**Reply to Reviewer 1 comments**

*Manuscript number: hess-2013-221*
*Title of the manuscript: Distributed hydrologic modeling of a sparsely-monitored basin in Sardinia, Italy, through hydrometeorological downscaling.*
*Authors: G. Mascaro, M. Piras, R. Deidda and E. V. Vivoni.*

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## Reply to Reviewer 1

First of all, we thank Reviewer 1 for her/his comments on our manuscript. In the following, the comments raised by Reviewer 1 are split into parts and copied in bold fonts to facilitate understanding of our answers. Since Reviewer 1 reported some parts of our answers to the first round of reviews, we used italics to highlight those parts. The references to pages and lines of the modifications made in the new manuscript version have been underlined.

Reviewer 1 provides first the following general comment.

**In my previous revision of the manuscript of Piras et al, I requested a major revision since no proper validation of the downscaling methods and the hydrological model are presented, in order to assess the uncertainties. Usually a major revision requires additional results or some changes in the methodology, instead the authors preferred to argue and just modify some text in the manuscript. The authors even refuse to show some simple comparisons, such as requested by reviewer n°1 in his first comment ("one-to-one (coarse vs high-resolution setup) comparison").**

**To my opinion this is not sufficient to address the issues mentioned in the previous revision. I recommend either a straight rejection, if the authors cannot provide new results to justify their methodology, or a major revision, again, if they are willing to revise their paper in a constructive way. At the very least, in the conclusion it should be clearly stated that there are strong uncertainties at the different steps of the modeling chain.**

In the first round of review, we have tried to address the concerns of Reviewer 1 providing detailed answers to each comment, without any intention to argue on her/his suggestions comments. Rather, we believe they are pertinent and helpful to improve the quality of our manuscript. The circumstance that our actions only resulted in some modification of the text, as stated by Reviewer 1, is motivated by the fact that most of Reviewers 1's concerns have been already addressed in previous papers by Mascaro et al. (2013) and Deidda et al. (2013).
We are well aware that our methodology, like any other, is affect by uncertainty and, as recommended by Reviewer 1, this has been further highlighted in the paper conclusions (<u>page 25, lines 1-17 in the new manuscript version</u>).

**Please find below some comments/suggestions to the answers provided by the authors:**

***Regarding the comments related to the uncertainty, we acknowledge that a complete approach would require the use of several combinations of Global and Regional Climate models, multiple downscaling methods, and multiple hydrologic models.***

**This is true, however at least it is possible to validate the different methods chosen for the catchment of interest.**

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We have validated the different steps of our procedure. This has been done mostly in two previous papers. Specifically:

- The selection of the combination of GCMs and RCMs with the best performances in the simulation of precipitation and temperature fields in the Rio Mannu basin has been previously done in a paper by Deidda et al. (2013).
- The multifractal downscaling model for precipitation and the downscaling scheme that provides hourly potential evapotranspiration from daily minimum and maximum temperature have been calibrated and validated in the Rio Mannu basin as described in Mascaro et al. (2013).
- The hydrologic model has been calibrated and validated as described in Mascaro et al. (2013).

To further clarify that we have performed the validation of each step of this procedure, we added additional paragraphs in the Method section (page 9, lines 10-23; page 10, line 1-6; page 11, lines 22-24; page 12, line 1-3; page 13, lines 22-23; page 14, lines 1-6).

