Research Papers
Issue RP0263
November 2015

Regional Models and geo-Hydrogeological Impacts Division

Evaluation of downscaling and bias correction techniques to link climate and geo-hydrological impacts models

By **Paola Mercogliano**
Meteo System & Instrumentation Laboratory, CIRA - Capua Regional Models and geo-Hydrogeological Impacts Division, CMCC - Capua
p.mercogliano@cira.it

Guido Rianna
Regional Models and geo-Hydrogeological Impacts Division, CMCC - Capua
guido.rianna@cmcc.it

Renata Vezzoli
Regional Models and geo-Hydrogeological Impacts Division, CMCC - Capua
renata.vezzoli@cmcc.it

Veronica Villani
Regional Models and geo-Hydrogeological Impacts Division, CMCC - Capua
veronica.villani@cmcc.it

and **Valentina Coppola**
Regional Models and geo-Hydrogeological Impacts Division, CMCC - Capua
valentina.coppola@cmcc.it

This report represents the Product P93c of Work Package 2.17 Action A of the GEMINA Project, funded by the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea. The authors would also like to thank NEXTDATA project for supporting this research.

SUMMARY This document is the product P93c of GEMINA project. It is aimed to collect the main results achieved from the application of bias correction and weather generators techniques to climate simulations to estimate weather-related geo-hydrological impacts. This activity is carried out 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 climate change effects 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 (WP A.2.6). Thus, in this document, the effects of downscaling and bias correction techniques on simulated/projected geo-hydrological hazards are investigated at different scales on the test case areas identified in WP A.2.17: Po river basin, Orvieto sites and the additional test case of Calore Irpino basin in southern Italy.

Keywords: Bias correction, statistical downscaling, geo-hydrological impacts

INTRODUCTION AND MOTIVATION

In the last years, the evaluation of the potential effect of climate changes on geo-hydrological hazards became one of the main topic in climate change research [44, 7, 38, 39, 6, 8]. To this aim, the different proposed modeling chains are generally formed by three macro-elements: climate models providing weather inputs, impact models differing for hazard, spatial scale, geomorphololological contexts and "linking approaches" mode. Basically, such ones fulfil two crucial roles: attempting to bridge the spatial gap currently existing between usual horizontal resolutions adopted in climate models (especially in the global ones); trying to correct (also partly) biases in weather forcing of interest currently affecting climate models in order to allow quantitative estimations of variations in hazards. In particular, regarding the second issue, the presence of biases in RCM outputs is mostly related to their horizontal resolution, i.e. for Europe, the state of art is about 25 km in ENSEMBLE project (www.ensembles-eu.org) or about 11 km in CORDEX project (http://wcrp-cordex.ipsl.jussieu.fr) that reflects in insufficiently resolved surface properties and parametrizations of sub-grid scale processes (i.e. deep convection, soil surface balances) strictly linked to occurrence of extreme weather events and geo-hydrological hazards. As showed in [29, 30, 48], the validation phase on control period reveals 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), while weather generators are used to produce synthetic time series starting from observed data. The adoption, in cascade to the RCM of a statistical methodology like bias correction or Weather Generators allows to cope mismatching problems and to provide, at the same time, a substantial correction of weather forcing distribution making them suitable as input for hydrological and impact models [42, 24, 25, 40]. It is worth to note that the adoption of such approaches introduces a further element of uncertainty to be taken into account in impacts studies [9, 19]. However, a deeper understanding about the performances and constraints of these techniques (either bias correction and weather generator) is crucial to assess their effects on impacts simulations and projections; that is the main aim of this work. Beyond an assessment about relative performances in reproducing weather variables on the areas, the goal concerns an increasing awareness about how these approaches could affect the derived components of soil surface budgets strictly governing the occurrence of geo-hydrological hazards. So, the main aims of this research paper are to display the capability of bias correction and weather generator techniques to reproduce observed weather (mostly precipitation and 2m temperature) variables and their statistics and to assess the impact of these techniques in the capability of the modeling chain described in [46] to reproduce observed geo-hydrological hazards.

In the following we describe (a) the test cases areas for landslides and floods/droughts phenomena; (b) the bias correction and the weather generator techniques used together with the comparison of their impacts on the assessment of the hydrological cycle. Specifically, Orvieto test case will be used to compare bias correction and weather generator approaches on precipitation and temperature and the related effects on hydrologically relevant variables, Calore Irpino river basin test case will be used to compare six different bias correction approaches and their effects on the hydrological cycle at basin scale, Po river basin test case provides a comparison between the performances of raw and bias corrected climate as input to reproduce observed discharges and the volume of high (a proxy for floods) and low (a proxy for droughts) flows.

TEST CASES

ORVIETO

The test case Orvieto (Central Italy), Fig.1, is 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 [27]. 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) [33].

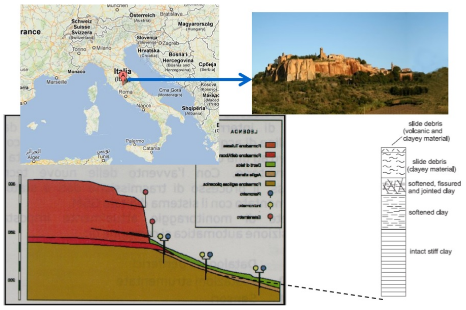


Figure 1:
Geographical location and schematic representation of Orvieto site

CALORE IRPINO BASIN

The Calore Irpino River basin covers an area of about 3058 km^2 in Campania, Fig.2. The River length is about 108 km long and the average discharge is 31.8 m^3/s at its outlet in the Volturno River. The Calore Irpino River basin is characterised by a micro-climate that, together with the water availability guarantee by the River itself, foster the cultivation of vegetables, vineyard and olive trees. The occurrence of climate changes may alter the equilibrium of this ecosystem with impacts on the local economy. The test case is a limited portion of the basin, i.e. the basin closed at the Montella section due to the availability of meteorological and hydrological data.

