rejected in Summer (Autumn) under RCP4.5 (RCP8.5) scenario. With more details, in Winter, RCP4.5 and RCP8.5 precipitations are characterised by slopes close to zero (0.01 and -0.003 mm/day/year, respectively) both higher than the one of the control period (-0.02 mm/day/year); in Spring, the slopes are positive: 0.03 and 0.02 mm/day/year, respectively versus 0.01 mm/day/year of the control period; in Summer, a negative tendency is found (-0.03 and -0.02 mm/day/year, respectively) comparable with the one (-0.03 mm/day/year) of the control period; and, in Autumn, the trend is positive (0.01 mm/day/year) for RCP4.5 projections and negative (-0.02 mm/day/year) according to RCP8.5 scenarios, in the control period the autumnal trend is positive (0.02 mm/day/year). For temperatures, both simulations in all seasons show positive trends; in particular, in Winter, RCP4.5 trend is higher than RCP8.5 one (0.04 vs 0.02°C/year) but lower than in the control period (0.05°C/year); the same considerations hold for Spring with trends equal to 0.05°C/year (control period); 0.02 (RCP4.5) and 0.002°C/year (RCP8.5). In Summer, the temperature growth rate of RCP4.5 simulation (0.07°C/year) is comparable with the one of the control period (0.06°C/year) and higher than RCP8.5 one (0.02°C/year); in Autumn, RCP8.5 simulation is characterised by a slope (0.05°C/year) comparable with the control period (0.05°C/year) and while RCP4.5 simulation slope (0.02°C/year) is lower.

The seasonal pdfs of precipitation and 2 meter mean temperature are reported in Fig.15. In Winter, the probability of null precipitation ($P \leq 1$ mm/day) is almost unvaried with respect to 1982-2011 period, while low precipitation rate show a slight increase in their frequency; for temperature a shift of about 1°C, toward right, in the modal value is evidenced under both scenarios, that show a different variability: between -15°C and 9°C (RCP4.5) and between -12°C and 9°C (RCP8.5); the variability in the control period is -15°C to 8°C. In Spring, the probability of $P \leq 1$ mm/day is increasing, while the pdf of $P > 1$ mm/day is substantially unvaried, also the pdf of temperature is almost constant. In Summer, the null precip-

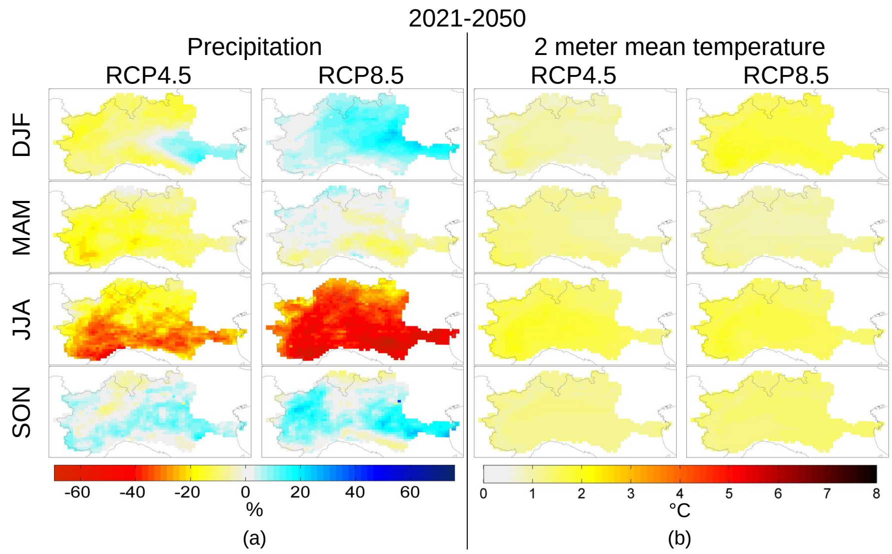

Figure 12:
Anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2021-2050 period with respect to 1982-2011.

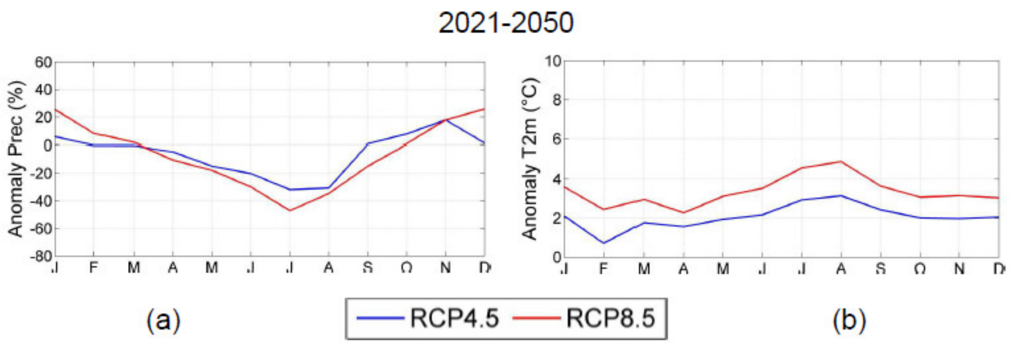

Figure 13:
Monthly anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2021-2050 period with respect to 1982-2011.

