Evaluation of climate change effects on the hydrology of a medium-sized Mediterranean basin affected by data sparseness

General Assembly 2014
HS7.4/AS4.21/CL3.8 -
Change in climate, Hydrology and Society

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Abstract

Many studies based on global and regional climate models agree on the prediction that the Mediterranean area will be most likely affected by climate changes with consequent reduced water availability and intensified hydrologic extremes. This study evaluates the effects of climate changes on the hydrologic response of a medium-sized Mediterranean basin through downscaling techniques and hydrologic simulations. The watershed is the Rio Mannu at Monastir basin (473 km^2), located in an agricultural area of southern Sardinia, Italy, which has suffered drought issues in the last decades. It is one of the seven study cases of a multidisciplinary European research project, CLIMB (Climate Induced Changes on the Hydrology of Mediterranean Basins). In such basins, characterized by strong climate variability and by a complex hydrologic response, process based distributed hydrologic models, DHMs, combined with regional climate models, RCMs, and downscaling techniques can help in the evaluation of the local impacts of climate change on water resources decreasing the uncertainty. Since the Rio Mannu basin is affected by data sparseness (meteorological and streamflow data are collected in non overlapping time periods and at diverse time resolutions), two statistical downscaling strategies for precipitation and potential evapotranspiration have been designed which allow to obtain the high-resolution input data required for the calibration of our hydrologic model, the TIN-based Real time Integrated Basin Simulator (tRIBS). We show how the DHM has been calibrated and validated with reasonable accuracy using the disaggregation tools. Next, the same downscaling algorithms have been used to fill the resolution discrepancy between RCMs and the hydrologic model. The outputs of four RCMs, selected as the best performing and bias corrected within the CLIMB project, have been downscaled and used to force the tRIBS during a reference (1971-2000) and a future (2041-2070) period. Several hydro-climatic indicators have been computed based on the time series and spatial maps produced by the DHM to assess the variation in Rio Mannu water resources budget and hydrologic extremes in the future period as compared to the reference one. Our results confirms what is generally predicted for the Mediterranean area, showing a basin future condition of more water shortages due to both reduced precipitations and increased temperatures.

Study Case and Dataset

Our study site is the **Rio Mannu basin (RMB)**, located in the southern Sardinia, Italy (Fig.1) and included within the CLIMB EU project (Ludwig et al., 2010):

