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STATISTICAL APPROACHES VERSUS WEATHER GENERATOR TO DOWNSCALE RCM OUTPUTS TO POINT SCALE: A COMPARISON OF PERFORMANCES

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Abstract: To properly evaluate weather variables regulating the occurrence of geo-hydrological hazards, the current constraints of climate models imply the need of adopting statistical approaches in cascade to GCM/RCM for the assessment of the potential variations associated to climate changes. Since, in the last years, several approaches, often freely available, have been proposed and applied to investigate various hazards in different geographical areas and geomorphological contexts, a deeper understanding about their performances and constraints is crucial; in the work, it is carried out focusing the attention on two kind of approaches widely adopted in impact studies: bias correction methods (in particular, quantile mapping tools) and weather generators. Both methodology have been applied to outputs of an high resolution RCM simulation carried out on Italian territory for analyzing two very localized (and then challenging) landslide case studies. 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 climate signal, physically detected by RCM, not only in outputs weather variables but also in derived components of soil surface budgets strictly governing the occurrence of landslide phenomena.

Keywords: climate changes; bias correction; quantile mapping; weather generator; geo-hydrological impacts; slope stability; regional climate models; soil surface hydrological budget

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INTRODUCTION

The potential effects of Climate Changes (CC) on the hydrological cycle (HC) and especially on weather-induced geo-hydrological hazards (strictly linked to HC) have aroused an increasing interest in recent years (Xu, 1999; Coppola *et al.,* 2014; Vezzoli *et al.,* 2014; Coe & Godt, 2012; Crozier, 2010).

However, to this aim, a proper reproduction of observed hydrological conditions ("minimum requirement" according to Wood *et al.,* 2004) through a correct estimate of the components of water/energy budgets and of weather forcing is needed. Such estimates that should be provided by fully physically based climate simulation chain formed by General Circulation Model (GCM) dynamically downscaled through Regional Climate Model (RCM) have often proven to be affected by remarkable biases making them not suitable for a direct application to studies on weather-induced geo-hydrological hazards.

The presence of biases is mostly related to the now achievable horizontal resolution, i.e. for Europe, in ENSEMBLE project (ensembles-eu.org) the maximum resolution is about 25 km; in CORDEX project (http://wcrp-cordex.ipsl.jussieu.fr) ensemble RCM models currently adopt a resolution about equal to 11 km. The horizontal resolution of climate models reflects in (a) spatial mismatch between the size of typically investigated areas in hydrological studies, ranging from regional to watershed scale for hydraulic impacts until the point scale for slope stability evaluations and (b) insufficiently resolved surface properties and parameterizations of sub-grid scale processes (i.e. deep convection, soil surface balances) strictly linked to occurrence of extreme weather events and geo-hydrological hazards. A well-established solution has been represented by the adoption, in cascade to GCM+RCM, of Statistical Approaches (SA) like Bias Correction (BC) or weather generators (WG) that, through the calibration on observed data, cope mismatching problems providing, at the same time, a substantial correction of weather forcing distribution making them suitable as input for hydrological models (Vrac *et al.*, 2013; Muerth *et al.*, 2013; Portoghese *et al.*, 2011).

As pointed out by Ehret *et al.* (2012) and Maraun (2013), the adoption of such approaches constitutes, in all respects, a further uncertainty element to take into account; for these reasons, intermediate results from GCM+RCM and subsequent correction procedure should ever be shown and clarified.

In last years, especially for hydraulic/water management impacts at regional/watershed scale, several researches tried to define constraints and capabilities of GCM+RCM+SA simulation chain (Muerth *et al.*, 2013; Guyennon, 2012) while, for much more localized landslide analyses at slope scale, few attempts to evaluate the entire chain can be found (Comegna *et al.*, 2013; Zollo *et al.*, 2104). Indeed, although the number of studies attempting to estimate the effect of CC on landslide phenomena is substantially increasing (Coe & Godt, 2012), in such works-reduced (GCM+RCM) or short-circuited (GCM+SA) chains have been preferred (Buma & Dehn, 1998; Collison *et al.*, 2007).

Therefore, in present work, three crucial issues have been addressed: (a) what are the current capabilities of such approaches and, on relative terms, (b) how can they improve numerical model outputs? (c) Adopting at point (slope) scale such approaches, is a substantial variation of projected climate signal provided by GCM+RCM detected on weather forcing and main components of hydrological balance (adding further uncertainties in simulation chain)?

The work is primarily focused on precipitation (for the main part) and temperature values, because of their key role in the trigger/reacceleration of landslide movements; although water and energy budget are influenced by further forcing (e.g. wind velocity, solar radiation), precipitation and temperature are usually assumed playing a main role (Hagemann *et al.*, 2011); furthermore, adequate (for length, resolution and quality) observed datasets required for implementation of SA are often not available for variables other than precipitation and temperature. The rational of this work is as follows: first the two landslide case studies and the GCM+RCM chain are described; then the performances of several SA in correcting the weather forcing are evaluated and, finally, the two questions are addressed and conclusions including the ability of SA to correct temperature values and hydrological components strictly associated to it (evapotranspiration processes), are drawn.

Case histories

The two selected case studies refer to sites in Italy: Cervinara (Southern Italy) and Orvieto (Central Italy) (**Fig. 1**); during recent years, the slopes of both areas are/have been affected by slope movements albeit with very different characteristics.

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. 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 (Tommasi *et al.*, 2012). A large number of slides affect the northern slope (Lembo-Fazio *et al.*, 1984). While the main historic landslide in this area (Porta Cassia 1900) was triggered by anthropogenic activities, further ongoing

Fig. 1 (a) Geographical location of the two case-histories; (b) Orvieto slope; (c) Cervinara landslide.

slow movements and their reactivations can be directly related to soil-atmosphere interaction (where precipitation, of course, represents the main source of input and evapotranspiration, on the other hand, governs soil water depletion). Monitoring (started on the slope in seven stations since 1982) allowed to identify deep movements along slip surfaces located in the softened part of the basal formation (displacement rate varies between 2 and 6 mm/year) and shallower movements involving the cover with higher displacement rates up to 7-12 mm/month. Previous studies show that landslide accelerations exhibited a strong correlation to cumulative precipitation values on time windows ranging from 15-30 days for the shallowest movements to the entire wet season for the deepest ones (e.g. Tommasi *et al.,* 2006).

The second case study concerns the Cervinara slope, located 50 km North-East to Naples, where on December, 16, 1999, a very rapid flowslide occurred following a total precipitation of 320 mm in about 50 h causing huge damage and five casualties (Olivares & Picarelli, 2003). In the area, highly fractured calcareous mountains are blanketed by a few meters thick loose unsaturated pyroclastic cover as result of the activity of Somma-Vesuvius and Campi Flegrei volcanoes. Thanks to the beneficial effect of negative pore water pressures, such steep silty-sandy covers are generally stable. However, precipitations can induce the increase in the water content, reducing suction and related apparent cohesion, leading, in extreme cases, to slope failure. Back-analysis of numerous cases in similar soils in Campania Region (Pagano *et al.*, 2010; Frattini *et al.*, 2004) showed how movements are triggered under coupled effect of particularly wet periods (i.e. soil-atmosphere interaction leads primarily to an increase in soil water content) followed by heavy rainfall events on 1d-2d time scale.