***In our case, to simulate the complex hydrologic process of a Mediterranean basin, we selected a physically-based hydrologic model to conduct high-resolution simulations. As it is well-known, this type of models requires a significant computational effort when run on multidecadal periods, as those involved in climate change studies. For example, the 256 years of simulations took us 880 hours of CPU time over 64 processors.***

**This probably overkill, by comparison with the available data (3 years in the beginning of the XXth century). A clear justification about the use of such a model is lacking.**

We decided to use a process-based model like tRIBS, because we think that this type of models have the capability to simulate in continuous fashion the complex hydrologic response of semi-arid basins, like the Mediterranean ones. In this region, in fact, rainfall is intermittent, with a strong seasonal component and high interannual variability, and the land surface properties are extremely heterogeneous (Moussa et al., 2007). As a result, several possible basin wetness states can occur, which lead to a wide range of hydrologic conditions for runoff generation, including saturation and infiltration excess, and intermittent contribution from the groundwater (Piñol et al., 1997; Beven , 2002; Gallart et al., 2002). The tRIBS model has been previously applied in semiarid sites (Mahmood and Vivoni, 2011; Robles-Morua et al., 2012; Xiang et al., 2014) and proved able to capture several processes of the water and energy balances, and the strong non-linear relation between rainfall and runoff. These concepts were further explained in the paper (page 5, lines 10-13; page 12, line 23; page 13, line 1; page 23, lines 4-5). On the other hand, we also acknowledge that the use of a computer with relatively high computational demand have limited the possibility to explore all types of sources of uncertainty (page 25, lines 11-15).

***In a future study, we are planning to compare outputs of the hydrologic models that have been applied on the RMB by other research groups within the CLIMB project. This will allow addressing somehow the uncertainty of hydrologic simulations. This has been added in the paper conclusions (page 23, line 8-10).***

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**The identification of a proper hydrological modelling strategy is probably the first step, prior to make future projections with a given model with high uncertainties.**

The strategy to conduct hydrologic simulations has been decided by the partners of the CLIMB project when the project proposal was submitted. It consisted of running several models with different degree of complexities in the seven study sites of the project with the main goal of addressing the uncertainty of model structure. In the Rio Mannu basin, three models have been applied and, in our paper, we presented results returned by tRIBS. As previously mentioned, a future study will be devoted to compare the outputs of all the three models to address the hydrologic model uncertainty and to better identify strengths and weaknesses of the different approaches (e.g., complex vs. simpler models).

***The hydrometeorological dataset used to calibrate the hydrologic model included:***
***- Daily discharge data at the Rio Mannu basin outlet for 11 years from 1925 to 1935. These data were acquired from the technical reports of the Italian Hydrologic Survey. After a quality control based on the analysis of the stage-discharge relations published every year and other notes present in the reports, we were able to identify three years that we judged as those with the most accurate data.***
***- Daily rainfall data from 12 gages within or near the basin in the same period 1925 -1935.***
***- Daily minimum and maximum temperature from one thermometric station located close to the basin in the same period.***

**This is clearly no enough hydro-meteorological data, to perform a climate change impact study with such a complex modelling chain.**

The modeling chain includes three main steps, including selection of climate models, downscaling of precipitation and potential evapotranspiration, and hydrologic modeling. The dataset reported above is referred to the period that we used to calibrate and validate the hydrologic model. In Mascaro et al. (2013), we explicitly mentioned that this dataset could not be directly used to apply process-based hydrologic models like tRIBS, which instead require precipitation and meteorological data at high time resolution. For this reason, the goal of that study was to propose an approach to circumvent this problem based on two statistical downscaling tools that allow creating the high-resolution forcing (precipitation and potential evapotranspiration) required to perform detailed hydrologic simulations at hourly time resolution. This has been further clarified on page 14, lines 4-6 and page 23, lines 7-9. The downscaling tools (also adopted in the second step of the modeling chain) have been calibrated and validated using data collected at high resolution over more recent time periods. As reported in the reply to a previous comment, we have added paragraphs in the Methods section to explain the data used to calibrate the steps of our modeling chain, as well as the performances of the validation tests.

We also point out that, as it may be sometimes suggested by a wrong (in our opinion) terminology used in some papers, the bias correction and the downscaling tools are two distinct pieces of the modeling chain: the bias correction has the goal of correcting the discrepancies between climate model outputs and observations of precipitation and temperature, while the downscaling tools have the aim of reproducing the statistical variability of these variables at higher spatial and temporal resolution. This

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concept has been further clarified on page 5, lines 13-18.