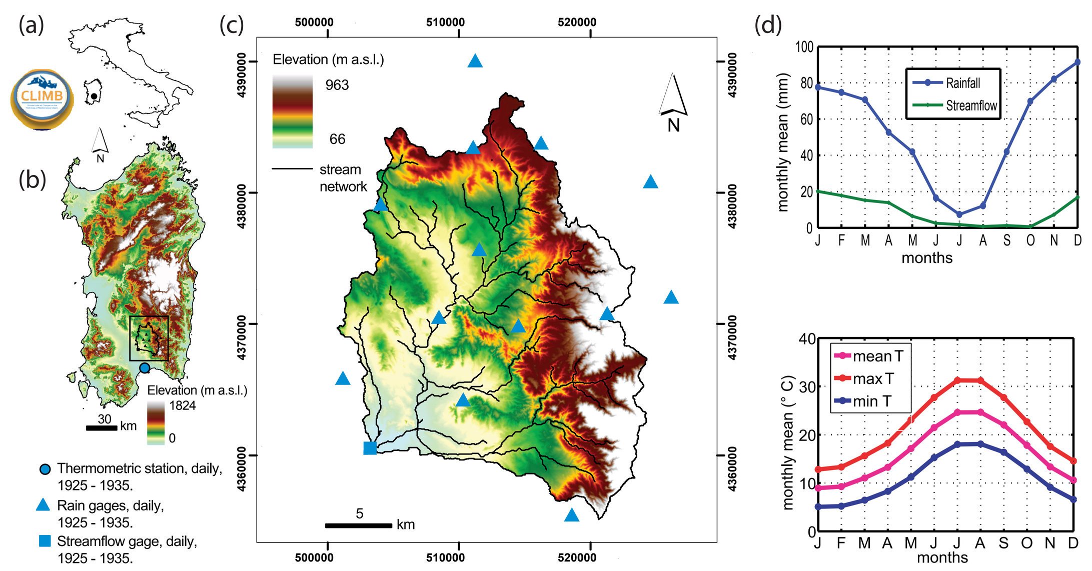


Fig. 1 - Location of the RMB within (a) Italy and (b) the island of Sardinia. (c) Digital elevation model (DEM) of the RMB including UTM coordinates. Panels (b) and (c) also report the position of the thermometric station, rain gages and streamflow gage at the basin outlet with daily data observed during the years 1925-1935. (d) Monthly variability of climatological means of rainfall, streamflow and temperature.

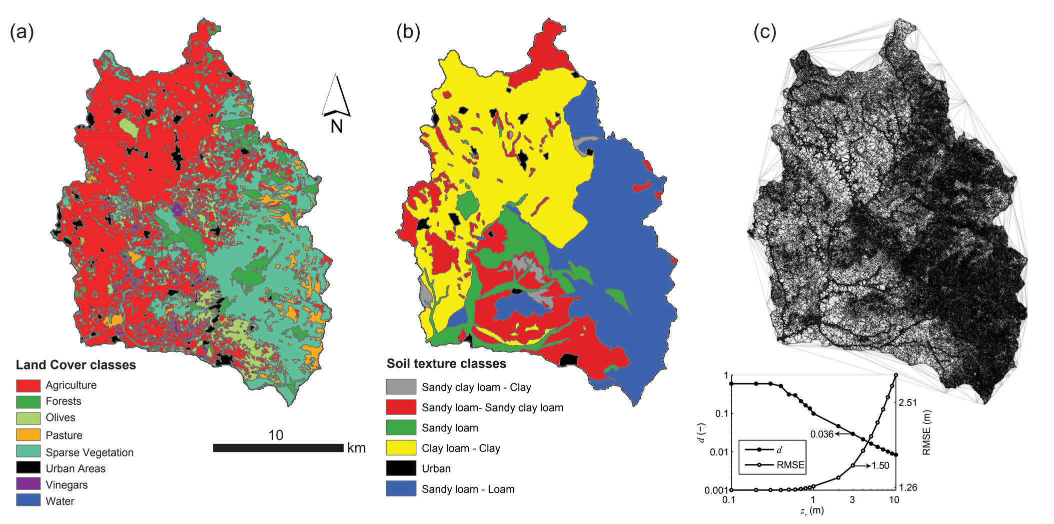


Fig. 2 - (a) Land cover map. (b) Soil texture map. (c) Triangulated Irregular Network used as domain for the simulation with the tRIBS model.

Hydrometeorological dataset

As many Mediterranean catchments, the RMB is affected by **data sparsness**: precipitation, streamflow, and meteorological data were collected within different historical periods and at diverse temporal resolution (Figs. 1, 3).

1925 — 1935 — 1986 — 1995 — 1996 — 2010 — time

- **Daily** streamflow at the outlet
- **Daily** precipitation (12 gages)
- **Daily** T_{max} and T_{max} (1 station)

- **1-min** precipitation (204 gages)
- **Hourly** meteorological data (1 station)

- Calibration period to be chosen in 1925-1935, when streamflow observations are available.
- In 1925-1935, only daily precipitation and minimum and maximum temperature were collected.

High resolution meteorological data of recent years were used to develop ***downscaling strategies*** *for* ***precipitation*** *and* ***potential evapotranspiration****.*

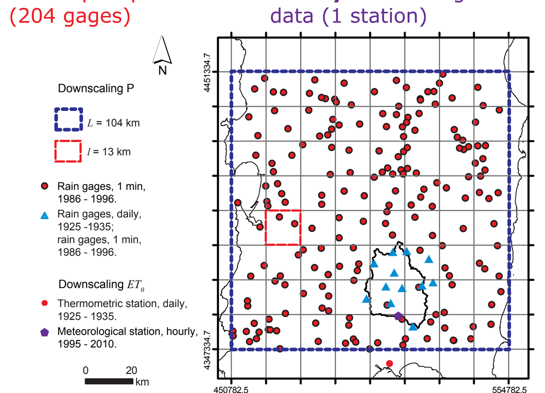


Fig. 3 - Location of rain gages, meteorological stations and streamflow gage. Blue is used for daily stations, while red and violet for high-resolution stations.