For both case studies, daily observed precipitation, minimum and maximum temperature are available on the control period 1981-2010. For Orvieto, the reference weather station is collocated on the top of slab very close to the investigated slope; for Cervinara, the nearest available station is located in the town of San Martino Valle Caudina (SMVC) for which nonetheless data are absent for 2 years (1999 and 2000); it is less than 5 km and characterized by similar orographic features (altitude and exposure).

Climate simulation chain

The numerical climate simulation chain, adopted in this work, is formed by a GCM, CMCC-CM with horizontal resolution of 0.75° (Scoccimarro *et al.*, 2011), dynamically downscaled at 0.0715° (about 8km) through the non-hydrostatic RCM COSMO-CLM (Rockel *et al.*, 2008; Steppeler *et al.*, 2003), climate version of the operational mesoscale weather forecast model currently developed by the European Consortium COSMO. The climate simulations cover the entire Italian territory for the period 1971-2100; on period 1971-2005 GCM is forced by IPCC 20C3M protocol while, for the remaining period, by RCP 4.5 and RCP 8.5 scenarios (Meinshausen *et al.*, 2011).To assess the performances of COSMO-CLM, further simulations have been performed adopting as forcing ERA40 reanalysis (horizontal resolution of 1.125°, Uppala *et al.,* 2006) for the period 1971-2000 or ERA-Interim reanalysis (horizontal resolution of 0.703°, Dee *et al.,* 2011) for the period 1979-2011.

On control period 1981-2010, comparing over three identified areas of Italian territory the seasonal cycles of temperature (**Fig. 2** upper part) and precipitation (**Fig. 2** lower part) observed (E-OBS dataset; Haylock *et al.*, 2008) and simulated by RCM (ERA Interim or GCM driven), the average performances of climate chain can be assumed fully comparable with the other state of art RCM simulations on the same domain (Kotlarski *et al.*,, 2014); moreover, it worth noting that, for such assessment, the relevant assumption for which, during the years (2006-2010) not covered by observed data about greenhouse gases emissions, projections under RCP4.5 and RCP8.5 return similar values, is likely supported by the direct comparison (for these reason, on 2006-2010, data retrieved under RCP4.5, are used).

For temperature and precipitation, the main source of errors result induced by GCM (Bosshard *et al.,* 2013; Dequè *et al.*, 2007) mainly for temperature while, concerning precipitation values, more significant biases (mainly for Northern Italy) arise also for ERA-driven simulation (Bucchignani *et al.*, 2013a; 2013b).

Specifically, in the work, only outputs related to areas of interest are taken into account; to this aim, it is crucial to recall that, despite cases studies are substantially constituted by single slope, simply assuming weather variables from nearest model grid point is meaningless since the nominal resolution of

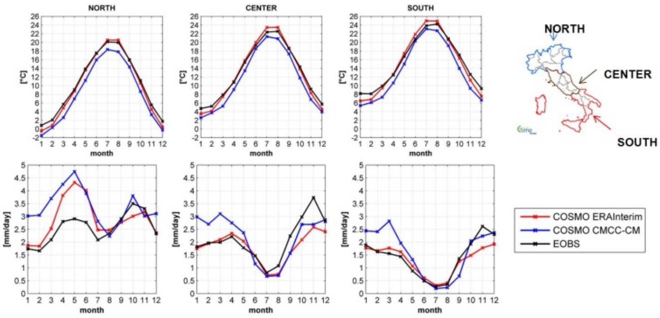

Fig. 2 Modeled and observed seasonal cycles of the surface temperature (upper part) and precipitation (lower part) for the three sub-areas shown in upper right corner.

RCM (in this case about 8km) not corresponds to the effective resolution; indeed, due to aliasing effects, outputs have to be filtered, at least, up to 2-3 times the horizontal resolution while other parameterizations associated to advection dynamics could require also higher filtering (Pielke, 2002 and Grasso, 2000). Similarly to Skamarock (2004) and Bierdel *et al.* (2012), Kapper *et al.* (2009) adopting COSMO-CLM as RCM propose effective resolution values ranging from $3\Delta x$ to $7\Delta x$, depending on the investigated parameter and its model representation. Based on such findings, for two case studies, RCM precipitation values are provided as average modeled value on 5x5 grid points surrounding the investigated slopes. Moreover, further tests (Mercogliano *et al.*, 2014) aimed to evaluate output variations under the three configurations (3×3, 5×5 and 7×7 grid points) return fully equivalent results. As pointed out by Maraun (2013), it should be recognized that this could necessarily increase the scale gap between modeled outputs and observed point and partly exacerbate inflation problems.

Statistical approaches

In order to overcome the current limitations of climate simulations and make climate outputs suitable for impact tools, two different kind of statistical approaches have been taken into account: bias correction (BC) techniques and weather generators (WG); the former provides a re-scaling of climate model output in order to reduce the effects of systematic errors (Teutschbein & Seibert, 2010) while, for the latter, the statistical characteristics of observed weather (raw for control period or perturbed according the findings of climate simulation) are used to produce synthetic time series of weather data respectively on current and future periods. Concerning BC methods, in the last years, a large number of approaches (comprehensive summaries are included in Teutschbein & Seibert, 2010; Lafon *et al.*, 2012) have been developed and widely tested in different geographical and geomorphological contexts providing key information about actual performances and capabilities.

Numerous researches (Zollo *et al.*, 2014; Teutschbein & Seibert, 2010; 2012; Lafon *et al.*, 2012; Boe *et al.*, 2007) identify quantile mapping (or distribution mapping) approaches as the most efficient tools in removing biases. To briefly explain how this approach works, the exemplary procedure proposed by Teutschbein & Seibert (2012) can be used.

If $\boldsymbol{F_{RCM}}$ and $\boldsymbol{F_{OBS}}$ are the CDF (cumulative distribution function) of, respectively, simulated and observed precipitation, for day d , the bias corrected value $\boldsymbol{X}^*(\mathbf{d})$ of RCM precipitation $\mathbf{X(d)}$ is obtained using the equation:

$$\boldsymbol{X^*(d) = F_{OBS}^{-1}\left(F_{RCM}(X(d))\right) = h(X(d))} \quad (1)$$

The same approach is exploitable also for temperature. The main differences between the distribution mapping methods are due to $\boldsymbol{h}$ transformation. To this aim, Gudmundsson *et al.* (2012) propose the following classification: (a) distribution derived transformations (DDT) for which $\boldsymbol{F}$ adopts Bernoulli distribution to model occurrence and different optional approaches for intensities (Weibull, Gamma, lognormal, Exponential); (b) parametric quantile-quantile approaches (PA) according which the h is an algebraic relationship between simulated and observed quantiles; (c) non parametric transformations (also known as empirical quantiles) (EQ) where $\boldsymbol{F}$ is the empirical CDF and values falling between reference percentiles are obtained by interpolation (Boè *et al.*, 2007). In this work, freely available qmap R-package developed by Gudmundsson *et al.* (2012) is employed; moreover, for easy comparison, according a first screening (results not shown), on monthly scale, only the best approaches for each transformation type are taken into account:

(a) for DDT, as showed in other works (Piani *et al.*, 2010; Lafon *et al.*, 2012), Bernoulli-Gamma (BG) distributions largely outperform the other ones showing as the most appropriate for precipitation;
(b) for PA, the approach called "exponential tendency to an asymptote" (ES) relation ($\boldsymbol{P_o}$ and $\boldsymbol{P_m}$ are respectively observed and modeled daily precipitation):

$$\boldsymbol{P_o = (a + bP_m)\left(1 - e^{-(P_m - x)/\tau}\right)} \quad (2)$$

proves to be more performing than the others probably thanks to its flexibility;
(c) for EQ, two approaches (Quant and RQuant), showing satisfying similar performances, are selected; in particular, in Quant approach, values between reference quantiles are interpolated through linear or cubic function while for RQuant a

robust estimate of the reference modeled quantile is performed using local linear least squares through *n* nearest points regression while, for values falling between these, linear or cubic approach is again implemented; for investigated case histories, Quant and RQuant prove to be relatively unaffected by adopted interpolation function (linear is chosen) while a constant correction (Boe *et al.*, 2007) is implemented for values beyond the current observed range.

In last years, stochastic weather generators (WGs) have been widely adopted to provide weather time series coherent with statistical features corresponding to observed statistics in a site; nevertheless, they have been frequently used as tools for statistical downscaling from GCMs (Kilsby *et al.*, 2007; Fatichi *et al.*, 2011).

According the main difference between them, two main methods are recognizable: "Richardson type" approaches in which the occurrence of wet and dry series is modeled according Markov chain procedure and "Racsko type" approaches in which wet/dry series are estimated as "random variables" adopting as weight or "selection probability" the proportion of observed events (Racsko *et al.*, 1991). Semenov & Barrow (1997) point up how the second ones reproduce more confidently also rare events not being affected by 'limited memory' as in "Richardson type". For these reasons, in this work, freely available LARS-WG (Long Ashton research Station- Weather Generator) based on "Rackso type" approach is employed. exhibiting performances fully in line with other state-of-art WGs (Semenov *et al.*, 1997;1998;1999).

In addition of precipitation occurrence, LARS-WG utilizes semi-empirical distributions for assessing daily precipitation and solar radiation. 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; finally, other climate variables like minimum and maximum temperatures are estimated in a subsequent further stochastic process conditioned on wet/dry status.

In order to roughly assess the potential effect of CC on weather forcing, on monthly scale, main observed statistics are perturbed by corresponding anomalies retrieved by climate simulations (i.e. precipitation cumulative values and standard deviations of temperature as ratio, mean minimum and maximum temperatures as differences) providing weather time series consistent with modified scenarios; for investigated case studies, a sensitivity analysis (results not shown) allow to understand how time series with a minimum length of 300 years are able to satisfactorily reproduce current climate features while climate signals to perturb observed statistics are provided by simulation chain (GCM+RCM) displayed in previous paragraph.

Evaluation of performances of BC/WG approaches

Time span 1981-2010 is assumed as reference period; on it, observed and modeled monthly cumulative values (a) and monthly wet days (b) are respectively displayed for Orvieto (**Fig. 3**) and Cervinara (**Fig. 4**). The quantitative comparison between the cumulative monthly values allows us to substantiate the current constraints of chain GCM + RCM; except for the first half of the year to Orvieto, it (magenta line) returns a remarkable underestimation, mainly failing to reproduce the observed autumn peak, in the two cases, it is greater than that detected in late winter.

In terms of wet days, simply averaging the values over 5x5 grid points, the overestimation is evident; however, to partially reduce the effect of mismatch between the observed values for the point and modeled on 40x40 km area, the computation is also carried out (shaded magenta line) considering days with precipitation values higher than 0.2 mm (the same resolution supplied by adopted measuring instruments).

In this case, for both, the overestimation, albeit at a much lower level, persists during the first part of the year while trend is reversed for the remaining part with a slight underestimation of rainy days; it shows how several detected limits of the chain GCM+RCM remain linked to the scale; on the other hand, if the computations are repeated for the single grid point (neglecting above recalled constraints of such choice) closest to the measurement point (results not shown), the underestimation of the cumulative values remains at quite comparable levels and only very few improvements are returned in term of wet days.

Conversely, all statistical methods induce a more appropriate reproduction for monthly cumulative values and wet days; nevertheless from charts it is clear to observe how not all methods perform equally well: in particular, adopting distribution derived transformation (BG approach) mainly during wet season do not achieve adequate corrections. Gudmundson *et al.* (2012), obtaining similar findings, justify them recalling the theoretical assumptions of approach under which modeled and observed parameters of the distributions are identified separately not guaranteeing a proper transformation. Moreover, LARS-WG is able to remarkably well adjust GCM+RCM outputs for Orvieto, while it returns poorer performances for Cervinara perhaps restricted by available dataset. Finally, by virtue of their high flexibility, parametric (PA) and empirical quantiles (EQ) show the best skills in reducing errors with small deviations. To effectively sum up the performances of different approaches, two samples

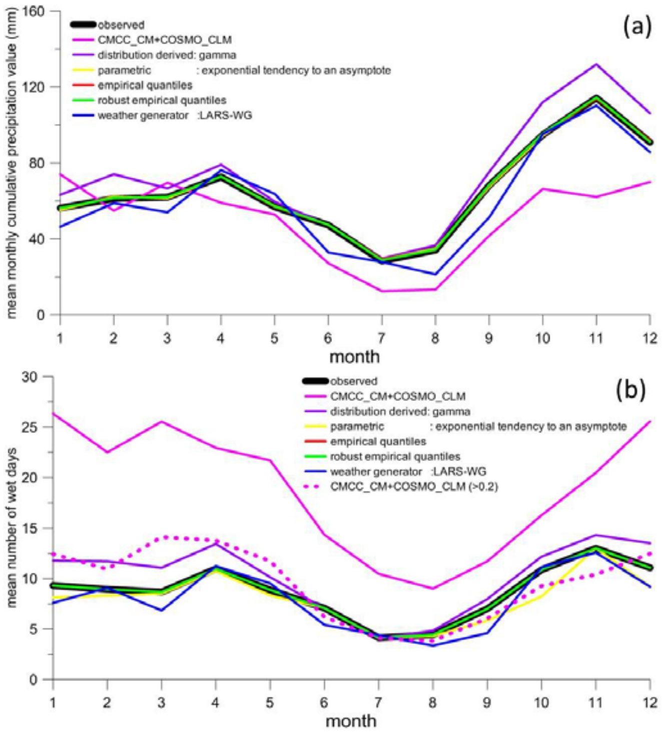

Fig. 3 (a) Monthly cumulative values. (b) Mean monthly number of wet days. Black line: observed values; magenta line: simulated values through climate models GCM+RCM; other lines: simulated values through BC or WG approaches for Orvieto case study.