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 val-

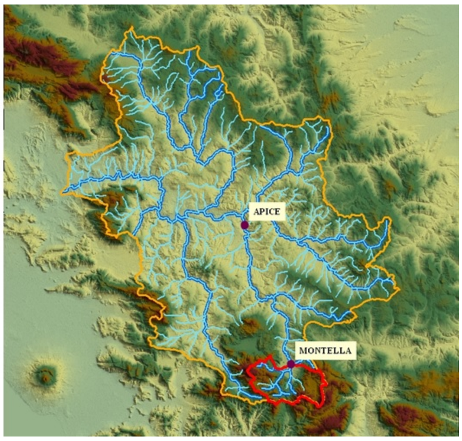


Figure 2:
Calore Irpino basin and sub-basin closed at Montella

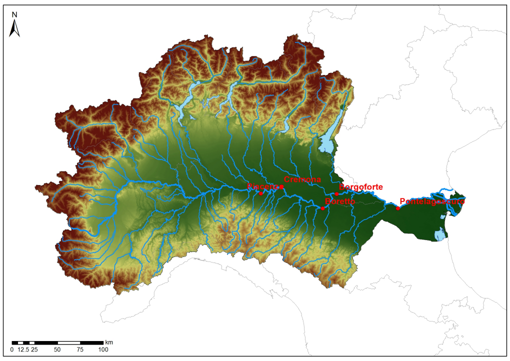


Figure 3:
Po basin: hydrological network and main closure sections

ley 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, [45] and signal of changes in precipitation and temperature are present in climate observations [34, 5, 31].

BIAS CORRECTION AND WEATHER GENERATOR TECHNIQUES

A proper reproduction of observed hydrological conditions ("minimum requirement" [43]) through a correct estimate of the components of water/energy budgets and of weather forcing is needed to investigate the potential effects of climate changes on the hydrological cycle and, especially, on weather-induced geo-hydrological hazards. Within GEMINA project the focus has been mostly on precipitation and temperature values [35, 36, 48, 28, 38, 39], because of their key role in the hydrological cycle [14] that regulates the triggering/reacceleration of landslide movements and floods/droughts occurrence. Furthermore, adequate (for length, resolution and quality) observed datasets required for implementation of statistical methods are often not available for variables other than precipitation and temperature. In the next a brief description of bias correction techniques and weather generator tested is given. Note that other bias correction techniques like linear scaling and analogs have been previously tested [48, 37, 35, 36].

BIAS CORRECTION TECHNIQUES

Bias correction techniques provide a re-scaling of climate model output in order to reduce the effects of systematic errors [29]. In the last years, several approaches [29, 17] have been developed and tested in different geographical and geomorphological contexts providing key information about actual performances and capabilities. Numerous researches [48, 29, 30, 17, 2] identify quantile mapping (or distribution mapping) approaches as the most efficient tools in removing biases, the approach is based on the following relationship

$$F_O(x) = F_S(x) \qquad (1)$$

where $F_O(x)$ and $F_S(x)$ are the cumulative distribution functions of, respectively, the observed and simulated datasets for the variable X. The bias corrected value x^* obtained using the equation:

$$x^* = F_O^{-1}(F_S(x)) = h(x). \tag{2}$$

The main differences between the distribution mapping methods are due to $h(x)$ transformation and they can be classified as [13]:

- distribution derived transformations for which $h(x)$ adopts Bernoulli distribution to model occurrence and different optional approaches for intensities, in this study the Bernoulli-Weibull, Bernoulli-Gamma, Bernoulli-Lognormal and Bernoulli-Exponential mixture have been considered;
- parametric quantile-quantile approaches according which $h(x)$ is an algebraic relationship between simulated and observed quantiles;
- non parametric transformations (also known as empirical quantiles) (EQ) where $h(x)$ is the empirical CDF and values falling between -reference percentiles are obtained by interpolation

DISTRIBUTION DERIVED TRANSFORMATIONS

This approach is valid for adjusting modelled precipitation and it assumes that F is a mixture of the Bernoulli and the Gamma (or Weibull or Lognormal or Exponential) distribution. The Bernoulli distribution models the probability of precipitation occurrence (π) and the other distribution $G(x > 0)$ the intensity. The cumulative distribution function $F.$, of both observed and simulation datasets is defined as

$$F.(x) = \begin{cases} (1-\pi) + \pi \times G.(x) & \text{if } x > 0 \\ 1-\pi & \text{if } x = 0 \end{cases} \tag{3}$$

PARAMETRIC QUANTILE-QUANTILE APPROACHES

In parametric quantile-quantile approaches,the distribution of the modelled data is adjusted to match the distribution of the observations using a parametric transformations to the quantile-quantile relation of observed and modelled values. Different $h(x)$ functions are possible to link the observed values x_O to the simulated x_S ones

$$x_O = \begin{cases} bx_S & \text{scale} \\ a + bx_S & \text{linear} \\ b{x_S}^c & \text{power} \\ b(x_S - x_0)^c & \text{power.}x_0 \\ (a + bx_S)(1 - \exp^{-x_S/\tau}) & \text{expasympt} \\ (a + bx_S)(1 - \exp^{-(x_S - x_0)/\tau}) & \text{expasympt.}x_0 \end{cases} \tag{4}$$

where a, b, c, x_0 and τ are free parameters to be calibrated. For precipitation, all parametric transformations are fitted to the continuous part of the distribution function (x>0) and modelled values corresponding to the dry part of the observed empirical distribution function are set equal to zero.