Hydrologic Model Calibration

- We calibrated the **TIN based real time integrated basin simulator (tRIBS)** hydrologic model (Fig. 5), using precipitation and potential evapotranspiration (ET_0) forcings disaggragated at hourly resolution (Fig. 4), as described by Mascaro et al. (2013).
- tRIBS is a process-based distributed hydrologic model (DHM), able to simulate the coupled water and energy balance at high spatial and temporal resolution (Fig. 5).
- Precipitation was downscaled from daily to hourly resolution and from 104 km to 13 km (Fig. 3) using the Space Time RAINfall (STRAIN) multifractal model (Deidda et al., 2004; Badas et al., 2006) (Fig. 4).
- ET_0 was disaggregated at hourly resolution from daily T_{max} and T_{min}, using dimensionless functions based on the Penman-Monteith and Hargreaves formulas, and calibrated with hourly meteorological data available from 1995 to 2010 (Fig. 4).

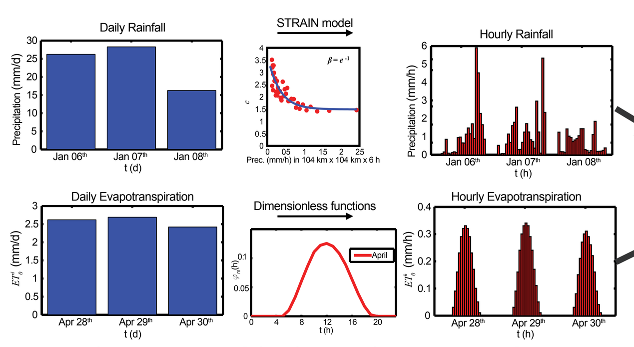


Fig. 4 - Schematization of the downscaling strategies for precipitation and ET_0, and generation of hourly forcing for tRIBS.

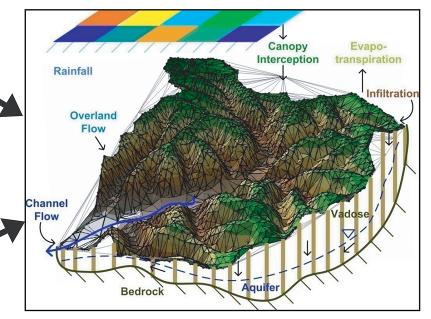
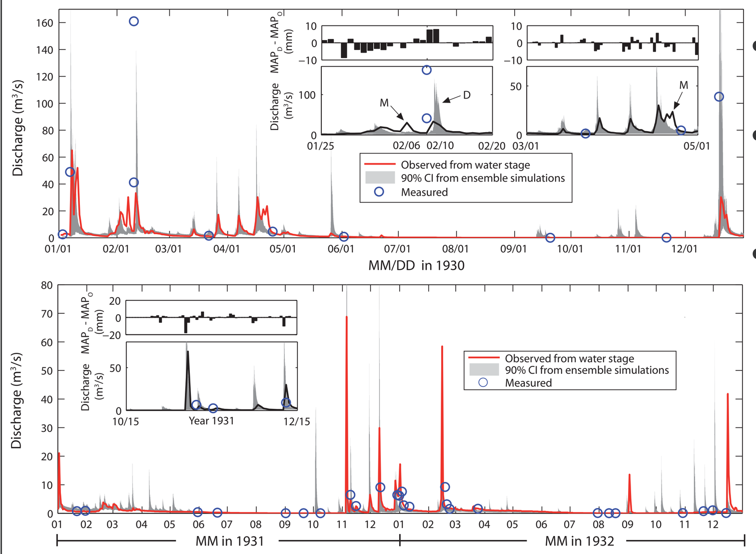


Fig. 5 - Coupled hydrologic processes represented in `tRIBS model over a complex triangulated terrain (Ivanov et al. 2004).