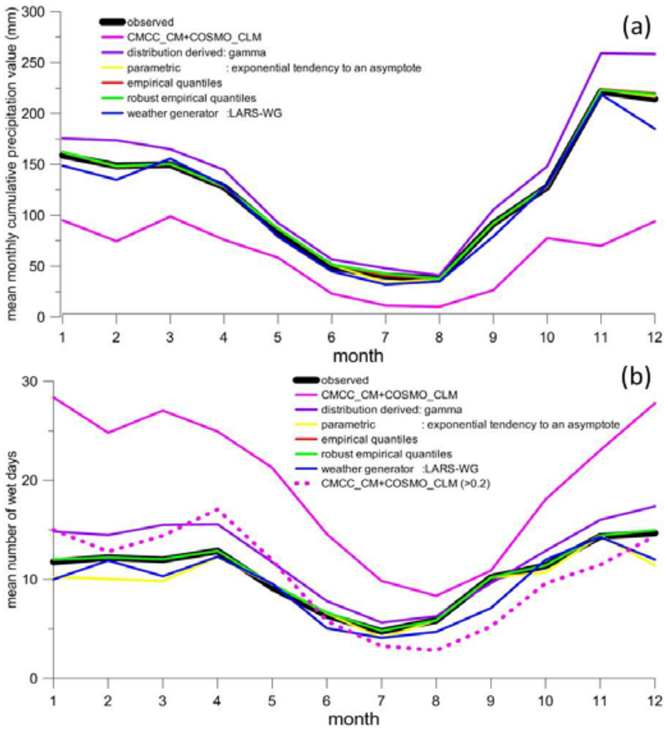

Fig. 4 (a) Monthly cumulative values. (b) Mean monthly number of wet days. Black line: observed values; magenta line: simulated values through climate models GCM+RCM; other lines: simulated values through BC or WG approaches for Cervinara case study.

Cramer-von Mises (CvM) test can be adopted (**Table 1**); it is non parametric test to determine if independent samples can be assumed as drawn from the same distribution and already adopted in previous analogous evaluation studies; (Vrac *et al.*, 2013; Michelangeli *et al.*, 2009). The null hypothesis $\boldsymbol{H_0}$ that the samples are sorted from the same distribution $\boldsymbol{F}$

$$\boldsymbol{H_0}: \boldsymbol{F_m(x)} = \boldsymbol{F(x)} \quad (3)$$

is tested against the alternative hypothesis H1 that the samples are drawn from different distributions

$$\boldsymbol{H_1}: \boldsymbol{F_m(x)} <> \boldsymbol{F(x)} \quad (4)$$

Briefly, it provides a measure of the distance between empirical and modeled CDFs, $\boldsymbol{F(x)}$ and $\boldsymbol{F_m(x)}$ respectively, (Darling, 1957), through integrated squared difference between them:

$$\boldsymbol{CvM} = \int_{-\infty}^{\infty} (|\boldsymbol{F_m(x)} - \boldsymbol{F(x)}|)^2 \, \boldsymbol{dx} \quad (5)$$

In **Table 1**, the results are reported in terms of p-value representing the probability associated to CvM under which both samples can be assumed not coming from the same underlying distribution. On monthly basis, for daily precipitation in both case studies, in addition to BC and WG approaches, also the results related to raw RCM are listed. In both locations, CDFs provided by RCM are significantly different by observed ones for almost the entire year except for two dry months (Aug-Sep for Orvieto and Jul-A for Cervinara) when probably a large occurrence of zero values could partly cover the differences between CDFs (however, in these cases, p-values are higher than 0.66); by adopting BG approach, a moderate improvement is obtained mainly for dry months while it seems to fail to adequately correct rainfall patterns during wet months (Oct-Apr for Orvieto and Nov-Apr for Cervinara) probably due to the limited flexibility of the approach while equally simple methods but less conditioned by the starting assumptions (as WG and ES) produce substantial improvements with few occasional exceptions.

Table 1. Assessment of performances of raw RCM and SA in terms of Cramer-von Mises statistical test.

Finally the overall overlapping of the methods EQ (Quant and RQuant) to the observed data (both in terms of cumulative values that wet days) results in p-values less than 0.33 throughout the entire year confirming the high potentialities of such approaches.

Beyond an effective reproduction of precipitation cumulative values and occurrence that represent the minimum requirement for BC/WG tools, on control period, a proper evaluation of the effects of CC on landslide movements require to deal with the following two issues: (a) the persistence of the climatic signal estimated on physical basis by regional climate models after the application of BC/WG and (b) the simulation of the extreme rainfall values usually inducing (on different time scales) the trigger/reactivation of slope movements.

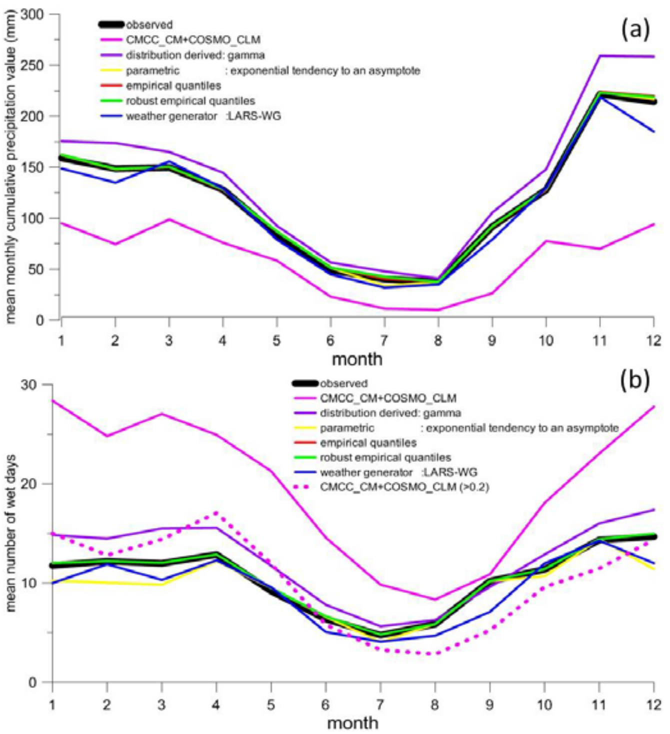

Fig. 5 Climatic signal provided by comparing monthly cumulative values on future 2071-2100 (RCP 8.5) and cntrol period 1981-2010. Magenta line: simulated values through climate models GCM+RCM; other lines: simulated values through BC or WG approaches; a) for Orvieto and b) for Cervinara case studies.

Regarding the first point, in **Fig. 5** the ratio between monthly cumulative rainfall values estimated by raw RCM or adopting in cascade either BC or WG approaches for 2071-2100 under RCP 8.5 and control period 1981-2010 is displayed. Broadly, for both cases, two different periods are recognizable: the first one characterized by an average increase/invariance of rainfall values and roughly coincident with cold/wet season in Mediterranean regions (Nov-Feb for Cervinara and Oct-Mar for Orvieto) and second one for which the opposite is estimated (Mar-Oct for Cervinara and Apr-Sep for Orvieto); all statistical tools satisfactorily reproduce the seasonal pattern estimated by RCM; nevertheless, the WG LARS-WG shows worst performances probably due to the simplified method adopted for taking into account the potential effect of CC in the approach while, in some cases, between the BC approaches, Gamma model show the larger deviations from raw RCM estimated values (probably because of above recalled constraints).