***The precipitation downscaling model was calibrated using:***
***- Precipitation records at 1-min resolution from 204 automatic rain gages observed during the years 1986–1996 in the coarse grid of 104 km x 104 km shown also in Fig. 1b of this manuscript. Note that this domain entirely includes the catchment.***
***The downscaling algorithm that allows deriving the hourly potential ET was calibrated using:***
***- Hourly meteorological data from 1 station over the period 1995–2010. The observed meteorological variables include all the variables required to apply the Penman-Monteith formula.***

**On the opposite, I agree this dataset allows calibrating the downscaling methods over the domain size. What about validation for the catchment of interest? Sometimes downscaling methods perform well on a coarse resolution but have some troubles locally. For example the validation could be performed with a split sample test in the catchment of interest.**

**Another idea would be to use this data set to force a hydrological model during the period 1986-1996, since observed discharge is not available, it could be a hydrological model that requires either no calibration (simple water balance models) or a model with tables allowing to relate its parameters to land use and soil properties (ex: SCS-CN, SWAT…). Can the parameters of the RMB model be fixed a-priori without calibration?**

We fully agree with Reviewer 1 about the need to validate the downscaling tools in the catchment of interests. We have tested the ability of both downscaling tools to reproduce precipitation and potential evapotranspiration in our catchment of interest and presented results in Mascaro et al. (2013).

The precipitation downscaling tools was validated in two ways. First, we compared the empirical cumulative density functions (ECDFs) of observed and simulated fields at high resolution in the entire coarse domain, as shown in the following figure taken from Mascaro et al. (2013; Fig. 6). This figure was obtained with high-resolution data available from 1986 to 1996. Next, we considered the period 1925-1935 where we conducted the hydrologic simulations and when only data at daily resolution are available. The second validation of the downscaling model was performed by comparing observed and simulated series of the daily mean areal precipitation (MAP) in the basin. The precipitation downscaling model was applied from the coarse to the fine resolution generating an ensemble of 50 disaggregated fields. The simulated MAP series was derived by aggregating the synthetic grids at daily resolution and computing the spatial basin average. The observed series was instead obtained by applying Thiessen polygons to the observations of the 12 available gages. The following table (Table 7 of Mascaro et al., 2013) reports the Root Mean Square Error (RMSE) and Bias between the observed and the ensemble average from the downscaling model for the period 1925–1935. The RMSE computed for rainy days has little interannual variability (average value of 4.38 mm), while the bias, again calculated for rainy days, is negative (mean of −0.89 mm), indicating that the downscaling procedure tends to slightly underestimate the observed MAP (less than 10 %).