- One year of calibration (1930) and two years of validation (1931-1932).
- Manual calibration of model parameters, selected within physically plausible ranges.
- Despite several sources of uncertainty in observations and model parameterization, calibration and validation performances are adequate (Fig. 6; Mascaro et al., 2013).

Time scale	Calibration NSC Min, Mean, Max	Validation NSC Min, Mean, Max
Daily	-3.53, 0.07, 0.61	-0.99, 0.02, 0.42
Weekly	-5.50, 0.46, 0.83	-0.72, 0.13, 0.47
Monthly	-0.06, 0.55, 0.89	0.30, 0.25, 0.74

Fig. 6 - (a) Result of the tRIBS model calibration (year 1930). Comparison between the observed discharge against the 90% confidence intervals (CI) derived from the 50 ensemble simulations of the tRIBS model. In the insets, a zoom on two periods with significant flood events is reported to better visualize the comparison. The circles represent the discharge values measured by the Italian Hydrologic Survey to update the rating curve. (b) Same as (a) for the validation period (years 1931-1932).

Future Climate Forcing

- Outputs of four **Regional Climate Model (RCMs)** were validated, bias-corrected (Deidda et al., 2013), and disaggregated at hourly resolution to generate the forcing for tRIBS.
- The four RCMs are the best performing combinations of two GCMs and three RCMs.

	Climatological center and model	Acronym	
GCMs	Hadley Centre for Climate Prediction, Met Office, UK HadCM3 Model (high sensitivity)	HadCM3	H
	Max Planck Institute for Meteorology, Germany ECHAM5 / MPI OM	ECHAM5	E
RCMs	Swedish Meteorological and Hydrological Institute (SMHI), Sweden RCA Model	RCA	RC
	Max Planck Institute for Meteorology, Hamburg, Germany REMO Model	REMO	RE
	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands RACMO2 Model	RACMO	RM

GCMs	RCMs	Acronym of selected RCMs
HadCM3	RCA	HRC
ECHAM5	RCA	ERC
ECHAM5	REMO	ERE
ECHAM5	RACMO	ERM

- Two time slices: Reference (REF 1971-2000) and Future (FUT 2041-2070) periods.
- All RCMs predict **decreased mean annual MAP** (mean areal precipitation), and **increased mean annual temperature T** (Fig. 7 a,b).
- MAP is predicted to slightly increase in winter months (Fig. 7c) and decrease in the other seasons, while T is expected to increase throughout the year (Fig. 7d). The model HRC presents the largest variations.

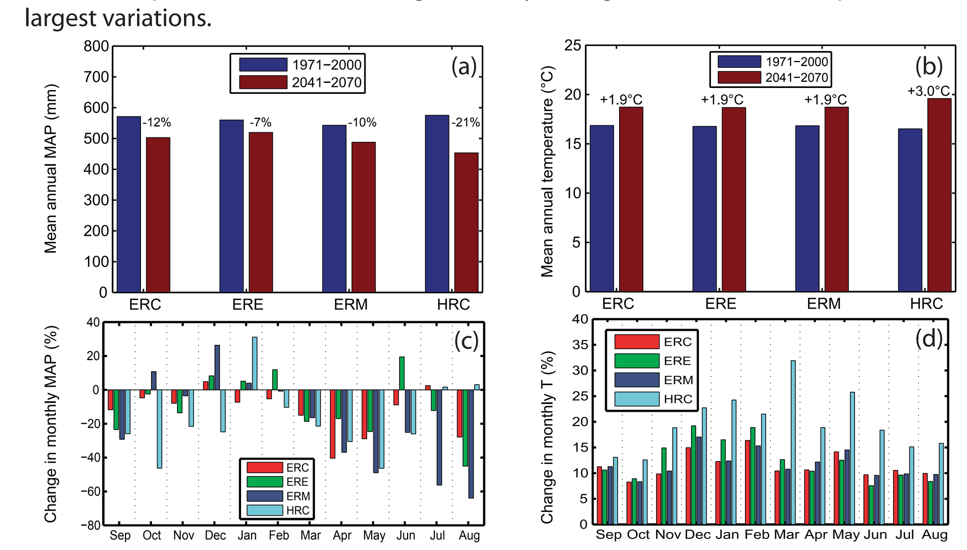


Fig. 7 - (a)-(b) Mean annual MAP (a) and T (b) in REF and FUT periods. (c)-(d) Relative change in monthly MAP (c) and T (d).