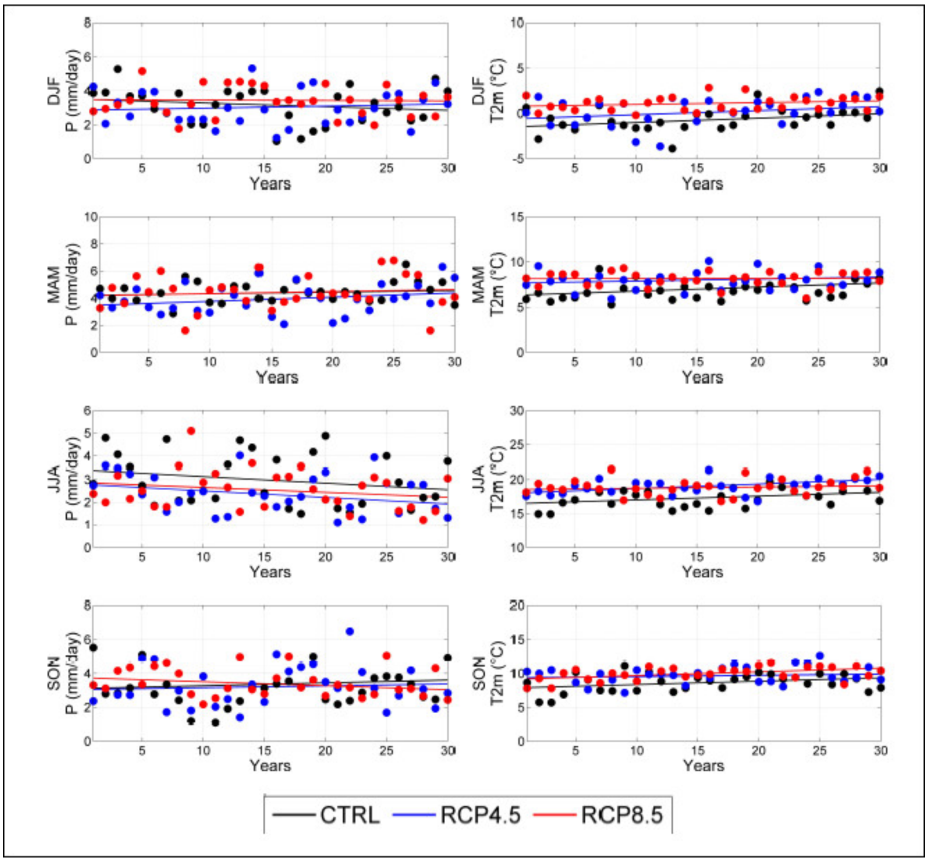

Figure 14:
Trend in average seasonal precipitation and 2 meter mean temperature in the 2021-2050 under RCP4.5 (blue) and RCP8.5 (red). Trend in the control period (black) is reported for comparison.

itation is constant for RCP4.5 and increasing for RCP8.5, and precipitations between 1 to 10 mm/day show a higher frequency than in the control period; the shape of the temperature pdfs is similar to the control period but shifted of about 1°C towards right. In Autumn, the probability of $P \leq 1$ mm/day is similar to the control period for both scenarios, and low precipitation are less frequent than in the 1982-2011 period; the shape of the temperature pdf is similar to the control period, with a plateaux at 6°C that persists also in the 2021-2040 period.

Period 2041-2070 The second period considered is 2041-2070. Within this period, RCP4.5 and RCP8.5 climate projections show more variability than in the 2021-2050 period previously analysed. Both RCP4.5 and RCP8.5 scenarios project the decrease of spring and summer precipitations (Fig.16(a)). Under the stabilization scenario RCP4.5, in Spring, the precipitation varies of -7.9% mostly on the north-eastern side of basin, while under RCP8.5 the reduction is slightly higher, -9.2%, and the most affected areas are localised on the Apennines (southern boundary of the basin). Under both scenarios, about 1/3 of the summer precipitation is lost on the entire basin, in particular in the Po valley, while in Autumn, the precipitation is expected to increase, but the spatial distribution of the anomaly is different. According to RCP4.5, the precipitation increases (18%) all over the basin, instead following RCP8.5, positive changes are mostly localised along the Po river main channel and negative on the Apennines, and in average the total precipitation is constant being the average anomaly equal to 0.9%. Under RCP4.5, winter precipitation slightly reduces, -3.8%; mostly in the western part of Po Valley and on the Apennines, while on Alps is almost unvaried; considering RCP8.5 precipitation increases, 7.3%, mostly on the north-eastern side of the basin. For temperature, Fig.16(b), both scenarios project a positive anomaly in all the seasons, ranging between 1.7°C in Spring and 3.1°C in Summer and between 2.4°C in Spring and 3.7°C in Summer, for RPC4.5 and RCP8.5 projections, respectively. Figure 17 shows the anomaly in monthly precipitation (a) and 2 meter mean precipitation (b). For precipitation, Fig.17(a), the highest uncertainties, i.e differences between the projections, are detected in January: RCP4.5 presents a negative (-11%) anomaly while RCP8.5 a positive (+17%) one and in September, where RCP4.5 anomaly is positive (+24%) and the one associated to RCP8.5 is negative (-8.3%). The shape of the monthly temperature anomaly, Fig.17(b), is quite similar for both scenarios but magnitude is quite different, 0.8-3.3°C for RCP4.5 and 1.8-4.1°C, for RCP8.5. Precipitation projected trends, Fig.18 are both positive in Winter, 0.01 mm/day/year for RCP4.5 and 0.02 mm/day/year for RCP8.5; both negative in Spring, -0.01 mm/day/year (RCP4.5) and -0.07 mm/day/year (RCP8.5) and Summer, -0.01 mm/day/year (RCP4.5) and -0.03 mm/day/year (RCP8.5) and positive for RCP4.5, 0.02 mm/day/year and negative -0.02 mm/day/year for RCP8.5. The RCP8.5 spring and summer trends are statistically significant according to Mann-Kendall test with a confidence level of 5%. The precipitation variability of control period and projections is comparable in Winter and Spring, while in Summer both projections show lower precipitation and, in Autumn, the RCP4.5 is characterised by a higher interannual variability than RCP8.5 and the control period. Temperature trends are positive for both scenarios in all the seasons, and, with the exception of Winter, all statistically significant. The RCP4.5 temperature trends are equal to 0.001°C/year (Winter), 0.04°C/year (Spring), 0.06°C/year (Summer) and 0.08°C/year (Autumn); for RCP8.5 estimated trends are 0.06°C/year (Winter),