NONPARAMETRIC TRANSFORMATIONS

A common approach is to solve Eq.(2) using the empirical cumulative distribution function of observed and modelled values instead of assuming a parametric distributions. Different approaches are possible, among them:

- SSPLIN: a smoothing spline is used to fit the quantile-quantile plot of observed and modelled timeseries;

- QUANT: regularly spaced quantiles are used to characterise the empirical cumulative distribution function of observed and modelled timeseries, linear interpolation is used for the remaining quantiles;
- RQUANT: as in QUANT but using local linear least square regression.

All these methods are implemented in Clime [4] and are based on the freely available in *qmap* R-package [12]. Figure 4 reports the comparison, among observed, GCM/RCM simulated and bias corrected precipitation (1972-2001) and temperature (1972-1994) timeseries at the station of Montella (Calore Irpino test case).

The quantitative comparison between the average monthly precipitation observed, simulated and bias corrected show that parametric quantile-quantile and non parametric techniques outperform the distribution derived transformations methods based on Bernoulli distribution, while for temperature non parametric techniques reproduces better the observed average values across the year. However, the non parametric two-sample Kolmogorov-Smirnov goodness-of-fit hypothesis test (see pvalues in Fig.4's legend) indicates that, with a confidence level of 5%, QUANT and RQUANT bias corrected precipitation and QUANT bias corrected temperature are drawn from the "same" underlying continuous population, i.e. have the same distribution, of observations.

WEATHER GENERATOR

Recently, stochastic weather generators are used as tools for statistical downscaling from GCMs [16, 10]. Weather generators are classified as “Richardson” type when the occurrence of wet and dry days is modelled according Markov chain procedure and “Racsko” type when wet/dry series are estimated as “random variables” on the basis of the proportion of observed events [26].

In this study, for precipitation only, we applied the freely available LARS-WG (Long Ashton research Station- Weather Generator) based on “Rackso” type approach. On monthly scale, daily values are selected as random variables chosen by fixed intervals having as selection probability the relative proportion of events; after, in each class, an uniform distribution is adopted. Other climate variables like minimum and maximum temperatures are estimated in a subsequent further stochastic process conditioned on wet/dry status. Figure 5 provides, for the 1981-2010 period, the comparison among observed, GCM/RCM, bias corrected and weather generator downscaled precipitation for Orvieto test case.

The quantitative comparison between the cumulative monthly values and wet days return that the performances of the weather generator are comparable to those of non parametric methods and parametric quantile-quantile methods. [41] reports a comparison of the performances of the different approaches using the no parametric two samples Cramer-von Mises (CvM) test. The test results show that (a) CDFs provided by RCM are significantly different by observed ones for almost the entire year except in dry months when probably a large occurrence of zero values could partly cover the differences between CDFs; (b) distribution derived approaches provide a moderate improvement in dry months but it seems to fail to adequately correct rainfall patterns during wet months probably due to the limited flexibility of the approach; (c) non parametric methods outperform the other approaches both in terms of cumulative values that wet days.

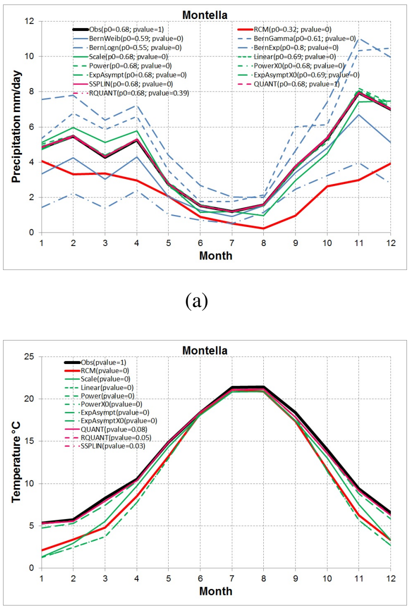


Figure 4:
Comparison among observed, GCM/RCM simulated and bias corrected (a) precipitation and (b) temperature timeseries at Montella station

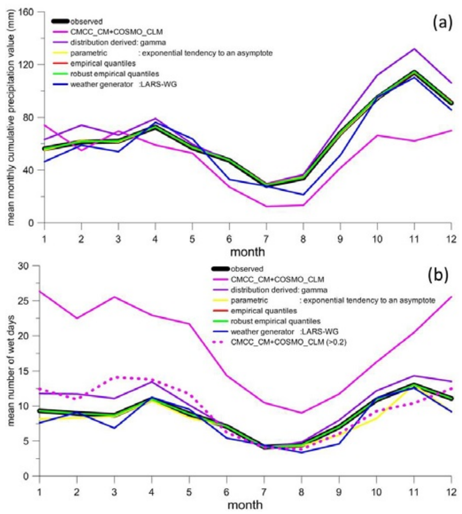


Figure 5:
(a) Monthly cumulative values. (b) Mean monthly number of wet days. Black line: observed values; magenta line: simulated values through climate models GCM/RCM; other lines: simulated values through BC or WG approaches for Orvieto case study. Source [41]

EFFECTS OF BIAS CORRECTION ON HYDROLOGICAL CYCLE AND ON GEO-HYDROLOGICAL HAZARDS

This section is devoted to understand the effects of the above described bias correction approaches in the simulation of the main components of the soil water balance since soil water content is one of the triggering factor for geo-hydrological hazards. The main components of soil water balance are precipitation as ingoing flow and evapotranspiration, runoff, infiltration as main outgoing flows.

ORVIETO TEST CASE

For Orvieto test case, the analysis are performed considering raw and Rquant bias corrected precipitation and temperature time-series, in particular, Fig.6(a) reports the comparison with observations for precipitation, maximum and minimum temperature, diurnal temperature range before and after the bias correction and Fig.6(b) the effects on runoff in clay and sand soils, potential evaporation and actual evaporation in clay and sand soils estimated respectively from observed, raw and bias corrected values. The analysis have been carried out using HELP (Hydrologic Evaluation of Landfill Performance) [1]. For the estimation of the main components of the soil water balance using observed, raw and bias corrected precipitation and temperature data please refer to [41, 40].