Impacts of Climate Change on Hydrologic Response

- The tRIBS hydrologic model was forced with the disaggregated outputs of the four RCMs, for the REF and FUT periods.
- A total of 240 years of simulations were performed using the parallelized version of tRIBS (Vivoni et al., 2011) in the Saguaro super computer at Arizona State University.

Stream Discharge

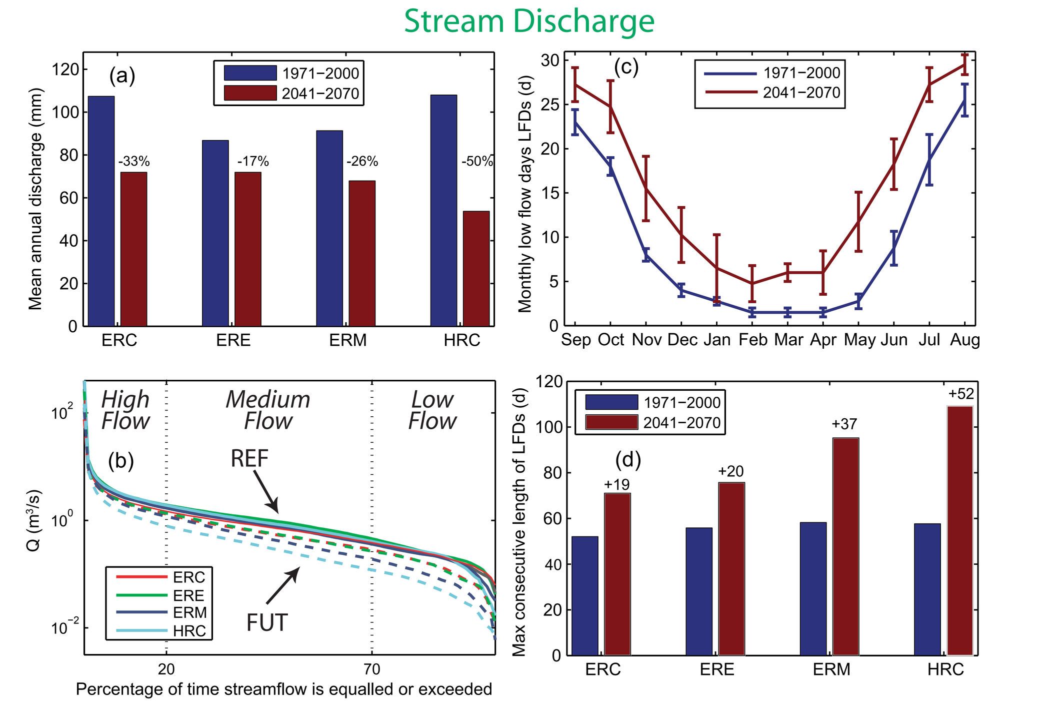


Fig. 8 - (a) Mean annual discharge in REF and FUT. (b) FDCs at the basin outlet (continuous lines for REF and dashed for FUT). (c) Mean and standard deviation of low flow days (LFDs) for each month. (d) Maximum length of consecutive LFDs.

- Future projections indicate, in all cases, a **decreasing mean annual discharge** up to 50% (Fig. 8a).
- This is confirmed by the downward shift in the Flow Duration Curves (FDCs) (Fig 8b) over the entire range of exceedance probabilities.
- As a result: (i) the number of low flow ($Q < Q_{70\%\ REF}$) days (LFDs) increases in all months (Fig. 8c), and (ii) the maximum length of consecutive LFDs per hydrologic year increases in FUT (Fig 8d).

Runoff components

- Changes in precipitation distribution impact the mechanisms of runoff generation, with increasing occurrence of infiltration excess runoff (IE) and perched return flow (PR), and decreasing occurrence of saturation excess runoff (SE) and groundwater exflitration (GE).