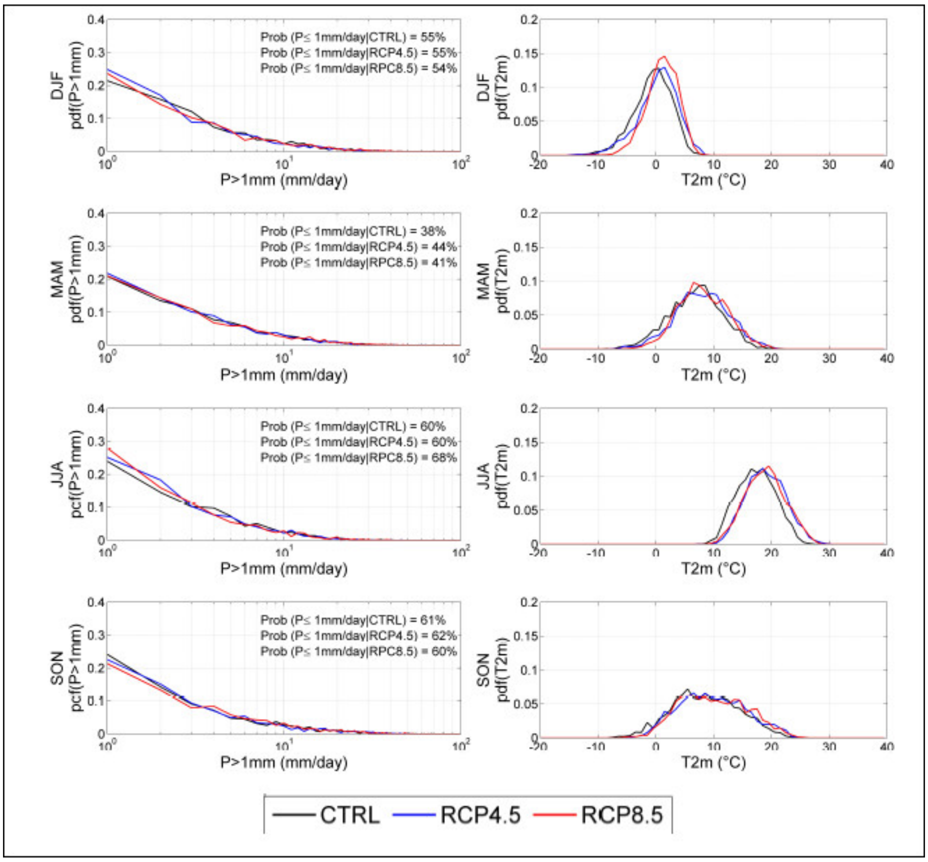

Figure 15:
Probability distribution function (pdf) of average seasonal precipitation and 2 meter mean temperature in the 2021-2050 under RCP4.5 (blue) and RCP8.5 (red). The control period pdf (black) is reported for comparison.