Concerning extreme rainfall values, to account for the different dynamics of previously investigated landslides, according Tommasi *et al.* (2006), the annual maximum cumulative precipitation over 120 days (P120d) is assumed as reference variable for clayey slow movements in Orvieto. In contrast, for Cervinara the maximum daily precipitation P1d is considered as reference value linked to occurrence of fast flowslides. On control period, the time series of such maxima (P120d and P1d) have been fitted through the General Extreme Value (GEV) statistical distribution. Through this way, the expected recurrence interval of a fixed (rainfall) event (i.e., the average time during which the magnitude of a particular event could be equaled or exceeded) can be assessed.

The recurrence intervals shown in the **Fig. 6** are quite different. In fact, landslide acceleration in clay is quite a frequent phenomenon, while flowslide triggering in pyroclastic covers is a far less common event.

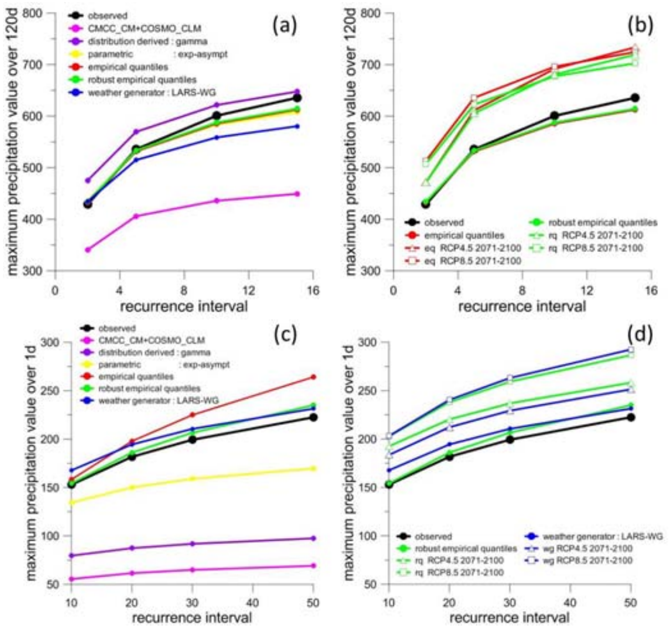

Fig. 6 Recurrence interval for maximum yearly values of precipitation (GEV statistical distribution). (a) Orvieto: cumulated precipitation over 120 days on current period . (b) the same considering also future period 2071-2100 (RCP 4.5 and RCP 8.5) (c) Cervinara: cumulated daily precipitation. (d) the same considering also future period 2071-2100 (RCP 4.5 and RCP 8.5).

For Orvieto (**Fig. 6** upper level), underestimation of monthly cumulative values of RCM induce a similar strong underevaluation of P120d values on control period; parametric and EQ approaches provide the best results albeit with slight biases for higher recurrence interval values; conversely, for Cervinara, the proper evaluation of maximum values on daily scale (P1d) represent a more challenging issue (**Fig. 6** lower level); indeed, besides to raw RCM, several approaches (ES, Gamma and partly Quant able to satisfactorily reproduce the other features of precipitation pattern) fail to adequately reproduce the GEV curve retrieved by observed data; since the empirical quantile approaches Quant and RQuant only differ for algorithm regulating the interpolation in modeled CDF, the result in **Fig. 6** lower level could suggest an higher capability of "local linear least sure regression" (used by RQuant) to correct the modeled CDF at higher percentiles.

Finally, for the two cases, the two approaches best reproducing GEV based on observed data (Quant and RQuant for Orvieto, RQuant and LARS-WG for Cervinara) are applied to RCM precipitation outputs for 2071-2100 under RCP 4.5 and RCP 8.5; they return similar evaluations with differences comparable to that retrieved on observed data.

In general terms, for both scenarios and reference values, P120d and P1d, a not negligible increase of the maximum is estimated; this result would led to an overall worsening of average slope stability conditions for both the case histories; however, it worth noting that such assessment is based on simplified assumptions neglecting, for example, the effect of evaporative processes and the precipitation rates actually infiltrating into the soil (depending also, for example, by antecedent soil water content).

In summary, both quantile mapping and weather generator approaches show, on average, satisfying performances; however, significant differences arise between them depending on investigated variable, case-histories or season; confirming the findings of Gudmundson *et al.* (2012), empirical quantiles methods outperform the others; for this reason, in last section, RQuant approach is adopted for investigating the effect of BC methods on estimation of main components of soil surface hydrological balance.

ASSESSMENT ABOUT THE EFFECT OF A BIAS CORRECTION APPROACH ON THE PROJECTED CHANGE SIGNAL

The last section is devoted, for the only Orvieto case study, to understand (a) what are the actual capabilities of BC approaches in correcting the main components of the hydrological balance, and (b) what could be the differences, adopting or not a BC approach in projected climate signal of such components (introducing an additional source of uncertainty).

To this aim, for Orvieto case study the only considered BC approach is RQuant (returning the best performances for precipitation pattern) while the climate signal is evaluated comparing the 2071-2100 time span under RCP 8.5 scenario and the control period 1981-2010; assuming a long time horizon and of "more severe" scenario should likely allow to observe higher weather forcing anomaly values and so represent a more challenging test.

Moreover, it should be stressed that, for such case study, the reacceleration for deep movements of landslide bodies is essentially regulated by water exchanges between soil and atmosphere experiencing on time spans often longer than four months; on these time horizons and because of low hydraulic conductivity of involved soils, ingoing water fluxes associated to precipitation infiltrated water and outgoing, due to actual evapotranspiration can represent comparable components. For these reasons, it could be investigating the effect of BC approaches not only on rainfall and main component of surface balance directly linked to it (runoff/infiltration) but also on temperature and induced evapotranspiration processes (actual and potential).In **Fig. 7**, in left column, on monthly scale, ratio (for cumulative precipitation) /difference (for temperature variables) between modeled (raw RCM or RCM+RQuant) and observed values are reported as lines while absolute values as bars; similarly, in right column, projected climatic signal is displayed as line (raw RCM or RCM+RQuant) while absolute evaluated future values as bars; while, in first row, the trends about precipitation values substantially resume above described results (**Figs 3** and **5**) the others display the performances related to temperature (respectively maximum Tmax, minimum Tmin and diurnal temporal range DTR). They allow pointing out several items: i) 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 approach manages to completely nullify such error; concerning the climate signal, the overall overlapping achieved for precipitation does not occur in this case but the anomaly differences seldom exceed 1°C.

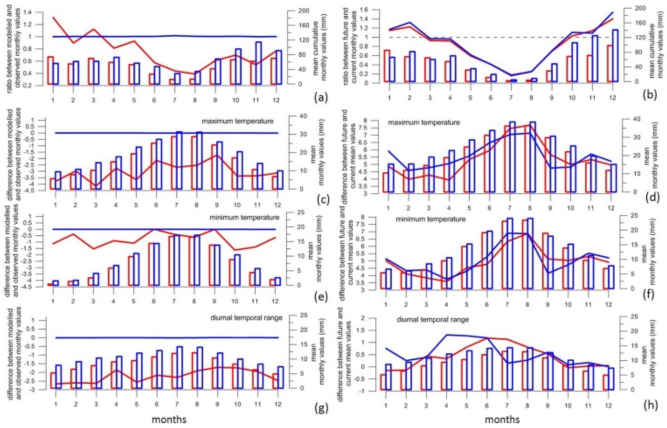

Fig. 7 Left column: continuous line ratio (first), difference (the other ones) between bias corrected (blue) or raw RCM (red) and observed value; absolute values are displayed as bars: (a) precipitation, (c) maximum temperature, (e) minimum temperature, (g) diurnal temporal range; Right column: continuous line ratio (first), difference (the other ones) between bias corrected (blue) or raw RCM (red) on future time span 2071-2100 (under RCP8.5) and control period 1981-2010; absolute values are displayed as bars: (b) runoff clay soil, (d) runoff sandy soil, (f) potential evaporation,(h) actual evaporation clay soil,(l) actual evaporation sandy soil.