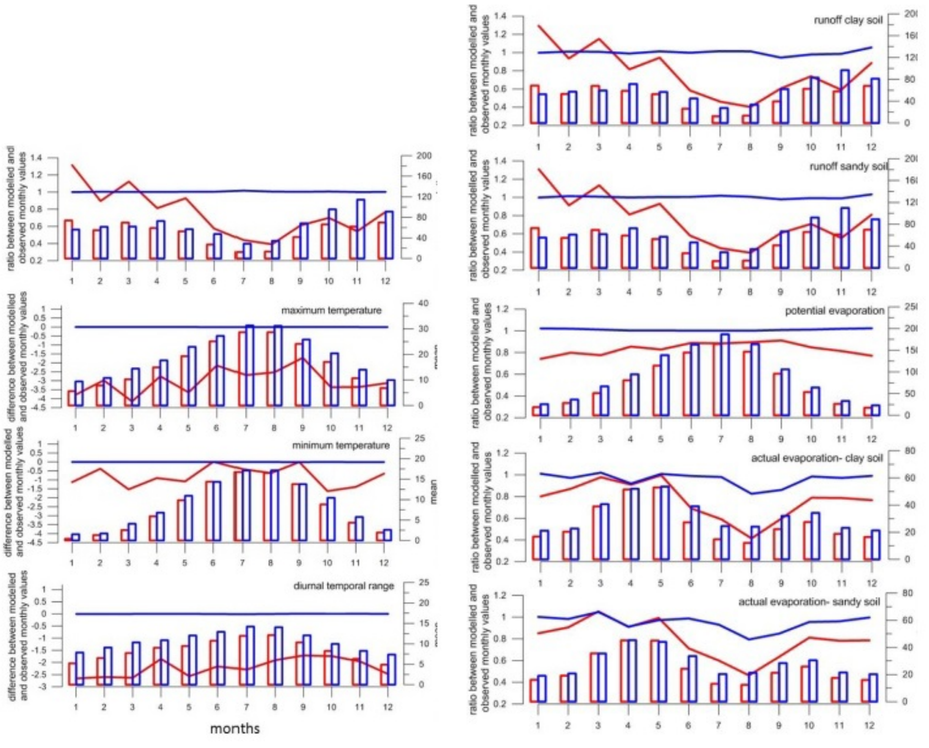
Figure 6(a) allows to point out that on control period, climate simulations return cold biases substantially different for Tmax and Tmin (for the first one, 2-4°C while for the second one not exceeding 1.5°C) and therefore probably depending on different capability to reproduce the atmospheric dynamics during day or night; on the other hand, also for temperature, regardless to its value, RQuant bias correction reduces the error.

In Figure 6(b) the performances of models driven by raw or bias corrected RCM are fully consistent with that displayed for precipitation in terms of runoff seasonal cycles (first two rows) being overestimated in the first part of the year and underestimated in the second one while a perfect overlapping is, generally, achieved using bias corrected climate; a slight worsening of the performances is observed in bias corrected driven model during the second part of dry season probably due to key role of precipitation temporal distribution that was not considered in this analysis. For potential evapotranspiration, the underestimation of maximum and minimum temperature results in an underestimation ranging between 60% and 85% with respect to values retrieved starting from observed data. The estimated actual evaporation (last two rows) is generally underestimated and during the dry season a substantial undervaluation of infiltration induces biases greater than 60%. At the same time, also models forced by BC values display worse performances mainly during the dry season revealing the ”summing” effect of the coupled errors (albeit small).

CALORE IRPINO RIVER BASIN TEST CASE

The hydrological cycle of Calore Irpino river basin closed at Montella river section is simulated through the physically based hydrological model TOPKAPI [32] that, for each couple of precipitation and temperature given as input, returns, among others, the estimated: discharge (m^3), net precipitation (mm), snow (mm), potential and actual evapotranspiration (mm), percolation (mm), surface runoff (mm), and soil saturation (%). For this test case, eight couples, among those in Fig.4, of precipitation and temperature timeseries are considered: observed, raw GCM/RCM, linear, power.x_0 and expasympt for parametric quantile-quantile methods and QUANT, RQUANT and SSPLIN for non parametric methods.

Figure 7 reports the comparison for the period 1972-1993 of the different simulations for the following variables: discharge, net precipitation, actual evapotranspiration, percolation, surface runoff and soil saturation. Note that only for discharge, the comparison with the observed value is possible, for the other variables the reference value will be the one simulated by TOPKAPI driven by observed climate. Results show a good agreement in the average performances of the different methods with exception of QUANT and power.x_0.



(a) (b)

Figure 6:
(a) Continuous line ratio (first), difference (the other ones) between bias corrected (blue) or raw RCM (red) and observed value; absolute values are displayed as bars, from top to bottom: precipitation, maximum temperature, minimum temperature, diurnal temporal range. (b) Continuous line ratio between bias corrected (blue) or raw RCM (red) and observed value; absolute values are displayed as bars, from top to bottom: runoff clay soil, runoff sandy soil, potential evaporation, actual evaporation clay soil, actual evaporation sandy soil. Source [41]