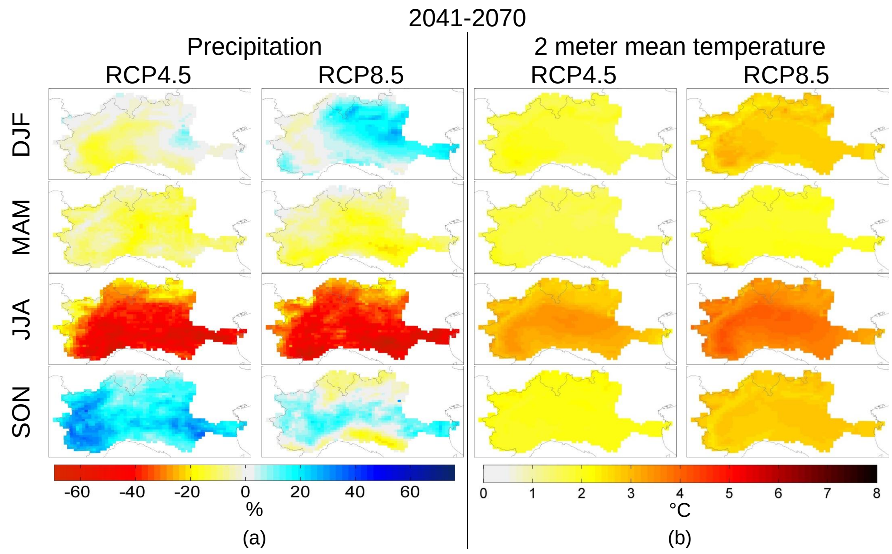

Figure 16:
Anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2041-2070 period with respect to 1982-2011.

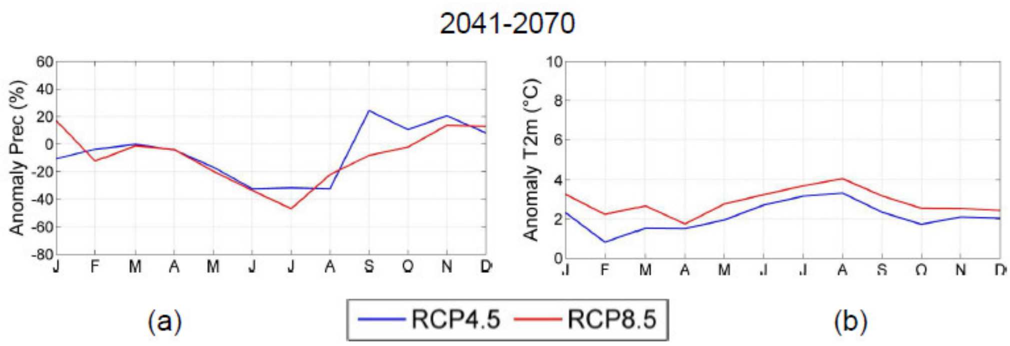

Figure 17:
Monthly anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2041-2070 period with respect to 1982-2011.

0.10°C/year (Spring), 0.17°C/year (Summer) and 0.10°C/year (Autumn) and, in average, temperatures are higher than in the control period.

The seasonal pdfs of precipitation and 2 meter mean temperature are reported in Fig.19. In Spring and Summer, the probability of $P \leq 1$mm/day is characterised by the highest variations, from 38% in the control period to a 45% either for RCP4.5 and RCP8.5, and from 60% to 63% (RCP4.5) and 67% (RPC8.5), respectively. Summer is also characterised by the highest increase in low (but higher than 1 mm/day) precipitations frequency, while limited changes are present in the other seasons. With the exception of Autumn where a frequency plateaux is found, the temperature pdfs are all characterised by a shift in the modal value. In average, RCP4.5 and RCP8.5 temperatures are characterised by higher extreme values than the control period.

Period 2071-2100

The third period considered is 2071-2100. Concerning precipitation (Fig.20(a)), RCP4.5 projection shows a positive anomaly in winter precipitations, in particular over Po Valley whereas negligible differences are found on Alps: on average, the positive variation is about 11%. RCP8.5 projection expects an increase of about 38% in the precipitation over the whole Po river basin. The RCP4.5 signal in winter precipitation is now positive, i.e. there is more precipitation than in the control period. A possible explanation is related to the positive temperature anomaly in Autumn/Winter that forces the evaporation from the soil increasing the air humidity fostering the winter precipitation. In Spring, under both scenarios precipitations reduce on the eastern part of the basin, the variation is more marked under RCP8.5. On the western Alps, according to RCP4.5 a light increase of precipitation is expected while following RPC8.5 it reduces; in average, the winter precipitation varies of -1.4% (RCP4.5) and -14% (RCP8.5). In Summer, the RCP4.5 precipitation reduction is almost the same (about -28%) of 2041-2070 period, but with no more evident dependency on altitude; under RCP8.5 scenario precipitation variation is -57%. In Autumn, RCP4.5 precipitation increases of about +5.3% and the variations are localised on Piemonte and eastern side of Po river main channel, similarly to the anomaly shown by RCP8.5 projections on 2041-2070; RCP8.5 precipitation reduces on Apennines and, partially, on Alps while it is unvaried on the Po Valley, the overall reduction is less than 5%. Concerning temperatures the positive anomaly detected in 2041-2070 projections is present and more marked, on average, for RCP4.5, it will range between +2.3°C in Winter and Spring and +3.5°C in Summer and, for RCP8.5, between 4.1°C in Spring and 7°C in Summer, Fig.20(b). Figure 21 shows the anomaly in monthly precipitation (a) and 2 meter mean precipitation (b). With the exception of March, October and November, the uncertainty in the magnitude of precipitation changes is high, beside that, the tendency is clear: precipitation increases between November and April(RCP4.5)/March(RCP8.5) and decreases in the rest of the year. Considering RCP4.5 scenario the changes range between -36% in August and +23% in November and between -67% in July and 46% in December for RCP8.5 projections. Thus, the 2071-2100 projection of precipitation are affected by a higher uncertainty than the previously analysed periods. This is reasonable considering the increasing differences in the projected emissions. Also in 2071-2100, the two simulations agree in the shape of the monthly temperature anomaly, Fig.17(b), that show a variability between 2.7-4.2°C for RCP4.5 and 3.6-5.2°C for RCP8.5.