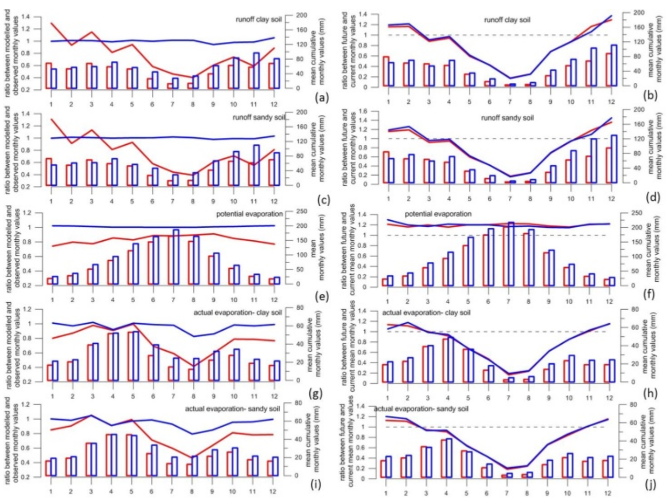

Fig. 8 Left column: continuous line ratio between bias corrected (blue) or raw RCM (red) and observed value; absolute values are displayed as bars: (a) runoff clay soil, (c) runoff sandy soil, (e) potential evaporation, (g) actual evaporation clay soil, (i) actual evaporation sandy soil; Right column: continuous line ratio between bias corrected (blue) or raw RCM (red) on future time span 2071-2100 (under RCP8.5) and control period 1981-2010; absolute values are displayed as bars: (b) runoff clay soil, (d) runoff sandy soil, (f) potential evaporation, (h) actual evaporation clay soil, (l) actual evaporation sandy soil.

In **Fig. 8**, seasonal cycles about the estimation (not observed data are available) of main components of soil surface balance are reported; they are calculated recurring to simple widely adopted approaches:

Table 2. Main parameters regulating infiltration-runoff (SCS-CN) and evaporation (FAO approach) soil behavior for typical sand and clay soils.

	CN_I (antecedent dry soil conditions)	CN_{II} (antecedent moderately wet soil conditions)	CN_{III} (antecedent wet soil conditions)	θ_{fc}	θ_{wp}
Sand	47.16	68	83.01	0.17	0.07
Clay	77.26	89	94.9	0.4	0.24

(a) infiltration $\boldsymbol{I}$ is computed as difference between daily precipitation $\boldsymbol{P}$ and runoff $\boldsymbol{Q}$ by SCS-CN approach (USDA, 1985):

$$Q = \begin{cases} 0 & P \le I_a \\ \frac{(P-I_a)^2}{P-I_a+S} & P > I_a \end{cases}$$

where $S = 25.4(\frac{1000}{CN} - 10)$ represents potential maximum soil moisture retention after runoff begins discriminating the water entering the soil according soil state conditions (antecedent 5 days rainfall volume) and soil surface properties (CN depending on soil texture and land cover) and I_a is initial abstraction ($0.2\ S$).

(b) potential evapotranspiration **PET**, representing the atmospheric demand, is estimated through Hargreaves formula (Allen *et al.*, 1998) :

$$PET = 0.0023 R_a (DTR)^{0.5} (T_m + 17.8)$$

where extraterrestrial radiation is estimated adopting FAO guidelines procedure.

(c) actual evapotranspiration ET, is assessed again through FAO crop approach (Allen *et al.*, 1998) for which atmospheric demand is computed using coefficients function of soil texture and land cover K_s eventually reduced on basis of current soil water availability (function of infiltration *I*) and vegetation conditions K_r.

(d)

Despite such components are also directly modeled by climate models, since they usually adopt physical parameterizations and soil parameters different from those considered, in order to allow the comparison under equivalent conditions, RCM temperature and precipitation values are simply used as input for proposed hydrological models. Moreover, also representing highly simplified assumptions, *I* and PET are estimated assuming as only weather forcing, respectively, precipitation and temperature while the coupled effect of two variables is shown in ET.

Furthermore, to take into account the effects of texture on soil response, for infiltration and actual evapotranspiration typical values for sand and clay are chosen (Allen *et al.*, 1998) while natural grassland is selected as reference land cover (**Table 2**).

Concerning runoff seasonal cycles (first two rows), the performances of models driven by raw or BC RCM are fully consistent with that displayed for precipitation: a considerable error for RCM (overestimating in the first part and underestimating in the second one) and a perfect overlapping achieved through bias corrected outputs; however, a slight worsening of the performances is obtained for BC- driven model during the second part of dry season probably due to key role played, in this case, also by rainfall event time distribution not taken into account in previous analyses; conversely, projected climate signal is fully equivalent (and coherent with that detected for precipitation) regardless of the large variations in the estimated absolute values. Anyway, very few variations are detected between the two soil types.

In third row, for potential evapotranspiration trends the underestimation of maximum and minimum temperature results in values for raw RCM driven models ranging between 60% and 85% than those obtained with observed data while a nearly perfect matching is returned using RQuant corrected temperatures; nonetheless, it is worth noting how the differences in temperature climate signal result in very low differences in PET climate signal; in both cases, increases, on average, higher than 20% are returned with slight monthly variations.

Finally, in the last two rows actual evaporation trends are displayed; assuming as water input estimated infiltration computed through SCS approach and upper boundary for evapotranspiration, PET provided by FAO approach enables to take into account the coupled effects of the errors associated to evaluation of both weather forcing.

For what concern the estimations from raw RCM outputs, in this case, the underestimation of evapotranspiration values prevails in the first part of the year while, during the dry season, associated to 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). Despite such differences, projected climate signals tend to fully matching with low deviations. In this regard, an interesting issue can be pointed out: according climate projection, the overall increase of potential evapotranspiration could result in an effective growing of outgoing evaporative fluxes only during wet season (Nov-Mar) while during the remaining part of the year, it could be nullified by estimated decreases in cumulative precipitation values and wet days inducing reductions of current values until 80% during the dry season. Also in this case, partly because of rough assumptions in proposed models, soil texture induces negligible variations.