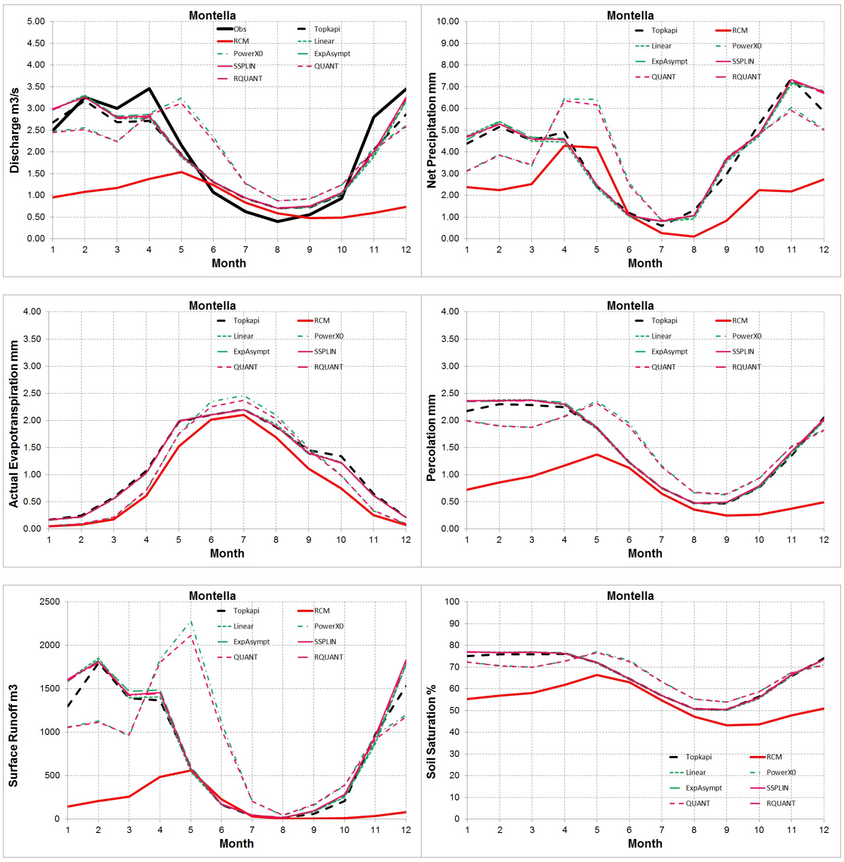


Figure 7:
Comparison over the period 1972-1993 of TOPKAPI outputs in terms of: discharge (observed values are reported too), net precipitation, actual evapotranspiration, percolation, surface runoff and soil saturation. Climate inputs are: observations (black), raw RCM/GCM (red)), bias corrected with linear, power.x_0, expasympt, QUANT, RQUANT and SSPLIN approaches. Parametric quantile-quantile methods are in green and non parametric methods in magenta.

PO RIVER BASIN TEST CASE

Po river basin is more complex to model than Calore Irpino due to its dimension and the high anthropogenic pressure on the water balance [21]: the industrial/civil water demand is estimated in 5 km^3/year and the volume regulated from Alpine lakes is about 1.3 km^3. These fluxes are modelled through the basin water balance model RIBASIM [15]. In this case, the bias in simulated precipitation and temperature is relevant for both the “natural” and “human driven” component of the basin water balance and their cumulated effects are synthesised by the error in simulated discharges at the closure section of Pontelagoscuro. Considering the results presented in [47, 50], for the Po river basin test case the most adequate bias correction techniques is the distribution derived quantile mapping: in particular, precipitation is assumed to follow a Gamma distribution and temperature a Gaussian one [39]. Figure 8 reports the comparison among seasonal and annual cycle for observed, raw and bias corrected temperature and precipitation in the control period 1982-2011.

The CMCC-CM driven simulation is affected by a general cold bias in all seasons 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 [18]; in particular, [11] have verified that CMCC-CM is generally affected by a cold bias up to -2°C over the Mediterranean area. The precipitation in CMCC-CM driven simulation is overestimated over Alps, instead, an underestimation occurs over the plain area. The performances of the GCM/RCM couple over the Italian territory have been investigated in [3, 22, 23, 47, 49]. With the application of bias correction, the average seasonal temperature field is correctly reproduced, with a mean bias close to 0°C in all seasons. Concerning precipitation, the most evident result is the reduction of the spring overestimation over Alpine arc and of autumn underestimation over Po plain (about 0.4 mm/day). A comparison between corrected, not-corrected values and observations in terms of annual cycles highlights the strong improvement of results due to the application of the quantile mapping technique: the COSMO-CLM/CMCC-CM cold bias is almost totally removed in all the months, as well as the winter and summer precipitation bias, with a strong reduction of the error characterizing spring months. It is worth noting that the application of quantile mapping allows an improvement in the representation of the seasonal spatial pattern, especially for precipitation.

The bias removal has impact on the simulated Po river discharges as shown in Fig.9 where the discharges obtained from TOPKAPI/RIBASIM simulations driven by CMCC-CM/COSMO-CLM and by bias corrected climate are compared with observations in terms of annual cycle and average high and low flows valume that are of interest for river water management.

The discharge ($Q_{CMCC-CM}$) simulated using raw precipitation and temperature timeseries follow the precipitation temporal distribution pattern with a delay in the spring peak while the autumnal peak is correctly located but underestimated; discharges results to be overestimated when precipitation exceeds the observed ones, e.g. in June and July, and underestimate if precipitation is less than the observed one, e.g. in November and December. The comparison between $Q_{CMCC-CM}$ and observed extreme flows shows an overestimation of the highest flow in summer and of lowest in winter, mostly related to the temporal distribution of precipitation. The discharges simulated using the bias corrected climate $Q_{CMCC-CM/QM}$ show