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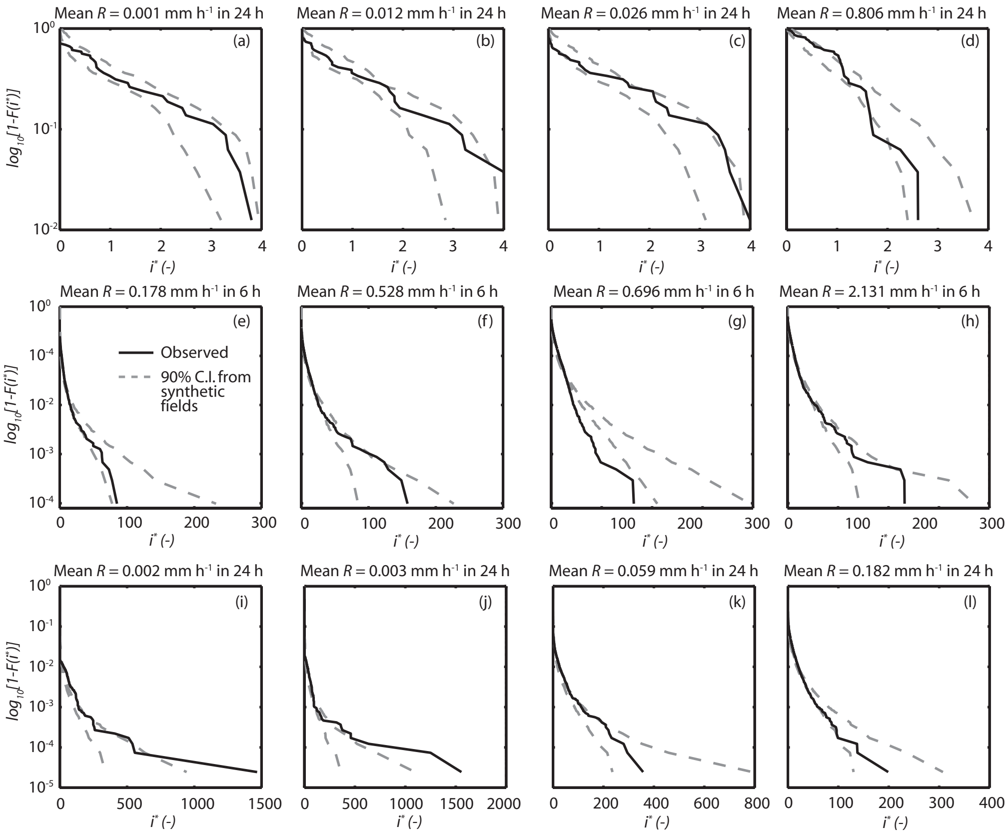


| Year | RMSE (mm) | Bias (mm) |
|---|---|---|
| 1925 | 4.34 | -1.06 |
| 1926 | 4.28 | -0.78 |
| 1927 | 4.18 | -1.49 |
| 1928 | 3.95 | -0.60 |
| 1929 | 4.19 | -1.31 |
| *1930* | *5.63* | *-0.64* |
| *1931* | *4.27* | *-0.76* |
| *1932* | *3.15* | *-0.74* |
| 1933 | 4.86 | -1.35 |
| 1934 | 3.97 | -0.29 |
| 1935 | 4.48 | -1.03 |
| All | 4.37 | -0.89 |

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The disaggregation method for the potential evapotranspiration ($ET_0$) was also validated. For the period 1995-2010 when hourly meteorological data are available, we computed (i) the hourly $ET_0$ using the Penman-Monteith formula, (ii) the hourly $ET_0$ using with the disaggregation method starting from minimum ($T_{min}$) and maximum ($T_{max}$) daily temperature. Given the use of season-dependent equations in the disaggregation procedure, we computed for each season the interannual mean RMSE and Bias. Results are presented in the following table (Table 6 of Mascaro et al., 2013), which shows that, despite the downscaling procedure slightly underestimates the hourly $ET_0$ (negative Bias), performances are overall fairly good, as indicated by the low RMSE.

As mentioned in a previous answer, these details were added in the Methods section (page 9, lines 10-23; page 10, line 1-6; page 11, lines 22-24; page 12, line 1-3).

| Season | RMSE (mm $h^{-1}$) | Bias (mm $h^{-1}$) |
|---|---|---|
| DJF | 0.019 | -0.004 |
| MAM | 0.031 | -0.009 |
| JJA | 0.039 | -0.015 |
| SON | 0.029 | -0.011 |

***We agree with Reviewer 1 that a longer period of calibration and validation would increase the robustness of the hydrologic model. The Rio Mannu basin was selected as one of the study sites of the CLIMB project (funded by the 7th Framework Program of the European Union) because of the presence of agricultural fields and of an experimental farm where several data of crop productivity are being collected. One goal of CLIMB is, in fact, to evaluate the impact of climate change on local economic activities. This basin possesses then ideal characteristics to accomplish the project goals.***