The RCP4.5 projection shows positive trends

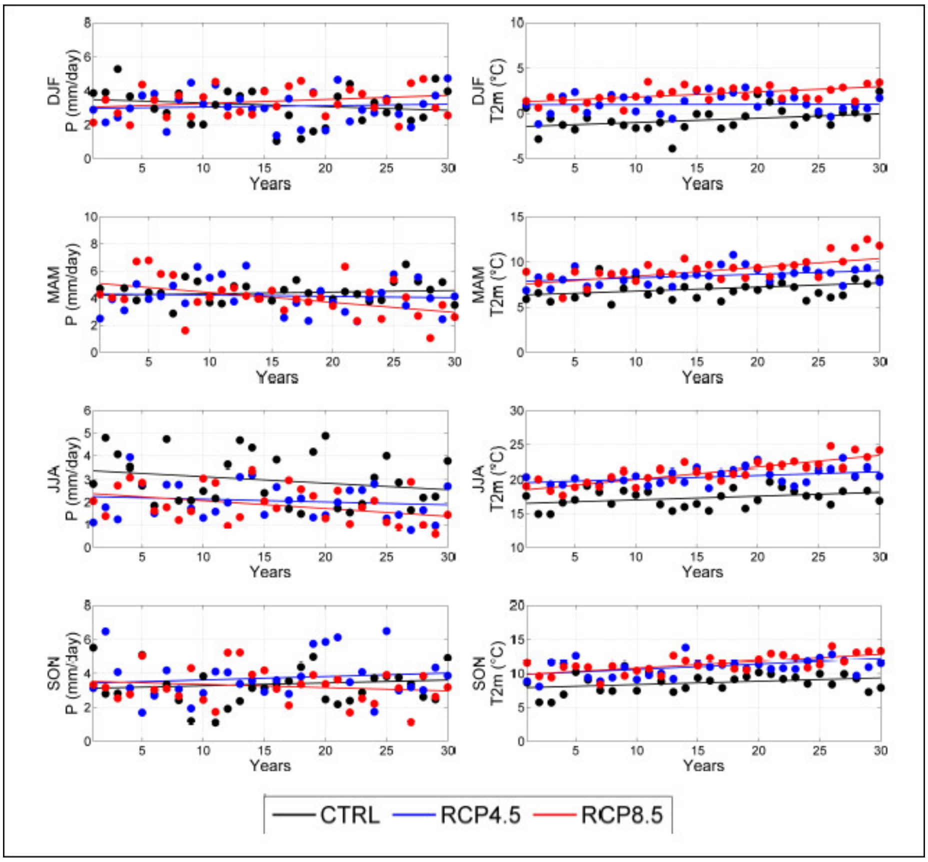

Figure 18:
Trend in average seasonal precipitation and 2 meter mean temperature in the 2041-2070 under RCP4.5 (blue) and RCP8.5 (red). Trend in the control period (black) is reported for comparison.