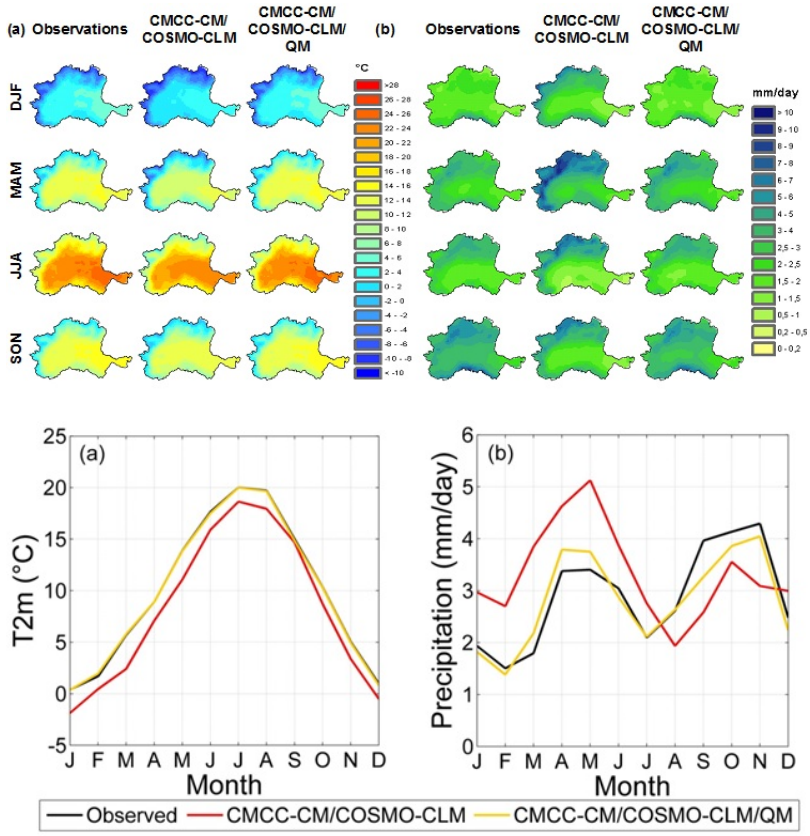


Figure 8:
First row. Climatology of Po river basin: seasonal (a) 2 meter mean temperature in °C and (b) precipitation in mm/day; for observations, COSMO-CLM driven by CMCC-CM, and bias corrected simulations. Second Row. Monthly areal averaged (a) 2 meter mean temperature in °C and (b) precipitation in mm/day for observations (black), COSMO-CLM driven by CMCC-CM (red), and bias corrected CMCC-CM/COSMO-CLM/QM (orange) simulated time series

a good agreement with observed ones either in terms of average values and high/low flows volume and temporal distribution.

CONCLUSIONS

This study illustrates how the application of the appropriate statistical downscaling technique may represent a valuable tool to correctly reproduce quantitatively and qualitatively the occurrence and evolution of weather-related geo-hydrological impacts in control period and, mainly, how these techniques could improve the evaluation of the soil water balance (characterized by highly non linear processes) that, in turns, modifies the geo-hydrological hazards occurrence and severity. The results indicate that the hybrid (dynamical and statistical) downscaling approach, generally, improves the capability of the climate-impact modelling chain in reproducing both qualitatively and quantitatively the observed variables. In particular, we test different bias correction and weather generator based techniques on different, in terms of climate and geo-hydrological hazard to be investigated, test cases to identify the pros and cons of each technique finding that non parametric approaches seems to outperform the others methods but attention should be paid when they are used out of their calibration range. Between parametric and distribution derived methods the latter has the advantage of correcting all the moments of the distribution function making this approach more suitable to deal with extremely high (low) precipitation and temperature values.

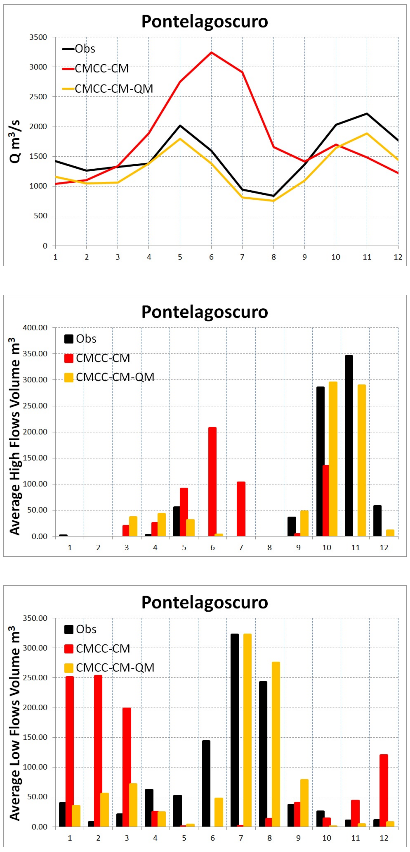


Figure 9:
First row. Climatology of Po river basin: seasonal (a) 2 meter mean temperature in °C and (b) precipitation in mm/day; for observations, COSMO-CLM driven by CMCC-CM, and bias corrected simulations. Second Row. Monthly areal averaged (a) 2 meter mean temperature in °C and (b) precipitation in mm/day for observations (black), COSMO-CLM driven by CMCC-CM (red), and bias corrected CMCC-CM/COSMO-CLM/QM (orange) simulated time series

As last we would like to remark that, these techniques, even if they introduce an additional element of uncertainty to the overall modelling chain [9, 19], do not alter the climate signal thus are a useful tool to provide qualitative and quantitative estimates of the climate change impacts on geo-hydrological hazards as shown in [39, 20, 48, 50, 49].

Bibliography

[1] *The Hydrologic Evaluation of Landfill Performance (HELP) model: Engineering documentation for version 3*. U.S. Environmental Protection Agency Office of Research and Development, 1994.

[2] J. Boe, L. Terray, F. Habets, and E. Martin. Statistical and dynamical downscaling of the Seine basin climate for hydro-meteorological studies. *International Journal of Climatology*, 27(12):1643–1655, 2007.

[3] E. Bucchignani, P. Mercogliano, M. Montesarchio, M.P. Manzi, and A.L. Zollo. Performance evaluation of COSMO-CLM over Italy and climate projections for the XXI century. In *Climate change and its implications on ecosystem and society: Proceedings of I SISC (Società Italiana di Scienze del Clima) Conference*, pages 78–89, 2013.

[4] L. Cattaneo, V. Rillo, M.P. Manzi, V. Villani, and P. Mercogliano. Clime: climate data processing in gis environment. *CMCC - Research Paper*, RP0257, 2015.