**Ideal except for the hydrometric data availability.**

Unfortunately, the number of stream gages monitored in the island of Sardinia has drastically diminished from the beginning of the last century. Most of the currently available stations (where the stage-discharge relations have been very rarely updated) are located in mountain areas, close to dams (the list can be found here http://www.regione.sardegna.it/documenti/1_19_20100105100339.pdf, but data are publicly available only for some of them). As a result, any modeling studies in basins with agricultural activities will suffer from the same problem. This has been highlighted on page 25, lines 4-6. As already mentioned, an important reason that drove the choice of this study site is the presence of an experimental farm, managed by one of the CLIMB partners (http://www.sardegnaagricoltura.it/index.php?xsl=443&s=47643&v=2&c=3516, in Italian), where several data of crop productivity are being collected.

***Unfortunately, in our watershed, observed discharge data were only available in the period 1925–1935. Furthermore, as mentioned in the answer to comment 1, after a quality control, we were able***

***to identify only three years (1930-1932) that we judged as those with the most reliable data.***

**If there are some agricultural activities in the catchment, it is likely that some land use change has occurred since 1932 (new agricultural practices, changes in irrigation systems..etc.), therefore the associated hydrological processes may be different in the period 1970-2000.**

The stationarity of the land cover distribution in the Rio Mannu basin has been tested in Mascaro et al. (2013) by carefully comparing the orthophotos available in years 1954 and 2006. We found that the main land cover distribution has not changed significantly. We cannot exclude that new agricultural practices and changes in irrigation systems have occurred. However, to our knowledge, there are not studies that incorporated these factors in hydrologic simulations, also because these data are very rarely available.

***As a matter of fact, the problem of lack of discharge data is common for other basins in Sardinia and for most Mediterranean catchments. Thus, if we want to estimate the impact of climate change on water resources and local economic activities in these study regions, the limitation of observed discharge records needs to be accepted most of the times.***

**I strongly disagree. We should first focus on sites with sufficient data and then try to adapt the methods and modelling schemes to un-gauged or partially gauged catchments. This is the same strategy for regionalization: the methods are first validated in catchments with sufficient data. When not enough data is available, novel modeling strategies should be used to cope with the lack of data instead of hiding the uncertainties behind an overly complex modelling framework.**

In principle, we agree on the fact that focusing on highly monitored sites helps developing methods that can be applied to poorly monitored locations. However, we also believe that it is necessary to provide an immediate answer to problems in areas with limited data, with the clear limitation of more uncertain outcomes. In addition, we do not think that our study site is completely unmonitored and that we hid the uncertainties behind an overly complex modeling framework. Our approach, in fact, cannot be considered extremely complicated, as it includes the ingredients of many climate change studies: (i) auditing and bias correction of global and regional climate models; (ii) use of downscaling tools; and (iii) use of a hydrologic model. As mentioned in previous answers, the reliability of this approach has been tested by validating and characterizing the uncertainty of global and regional climate models and downscaling tools against a large rainfall and meteorological dataset observed in the study catchment (12 rain gages and 1 meteorological station in a 472.5 km$^2$ basin, and 204 rain gages in the coarse scale domain). The main limiting factor of our approach has been the lack of long-term discharge records to calibrate the hydrologic model. We have explicitly recognized this limitation on <u>page 25, lines 4-6</u>. To address this limitation and identify a robust modeling tool, we have proceeded as follows. First, we have used a physically-based model where most of the parameters have been derived from literature values and the calibration has been limited to a few soil parameters. Second, to identify robust model parameters while using a relatively short record of observations, we selected a wet year (total annual runoff of 183 mm) with several flood events for calibration and two dry years (annual runoff of 76 and 71 mm) with a few floods for validation. Finally, we have tested the model performances with disaggregated forcings, while, in most climate change studies, hydrologic models are calibrated with high-resolution observed forcings. Overall, the simulation performances were adequate and gave us confidence in the robustness of our model. All these aspects have been discussed in Mascaro et al. (2013) and further illustrated in the new manuscript version (page 13, lines 22-23; page 14, lines 1-8). We think that our modeling exercise contains useful ideas that can be adopted to support climate change and modeling studies in regions with sparse hydrometeorological data, i.e. collected at different time resolutions over different periods.