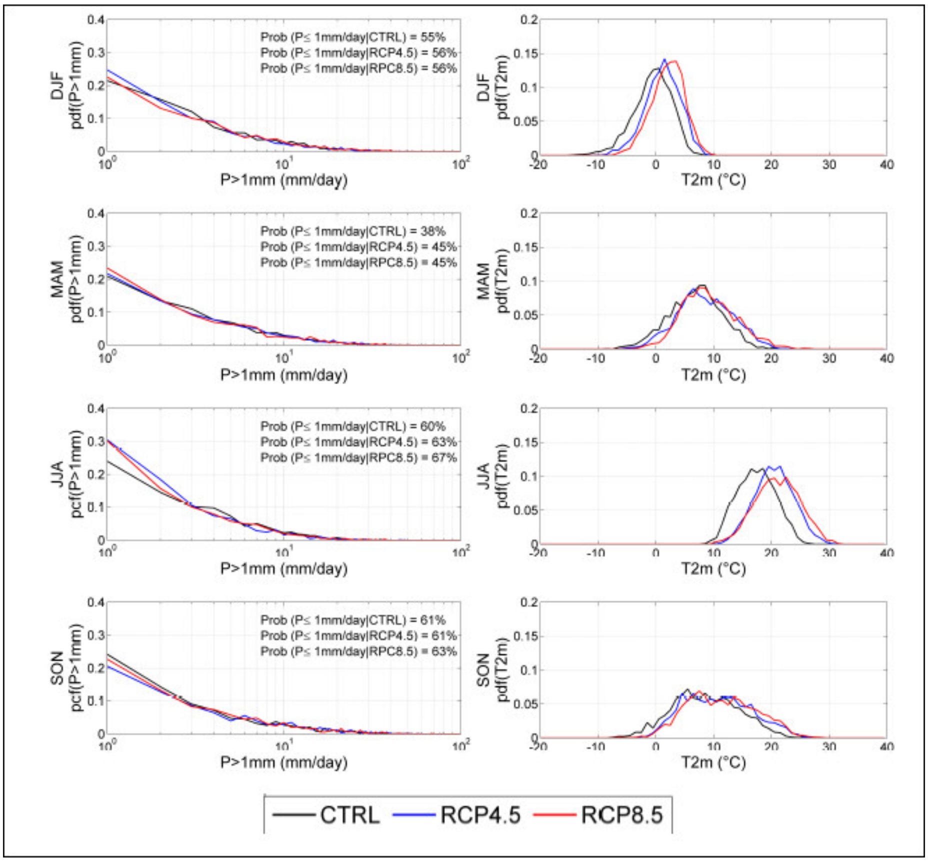

Figure 19:
Probability distribution function (pdf) of average seasonal precipitation and 2 meter mean temperature in the 2041-2070 under RCP4.5 (blue) and RCP8.5 (red). The control period pdf (black) is reported for comparison.

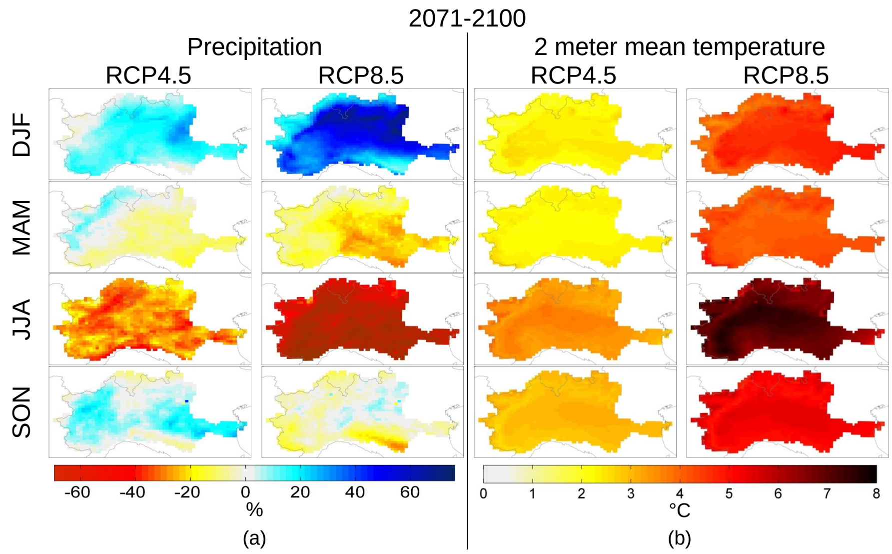

Figure 20:
Anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2071-2100 period with respect to 1982-2011.

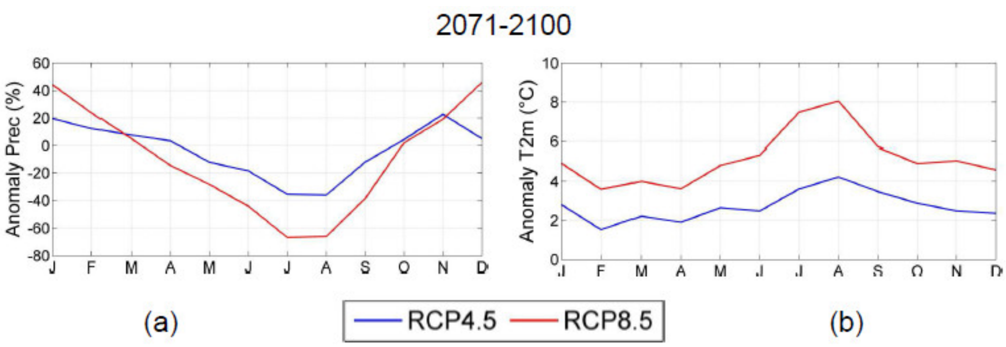

Figure 21:
Monthly anomaly of (a) precipitation (%) and (b) 2-meter mean temperature (°C) of CMCC-CM/COSMO-CLM simulations under RCP4.5 and RCP8.5 scenarios in the 2071-2100 period with respect to 1982-2011.

in Winter (0.03 mm/day/year) and Spring (0.01 mm/day/year) precipitations and negative in Summer (-0.04 mm/day/year) and Autumn (-0.03 mm/day/year), only, for Summer the null hypothesis of Mann-Kendall test is not rejected with a confidence level of 5%. The RCP8.5 projected precipitation is characterised by a positive trend in Winter (0.06 mm/day/year) and negative in the rest of the year, -0.04 mm/day/year (Spring), -0.02 mm/day/year (Summer) and -0.01 mm/day/year (Autumn), any of these trend is statistically significant. It is worth to note that, Winter and Spring precipitations show an inter-annual variability comparable to the control period, Fig.22. For temperature, under RCP4.5 scenarios, slightly negative trends are computed in Winter (-0.02°C/year) and Spring (-0.003°C/year), a positive trend is found in Summer (0.05°C/year) while, in Autumn, the trend is null. RCP8.5 temperatures are characterised by positive, and statistically significant, trends in all the seasons: 0.008°C/year in Winter, 0.09°C/year in Spring, 0.12°C/year in Summer and 0.09°C/year in Autumn.