[5] N. Ciccarelli, J. von Hardenberg, A. Provenzale, C. Ronchi, A. Vargiu, and R. Pelosini. Climate variability in north-western Italy during the second half of the 20th century. *Global and Planetary Change*, 63:185–195, 2008.

[6] J.A. Coe and J.W. Godt. Review of approaches for assessing the impact of climate change on landslide hazards. In *Landslides and Engineered Slopes, Protecting Society Through Improved Understanding*, volume 1, pages 311–377, 2012.

[7] E. Coppola, M. Verdecchia, F. Giorgi, V. Colaiuda, B. Tomassetti, and A. Lombardi. Changing hydrological conditions in the Po basin under global warming. *Science of Total Environment*, 493:1183–1196, 2014.

[8] M.J. Crozier. Deciphering the effect of climate change on landslide activity: A review. *Geomorphology*, 124:260–267, 2010.

[9] U. Ehret, E. Zehe, V. Wulfmeyer, K. Warrach-Sagi, and J. Liebert. Should we apply bias correction to global and regional climate model data? *Hydrol. Earth Syst. Sci.*, 16:3391–3404, 2012.

[10] S. Fatichi, V.Y. Ivanov, and E. Caporali. Simulation of future climate scenarios with a weather generator. *Advances in Water Resources*, 34:448–467, 2011.

[11] S. Gualdi, S. Somot, L. Li, V. Artale, M. Adani, A. Bellucci, A. Braun, S. Calmanti, A. Carillo, A. DellÁquila, M. Déqué, C. Dubois, A. Elizalde, A. Harzallah, D. Jacob, B. L'Hévéder, W. May, P. Oddo, P. Ruti, A. Sanna, G. Sannino, E. Scoccimarro, F. Sevault, and A. Navarra. The CIRCE simulations: Regional climate change projections with realistic representation of the Mediterranean Sea. *Bulletin of the American Meteorological Society*, 94:65–81, 2013.

[12] L. Gudmundsson. *qmap: Statistical transformations for post-processing climate model output*, 2014. R package version 1.0-3.

[13] L. Gudmundsson, J.B. Bremnes, J.E. Haugen, and T. Engen-Skaugen. Technical note: Downscaling RCM precipitation to the station scale using statistical transformations - a comparison of methods. *Hydrology and Earth System Sciences*, 16:3383–3390, 2012.

[14] S. Hagemann, C. Chen, O.J. Haerter, J. Heinke, D. Gerten, and C. Piani. Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *Journal of Hydrometeorology*, 12:556–578, 2014.

[15] Delft Hydraulics. Ribasim - river basin planning and management simulation program. Technical report.

[16] C.G. Kilsby, P.D. Jones, A.A. Burton, C. Ford, H.J. Fowler, C. Harpham, P. James, A. Smith, and R. Wilby. A daily weather generator for use in climate change studies. *Environmental Modelling and Software*, 22:1705–1719, 2007.

[17] T. Lafon, S. Dadson, G. Buys, and C. Prudhomme. Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods. *International Journal of Climatology*, 33:1367–1381, 2013.

[18] I. Macadam, A.J. Pitman, P.H. Whetton, and G. Abramowitz. Ranking climate models by performance using actual values and anomalies: Implications for climate change impact assessments. *Geophysical Research Letters*, 37(16), 2010.

[19] D. Maraun. Bias correction, quantile mapping and downscaling. revisiting the inflation issue. *Journal of Climate*, 26:2137–2143, 2013.

[20] P. Mercogliano, G. Rianna, and R. Vezzoli. Frequency variation of geo-hydrological hazards under climate change conditions in italy. *CMCC - Research Paper*, RP0264, 2015.

[21] A. Montanari. Hydrology of the po river: looking for changing patterns in river discharge. *Hydrology and Earth System Sciences*, 16(10):3739–3747, 2012.

[22] M. Montesarchio, M.P. Manzi, L. Cattaneo, E. Bucchignani, and P. Mercogliano. Performance evaluation of a regional climate simulation with COSMO-CLM in the Alpine space. *CMCC - Research Paper*, RP0173, 2012.

[23] M. Montesarchio, A.L. Zollo, E. Bucchignani, P. Mercogliano, and S. Castellari. Performance evaluation of high-resolution regional climate simulations in the Alpine space and analysis of extreme events. *Journal of Geophysical Research: Atmospheres*, 119, 2014.

[24] M.J. Muerth, B.G. St-Denis, S. Ricard, J.A. Velázquez, J. Schmid, M. Minville, D. Caya, D. Chaumont, R. Ludwing, and R. Turcotte. On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, 17:1189–1204, 2013.

[25] I. Portoghese, E. Bruno, N. Guyennon, and V. Iacobellis. Stochastic bias-correction of daily rainfall scenarios for hydrological applications. *Natural Hazards Earth System Sciences*, 11:2497–2509, 2011.

[26] P. Racsko, L. Szeidl, and M.A. Semenov. A serial approach to local stochastic weather models. *Ecological Modelling*, 57:27–41, 1991.

[27] G. Rianna, P. Tommasi, L. Comegna, and P. Mercogliano. Preliminary assessment of the effects of climate change on landslide activity of Orvieto clayey slope. In *Climate change and its implications on ecosystem and society: Proceedings of I SISC (Società Italiana di Scienze del Clima) Conference*, pages 507–522, 2013.

[28] G. Rianna, A.L. Zollo, P. Tommasi, M. Paciucci, L. Comegna, and P. Mercogliano. Evaluation of the effects of climate changes on landslide activity of Orvieto clayey slope. *Procedia Earth and Planetary Science*, 9:54–63, 2014.

[29] C. Teutschbein and J. Seibert. Regional climate models for hydrological impact studies at the catchment scale: A review of recent modeling strategies. *Geography Compass*, 4/7:834–860, 2010.