SUMMARY AND CONCLUSIONS

In summary, the main findings provided by research can be recalled:

(a) The performances of modeling chain formed by GCM + RCM does not currently authorize their use for the assessment of the effects of CC on geo-hydrological hazards (in particular in this study, precipitation and temperature have been considered); although over a long time horizon the goal should be the increase of spatio-temporal resolutions and an improvement of process descriptions (i.e. an explicit representation of deep convection, integration of state-of-art hydrological models in GCM/RCM) (Ehret *et al.*, 2012), on short term, the adoption (in cascade to RCMs) of statistical approaches (BC/WG) and the implementation of Ensemble prediction Systems (EPS) (related to every component of simulation chain) represents the most suitable ways; such result, retrievable in many other works, it could be much more apt for the impact studies particularly localized (such as landslides at slope scale).

(b) In this case, since the key issue is strictly related to performance analysis of SA in cascade to numerical climate chain GCM+RCM, single emission scenario, GCM and RCM have been considered; as highlighted by Teutschbein and Seibert (2013), such choice can be suitable only for testing procedures or single elements of simulation chain (as in this work) while for a proper assessment of climate change impact study, because of high uncertainties associated to whole procedure, ensemble runs (not only for GCMs or RCMs) should be preferred.

(c) Despite, in several comparing researches, QM approaches have been recognized to outperform the other BC approaches, substantial deviations in performances are retrievable among the different transformations methods according to the investigated area, season and, above all, the reference parameter; in particular, similarly to what found in Gudmundsson *et al.* (2012), non-parametric transformations constantly permit to achieve very good performances and, for this reason, it could represent the preferable choice despite the additional assumptions needed for the out-of-calibration values; at the same time, LARS-WG proves to be a reliable tool not only for the reproduction of the current precipitation pattern but also to take into account the effect of CC (regardless it adopts very simplified assumptions).

(d) The beneficial effect of the adoption of BC approaches is evident also considering “derived” variables as the main components of soil-surface hydrological balance (evaporation and infiltration) estimated through simplified approaches; moreover, the adoption of BC approaches tends not to significantly alter the climate signal projected by GCM+RCM climate simulations not adding a further contribution to overall uncertainty. Considering analysis at regional/watershed scale, these results are broadly consistent with those reported by Muerth *et al.* (2013) analyzing several complex hydraulic indicators through an EPS approach, while they appear to conflict with Hagelmann *et al.* (2011) according to which deviations in BC climatic signal can verify for specific locations and months mainly under substantial expected changes in rainfall/temperature patterns. For this reason, probably attempting to standardize reference variables or procedures, further analysis should be carried out.

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REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998) *Crop evapotranspiration – Guidelines for computing crop water requirements.* FAO Irrigation and Drainage Paper, No. 56, FAO, Rome.

Bierdel, L., Friederichs, P. & Bentzien, S. (2012) Spatial kinetic energy spectra in the convection permitting limited area. *NWP model COSMODE.Meteorologische Zeitschrift*, **21**(3), 245–258.

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

Bosshard, T., Carambia, M., Goergen, K., Kotlarski, S., Krahe, P., Zappa, M. & Schär, C. (2013) Quantifying uncertainty sources in an ensemble of hydrological climate-impact projections. *Water Resour. Res.* 49,1–14, doi:10.1029/2011WR011533.

Bucchignani, E., Mercogliano, P., Manzi, M.P., Montesarchio M. & Rillo, V. (2013) Assessment of ERA-Interim driven simulation over Italy with COSMO-CLM. *CMCC Research Paper*–RP0183

Bucchignani, E., Mercogliano, P., Montesarchio, M., Manzi, M.P. & Zollo A.L. (2013b) 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, Lecce, 23-24 settembre 2013, 78-89 ISBN 978 – 88 – 97666 – 08 – 0.

Buma, J. & Dehn, M. (1998) *A method for predicting the impact of climate change on slope stability*. Environmental Geology. vol. 35(2–3), 190–196.

Coe, J.A., & Godt, J.W. (2012) Review of approaches for assessing the impact of climate change on landslide hazards, In: *Landslides and Engineered Slopes, Protecting Society Through Improved Understanding* (ed. By E. Eberhardt, C. Froese, A.K. Turner & S. Leroueil) (Proceedings of the 11th International and 2nd North American Symposium on Landslides and Engineered Slopes, Banff, Canada, 3-8 June 2012, Taylor & Francis Group, London), v. 1, 371-377.

Collison, A., Wade, S., Griffiths, J. & Dehn, M. (2000) *Modelling the impact of predicted climate change on landslide frequency and magnitude in SE England.* Engineering Geology 55, 205–218.

Comegna, L., Picarelli. L., Bucchignani, E. & Mercogliano, P. (2013). Potential effects of incoming climate changes on the behaviour of slow active landslides in clay. *Landslides* **10**, 373–391.

Coppola, E., Verdecchia, M., Giorgi, F., Colaiuda, V., Tomassetti, B., Lombardi, A. (2014) Changing hydrological conditions in the Po basin under global warming. *Sci. Total Env.* **493**, 1183-1196, doi:10.1016/j.scitotenv.2014.03.003.

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

Darling, D.A. (1957) *The Kolmogorov-Smirnov, Crame´r-von Mises tests*, Ann. Math. Stat., 28, 823 – 838, doi:10.1214/aoms/1177706788.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. & Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q J R Met Soc* **137**, 553–597.

Déqué, M. (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. *Glob Planet Chang* **57**, 16–26.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., Liebert, J. (2012) Should we apply bias correction to global and regional climate model data? *Hydrol. Earth System Sci.* **16**, 3391–3404, doi:10.5194/hess-16-3391-2012.

Fatichi, S., Ivanov, V.Y. & Caporali, E. (2011) Simulation of future climate scenarios with a weather generator. *Advances in Water Resources* **34**, 448-467, doi:10.1016/j.advwatres.2010.12.013.

Frattini, P., Crosta, G.B., Fusi, N. & Dal Negro, P. (2004). Shallow landslides in pyroclastic soils: a distributed modelling approach for hazard assessment. *Engineering Geology* **73,** 277-295.

Grasso, L. D. (2000) The differentiation between grid spacing and resolution and their application to numerical modeling. *Bull. Amer. Meteorol. Soc.* **81(**3), 579-580.

Gudmundsson, L., Bremnes, J. B., Haugen, J. E. & Engen Skaugen, T. (2012) Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations - a comparison of methods. *Hydrology and Earth System Sciences* **9**, 6185-6201.

Guyennon, N., Romano, E., Portoghese, I., Salerno, F., Calmanti, S., Petrangeli, A. B., Tartari, G., & Copetti, D.: Benefits from using combined dynamical-statistical downscaling approaches – lessons from a case study in the Mediterranean region. *Hydrol. Earth Syst. Sci.* **17**, 705-720, doi:10.5194/hess-17-705-2013, 2013.

Hagemann, S., Chen, C., Haerter, O.J., Heinke, J., Gerten, D., Piani, C. (2011) Impact of a Statistical Bias Correction on the Projected Hydrological Changes Obtained from Three GCMs and Two

Hydrology Models. *J. Hydrometeor* **12**, 556–578, doi: 10.1175/2011JHM1336.1.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D. & New, M. (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. *J. Geophys. Res.* **113**, D20119, doi:10.1029/2008JD010201.

Kapper, K.L. (2009) Scale sensitive analysis of regional climate models. *Wissenschaftlicher BerichtNr.* **29**, Wegener Center Verlag Graz, ISBN 978-3-9502615-6-1.