The comparison among the seasonal precipitation pdfs show that in Spring, Summer and Autumn, the probability of $P \leq 1$ mm/day is higher than in the control period, with the highest probabilities associated to RCP8.5 values. In Winter, the RCP4.5 (RCP8.5) probability of $P \leq 1$ mm/day is equal to (less than) the control period one, Fig.23. Changes in low precipitation (but higher than 1 mm/day) frequency are detected in Summer (increase) and Autumn (decrease). For temperature the shift in the modal values is confirmed and more marked than in 2041-2070 period, Fig.23.

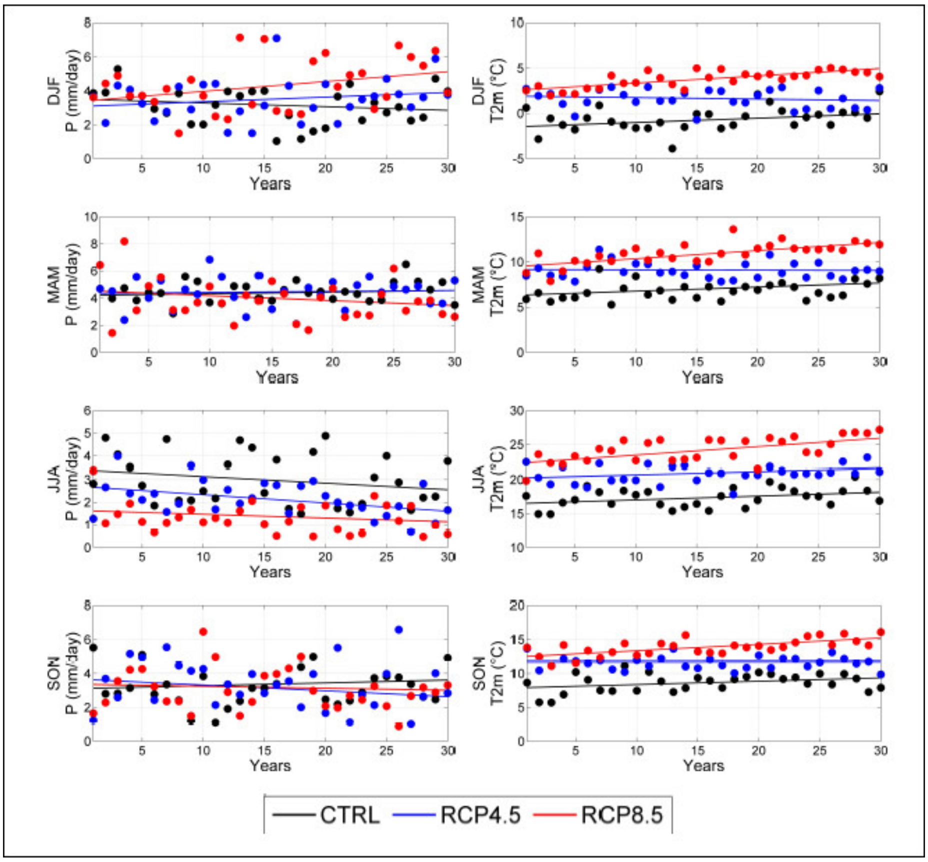

Figure 22:
Trend in average seasonal precipitation and 2 meter mean temperature in the 2071-2100 under RCP4.5 (blue) and RCP8.5 (red).
Trend in the control period (black) is reported for comparison.