***Regarding the hypothesis of stationarity of bias correction and more in general calibration relations and model parameters, which was assumed to hold in current and future climate, we acknowledge that, in principle, it may not be valid. However, as a matter of fact, it is assumed in the great majority of the climate change studies.***

**Indeed, many climate change studies are performed with little scientific grounds. I have nothing against climate change studies, but prior to make future projections the robustness and the skills of the methods should be assessed. This is the main motivation for projects such as COST-VALUE (http://www.value-cost.eu/). Since the hypothesis of stationarity can be tested, at least during historical conditions, there is no valid reason why this test should be avoided. See Maraun 2012, Tramblay et al. 2013 (references listed in the previous revision) or Teutschbein and Seibert 2013 (http://www.hydrol-earth-syst-sci.net/17/5061/2013/hess-17-5061-2013.html).**

The study from Maraun et al. (2012) based on a pseudo reality (i.e., regional climate models are alternatively used as observations) indicates that precipitation bias is stationary for most parts of Europe, but it may vary in semi-arid regions with strong convective activity, especially in summer. These areas are mostly located in North Africa. Our study basin is not affected by significant convective activity and summer rainfall is practically negligible. As a result, we believe that the hypothesis of stationary can be assumed in our study region, also given the lack of relatively long records of observations that can be used to test it.

## REFERENCES

Beven, K.: Runoff generation in semi-arid areas, in: Dryland Rivers, edited by: Bull, L. J. and Kirkby, M. J., J. Wiley & Sons, 57–105, 2002.

Deidda, R., Marroccu, M., Caroletti, G., Pusceddu, G., Langousis, A., Lucarini, V., Puliga, M., and Speranza, A.: Regional climate models' performance in representing precipitation and temperature over selected Mediterranean areas, Hydrol. Earth Syst. Sci., 17, 5041-5059, doi:10.5194/hess-17-5041-2013.

Gallart, F., Llorens, P., Latron, J., and Regüés, D.: Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees, Hydrol. Earth Syst. Sci., 6, 527–537, doi:10.5194/hess-6-527-2002, 2002.

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Mahmood, T. H., and Vivoni, E. R., A climate-induced threshold in hydrologic response in a semiarid ponderosa pine hillslope, Water Resour. Res., 47, W09529, doi:10.1029/2011WR010384, 2011.

Mascaro, G., Piras, M., Deidda, R., and Vivoni, E. R.: Distributed hydrologic modeling of a sparsely monitored basin in Sardinia, Italy, through hydrometeorological downscaling, Hydrol. Earth Syst. Sci., 17, 4143–4158, doi:10.5194/hess-17-4143-2013, 2013a.

Moussa, R., Chahinian, N., and Bocquillon, C.: Distributed hydrological modeling of a Mediterranean mountainous catchment – model construction and multi-site validation. J. Hydrol., 337, 35– 51, doi:10.1016/j.jhydrol.2007.01.028, 2007.

Piñol, J., Beven, K., and Freer, J.: Modelling the hydrological response of Mediterranean catchments, Prades, Catalonia. The use of distributed models as aids to hypothesis formulation, Hydrol. Process., 11, 1287–1306, 1997.

Robles-Morua, A., Vivoni, E. R., and Mayer, A. S.: Distributed hydrologic modeling in Northwest Mexico reveals the links between runoff mechanisms and evapotranspiration, J. Hydrometeor., 13, 785–807, doi:10.1175/JHM-D-11-0112.1, 2012.

Xiang, T., Vivoni, E. R., and Gochis, D. J.: Seasonal evolution of ecohydrological controls on land surface temperature over complex terrain, Water Resour. Res., 50, 3852–3874, doi:10.1002/2013WR014787, 2014.