[30] C. Teutschbein and J. Seibert. Bias correction of regional climate model simulations for hydrological climate change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, 456-457, 2012.

[31] S. Tibaldi, C. Cacciamani, and S. Pecora. Il Po nel clima che cambia. In P. Viaroli, F. Puma, and I. Ferrari, editors, *Atti XVIII congresso S. It E.*, volume 24 of *Biologia ambientale*, pages 21–28, 2010.

[32] E. Todini and C. Mazzetti. *TOPographic Kinematic APproximation and Integration User Manual and references*, 2007.

[33] P. Tommasi, P. Pellegrini, D. Boldini, and R. Ribacchi. Influence of rainfall regime on hydraulic conditions and movement rates in the overconsolidated clayey slope of the Orvieto hill (central Italy). *Canadian Geotechnical Journal*, 43:70–86, 2006.

[34] R. Tomozieu, V. Pavan, C. Cacciamani, and M. Amici. Observed temperature changes in Emilia-Romagna: mean values and extremes. *Climate Research*, 31:217–225, 2006.

[35] M. Turco, A.L. Zollo, G. Rianna, L. Cattaneo, R. Vezzoli, and P. Mercogliano. Post-processing methods for COSMO-CLM over Italy. *CMCC - Research Paper*, RP0171, 2013.

[36] M. Turco, A.L. Zollo, V. Rillo, and P. Mercogliano. GCM driven COSMO-CLM post-processed precipitation over Italy: control and future scenarios. *CMCC - Research Paper*, RP0179, 2013.

[37] M. Turco, A.L. Zollo, R. Vezzoli, C. Ronchi, and P. Mercogliano. Daily precipitation statistics over the Po basin: observation and post-processed RCM results. In *Climate change and its implications on ecosystem and society: Proceedings of I SISC (Società Italiana di Scienze del Clima) Conference*, pages 222–232, 2013.

[38] R. Vezzoli, M. Del Longo, P. Mercogliano, M. Montesarchio, S. Pecora, F. Tonelli, and A.L. Zollo. Hydrological simulations driven by RCM climate scenarios at basin scale in the Po river, Italy. In A. Castellarin, S. Creola, E. Toth, and A. Montanari, editors, *Evolving Water Resources Systems: Understanding, Predicting and Managing Water-Society Interactions Proceedings of ICWRS2014*, volume 364 of *IAHS Red Book*, pages 128–133, 2014.

[39] R. Vezzoli, P. Mercogliano, S. Pecora, A.L. Zollo, and C. Cacciamani. Hydrological simulation of po river (north italy) discharge under climate change scenarios using the {RCM} cosmo-clm. *Science of The Total Environment*, 521-522:346–358, 2015.

[40] V. Villani, G. Rianna, P. Mercogliano, and A.L. Zollo. Generator to downscale rcm outputs to slope scale for stability assessment: A comparison of performances. *EJGE*, 20:1495–1515, 2015.

[41] V. Villani, G. Rianna, P. Mercogliano, A.L. Zollo, and P. Schiano. Statistical approaches versus weather generator to downscale RCM outputs to point scale: A comparison of performances. *Journal of Urban and Environmental Engineering*, 8(2):142–154, 2014.

[42] M. Vrac, P. Drobinski, A. Merlo, M. Herrmann, C. Lavaysse, L. Li, and S. Somot. Dynamical and statistical downscaling of the french mediterranean climate: uncertainty assessment. *Natural Hazards Earth System Sciences*, 12:2769–2784, 2012.

[43] A.W. Wood, L.R. Leung, V. Sridhar, and D.P. Lettenmaier. Hydrologic implications of dynamical and statistical approaches to downscaling climate outputs. *Climate Change*, 62(1-3):189–216, 2004.

[44] C.Y. Xu. Climate change and hydrologic models: A review of existing gaps and recent research developments. *Water Resour. Management*, 13:369–382, 1999.

[45] D. Zanchettin, P. Traverso, and M. Tomasino. Po river discharge: a preliminary analysis of a 200-year time series. *Climatic Change*, 89:411–433, 2008.

[46] A.L. Zollo, P. Mercogliano, M. Turco, R. Vezzoli, G. Rianna, E. Bucchignani, M.P. Manzi, and M. Montesarchio. Architectures and tools to analyse the impacts of climate change on hydrogeological risk on Mediterranean area. *CMCC - Research Paper*, RP0129, 2012.

[47] A.L. Zollo, M. Montesarchio, M.P. Manzi, L. Cattaneo E. Bucchignani, and P. Mercogliano. Assessment of COSMO-CLM performances in simulating the past climate of Italy. *CMCC - Research Paper*, RP0145, 2012.

[48] A.L. Zollo, G. Rianna, P. Mercogliano, P. Tommasi, and L. Comegna. Validation of a simulation chain to assess climate change impact on precipitation induced landslides. In K. Sassa, P. Canuti, and Y. Yin, editors, *Landslide Science for a Safer Geoenvironment*, volume 1 of *Proceedings of World Landslide Forum 3*, pages 287–292, Beijing, 2014.

[49] A.L. Zollo, V. Rillo, E. Bucchignani, M. Montesarchio, and P. Mercogliano. Temperature and precipitation extreme events over italy: assessment of high resolution simulations with COSMO-CLM and future scenarios. *International Journal of Climatology*, 2015.

[50] A.L. Zollo, M. Turco, and P. Mercogliano. Assessment of hybrid downscaling techniques for precipitation over the Po River basin. In G. Lollino, A. Manconi, J. Clague, W. Shan, and M. Chiarle, editors, *Engineering Geology for Society and Territory*, volume 1, pages 193–197. Springer International Publishing, 2015. doi:10.1007/978-3-319-09300-0_37.

CMCC Research Papers

18

Centro Euro-Mediterraneo sui Cambiamenti Climatici

cmcc
Centro Euro-Mediterraneo
sui Cambiamenti Climatici