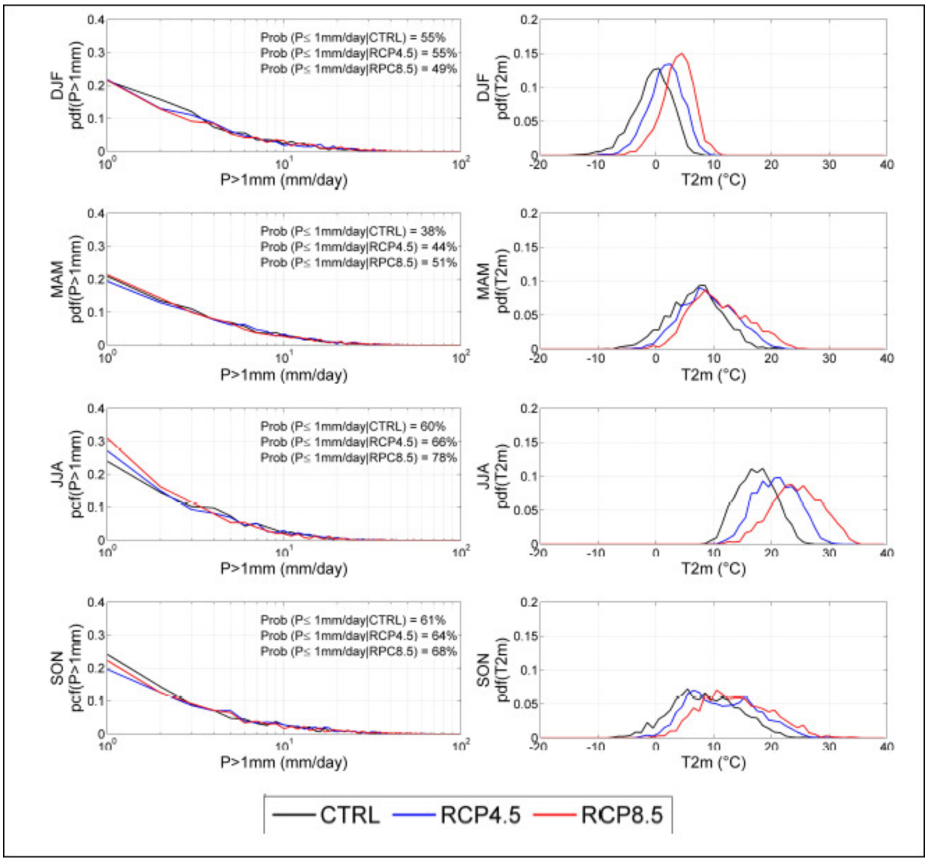

Figure 23:
Probability distribution function (pdf) of average seasonal precipitation and 2 meter mean temperature in the 2071-2100 under RCP4.5 (blue) and RCP8.5 (red). The control period pdf (black) is reported for comparison.

6. CONCLUSIONS

In the present work, a further intermediate step in the developing of the assessment of the potential effect of climate changes on geo-hydrological hazards is carried out: the estimate of the future trends (until 2100 under RCP4.5 and RCP8.5) of the variables, temperature and precipitation, mostly regulating soil processes which determine the hazards in selected hot spots: Po river basin (flood and low flow hazard), Cervinara and Orvieto (respectively, for fast and slow slope instability process); it follows the assessment of performances of simulation chain (for single “rings” or full asset) carried out in [32, 31, 5, 51, 45, 47, 46] and essentially consisting in: i)validation of numerical climate models, ii) developments of bias correction approaches and iii) calibration and validation of impact tools. The climate variables are provided by high resolution climate projections, performed within A.2.6 work package of GEMINA project [6, 7, 29, 52]; in accordance with was also recalled in the introduction, the high horizontal resolution (about equal to 8 km) characterizing the adopted RCM simulations, attempts to “narrow” the current gap existing between the spatial scale of climate simulation and impact tools; moreover, it represents a crucial added value in estimating the variation in geo-hydrological hazards strictly linked to a proper evaluation of extreme values, beyond representing an indisputable advantage, in general, also for average values on a domain, like Italy, characterized by a very complex geomorphology. The results achieved confirm the general findings according which, in a not so far future, Mediterranean areas could experience (1) warmer temperature inducing, in turn, (2) a more pronounced seasonality in precipitation, with wetter Autumns (RCP4.5) or Winters (RCP8.5) and drier Summers. However, although the “direction” of the indicated variations seems clear, their magnitude is affected by well known uncertainties related to climate projections (first and foremost, the one linked to the assumptions underlying RCPs). Since precipitation and temperature are the main drivers of surface processes, the uncertainty in their projections has to be taken into account to correctly estimate the geo-hydrological hazards related to climate change. Regarding the specific nature of hot spots, in the work, parameters of interest and their representation has been tailored according their peculiar features (i.e. extent, reference time spans of hazards) while keeping in mind the current weaknesses of climate simulation. Despite the number of cases is limited, even in this case as for the validation, a key point of the carrying out research is represented by the development of a framework entirely and blindly replicable in the study of other geo-hydrological (and not only) hazards. To this aim, it worth noting that the main difficulty is related to finding case studies properly documented allowing the calibration and validation of the impact tools on Italian domain; on the other hand, however, they are case studies representative for dramatically widespread phenomena in the Italian context. Finally, the next step, already in progress, is represented by evaluation of the effects of changes of weather variables on hazards through the adoption of the specific impact tools.

A. MANN KENDALL TEST

The non parametric Mann-Kendall test[25, 22] tests the H_0 hypothesis of trend absence versus the H_1 hypothesis of the existence of a preferential order in the observations. The test statistics S is computed on the basis of the relative ordering of all possible pairs of data points:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i). \tag{4}$$

where $sign(\cdot)$ is 1 if $(\cdot) > 0$ and -1 if $(\cdot) < 0$. The variable S is characterised by mean $\mu_S = 0$ and variance $\sigma_S^2 = n(n-1)(2n+5)/18$ The test variable Z_s is relate to S by

$$Z_s = \frac{S - sign(S)}{\sigma_S}, \tag{5}$$

the variable Z_s is distributed as $N(0,1)$, thus a comparison between Z_s and the inverse of $N(0,1)$ provides the critical value for Mann-Kendall variable. The monotonic trend has been estimated according to Thiel-Sen approach [20] as:

$$\beta = median\left[\frac{x_j - x_i}{j - i}\right], \quad \forall i < j \tag{6}$$

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