Kilsby, C. G., Jones, P. D., Burton,A. A., Ford, C., Fowler, H. J., Harpham,C., James, P., Smith, A. & Wilby, R. L. (2007) A daily Weather Generator for use in climate change studies. *Environmental Modelling and Software* **22**, 1705–1719.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K. & Wulfmeyer, V. (2014) Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci. Model Dev.* **7**, 1297–1333, doi:10.5194/gmd-7-1297-2014

Lafon, T., Dadson, S., Buys, G. & Prudhomme, C. (2013) Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods. *Int. J. Climatol.* **33**, 1367-1381.

Lembo Fazio, A., Manfredini, M., Ribacchi, R. & Sciotti, M. (1984) Slope failure and cliff instability in the Orvieto hill. *4th Int. Symp on Landslides*, Toronto, 2, 115-120.

Maraun, D. (2013) Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. *J. Climate* **26**, 2137–2143, doi: http://dx.doi.org/10.1175/JCLI-D-12-00821.1.

Meinshausen, M., Smith, S., Calvin, K., Daniel, J., Kainuma, M., Lamarque, J. F., Matsumoto, K., Montzka, S., Raper, S., Riahi, K., Thomson, A., Velders, G., & van Vuuren, D.P. (2011) The RCPgreenhouse gas concentrations and their extensions from 1765 to2300, *Climatic Change* **19**(1–2), 213–241, doi:10.1007/s10584-011-0156-z..

Mercogliano, P., Montesarchio, M., Vezzoli, R., Rianna, G., Zollo, A.L. (2014) High resolution climate scenarios on Mediterranean test case areas for the hydro climate integrated system. *CMCC Research Paper*–RP0233.

Michelangeli, P.A., Vrac M. & Loukos H. (2009) Probabilistic downscaling approaches: Application to wind cumulative distribution functions. *Geophys. Res. Lett.* **36**, L11708, doi:10.1029/2009GL038401.

Muerth, M.J., St-Denis, B.G., Ricard, S., Velázquez, J.A., Schmid, J., Minville, M., Caya, D., Chaumont, D., Ludwing, R. & Turcotte, R. (2013) On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrol. Earth System Sci.* **17**, 1189-1204.

Olivares, L. & Picarelli, L. (2003). Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils. *Géotechnique* **53**(2), 283-288.

Pagano, L., Picarelli, L., Rianna, G. & Urciuoli, G. (2010). A simple numerical procedure for timely prediction of precipitation induced landslides in unsaturated pyroclastic soils. *Landslides* **7**, 273–289.

Piani, C., Weedon, G.P., Best, M., Gomes, S.M., Viterbo, P., Hagemann, S. & Haerter, J.O. (2010) Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. *J. Hydrol.* **395**(3-4), 199-215.

Pielke, Sr.R.A. (2002) Mesoscale meteorological modeling. *Second International Geophysics Series* **78**, San Diego, California, USA: Academic Press.

Portoghese, I., Bruno, E., Guyennon, N., & Iacobellis, V. (2011) Stochastic bias-correction of daily rainfall scenarios for hydrological applications, Nat. *Hazards Earth System Sci.* **11**, 2497-2509, doi:10.5194/nhess-11-2497-2011.

Racsko, P., Szeidl, L. & Semenov, M.A. (1991) A serial approach to local stochastic weather models. *Ecological Modelling* **57**, 27-41.

Rockel, B., Will, A. & Hense, A. (2008) The regional climate model COSMO–CLM (CCLM). *Meteorol. Z* **17**(4), 347–348, doi:10.1127/0941-2948/2008/0309.

Scoccimarro. E., Gualdi, S., Bellucci, A., Sanna, A., Fogli, P., Manzini, E., Vichi, M., Oddo, P. & Navarra, A. (2011) Effects of Tropical Cyclones on Ocean Heat Transport in a High Resolution Coupled General Circulation Model. *J. Climate* **24**, 4368–4384.

Semenov, M.A. & Barrow, E.M. (1997) Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**, 397-414.

Semenov, M.A., Brooks, R.J., Barrow, E.M. & Richardson, C.W. (1998) Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. *Climate Research* **10**, 95-107.

Semenov, M.A. & Brooks, R.J.(1999) Spatial interpolation of the LARS-WG weather generator in Great Britain. *Climate Research* **11**, 137-148.

Skamarock, W.C. (2004) Evaluating mesoscale NWP models using kinetic energy spectra. *Monthly Weather Review* **132**, 3019–3032.

Steppeler, J., Doms, G., Schättler, U., Bitzer, H.W., Gassmann, A., Damrath, U. & Gregoric, G. (2003) Meso-gamma scale forecasts using the non-hydrostatic model LM. *Meteorol. Atmos. Physics* **82**(1-4), 75-96.

Teutschbein, C. & Seibert, J. (2010) Regional Climate Models for Hydrological Impact Studies at the Catchment Scale: A Review of Recent Modeling Strategies. *Geography Compass* **4**(7), 834–860, doi:10.1111/j.1749-8198.2010.00357.x

Teutschbein, C. & Seibert, J. (2012) Bias correction of regional climate model simulations for hydrological climate change impact studies: Review and evaluation of different methods. *J. Hydrol*, 456-457, 12-29.

Teutschbein, C. & Seibert, J. (2013) Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions? *Hydrol. Earth System Sci.* **17**, 5061–5077, doi:10.5194/hess-17-5061-2013.

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

Tommasi, P., Boldini, D., Caldarini, G. & Coli, N. (2012) Influence of infiltration on the periodic re-activation of slow movements in an overconsolidated clay slope. *Canadian Geotechnical Journal 2013* **50**(1), 54-67, 10.1139/cgj-2012-0121.

Uppala, S.M., Kållberg, P.W., Simmons, A.J., Andrae, U., Bechtold, V., Fiorino, M. & Woollen, J. (2005). The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society* **131**(612), 2961-3012.

USDA, Soil Conservation Service, (1985). National engineering handbook, section 4, hydrology. US Government Printing Office, Washington, D.C.

Vezzoli, R., Del Longo, M., Mercogliano, P., Montesarchio, M., Pecora, S., Tonelli, F., Zollo, A.L. (2014) Hydrological simulations driven by RCM climate scenarios at basin scale in the Po River, Italy. In: *Evolving Water Resources Systems: Understanding, Predicting and Managing Water–Society Interactions Proceedings of ICWRS2014, Bologna, Italy, June 2014* (ed. By A. Castellarin, S. Creola, E. Toth & A. Montanari) (IAHS Publ. 364, 2014), 128-133.

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

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P. (2004) Hydrologic implications of dynamical and statistical approaches to downscale climate model outputs. *Climate Change* **62**, 189–216.

Xu, C.Y. (1999) Climate Change and Hydrologic Models: A Review of Existing Gaps and Recent Research Developments. *Water Resour. Management* **13**, 369–382.

Zollo, A.L., Rianna, G., Mercogliano P., Tommasi, P. & Comegna. L. (2014) Validation of a simulation chain to assess climate change impact on precipitation induced landslides. In: *Landslide Science for a Safer Geoenvironment* (ed. By K. Sassa, P. Canuti & Y. Yin) (Proceedings of World Landslide Forum 3, Beijing), v. 1, 287–292.