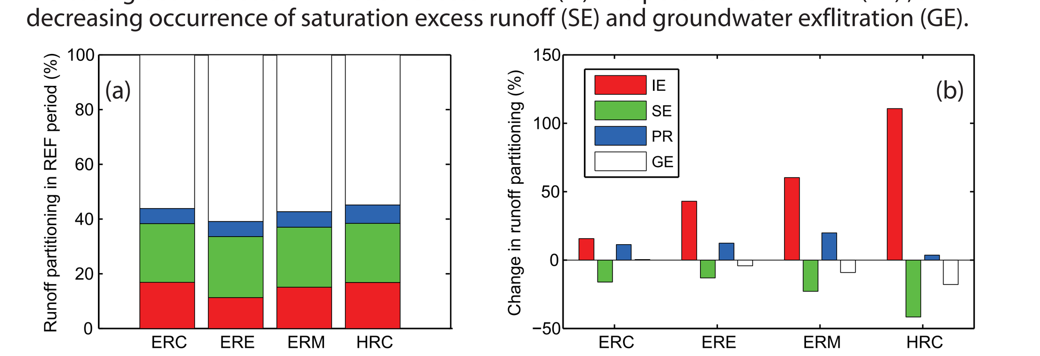


Fig. 9 - (a) Runoff partitioning in the REF period. (b) Relative change in runoff partitioning, (FUT - REF)/REFx100.

Soil moisture and evapotranspiration losses

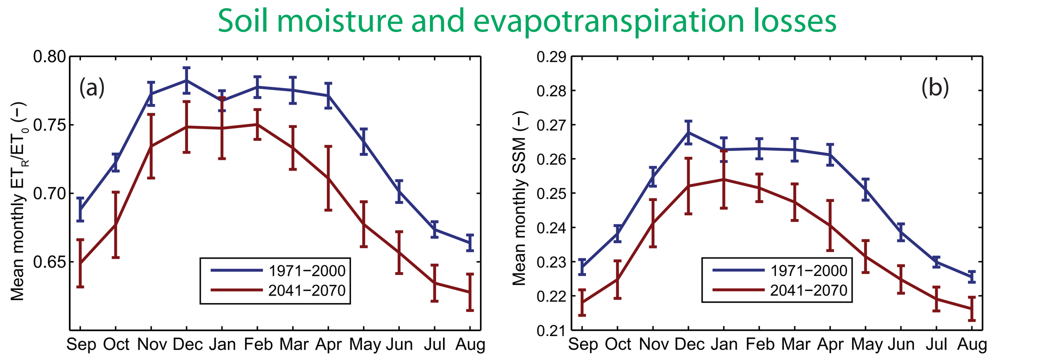


Fig. 10 - (a) Ratio of mean monthly basin averaged ET_R and ET_0, plotted as mean ± standard deviation of the RCMs. (b) Same as (a), but for the mean monthly basin averaged soil moisture in the top 10 cm (SSM).

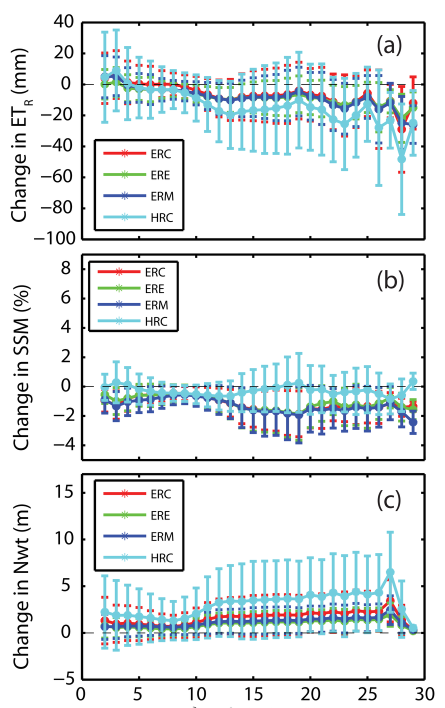
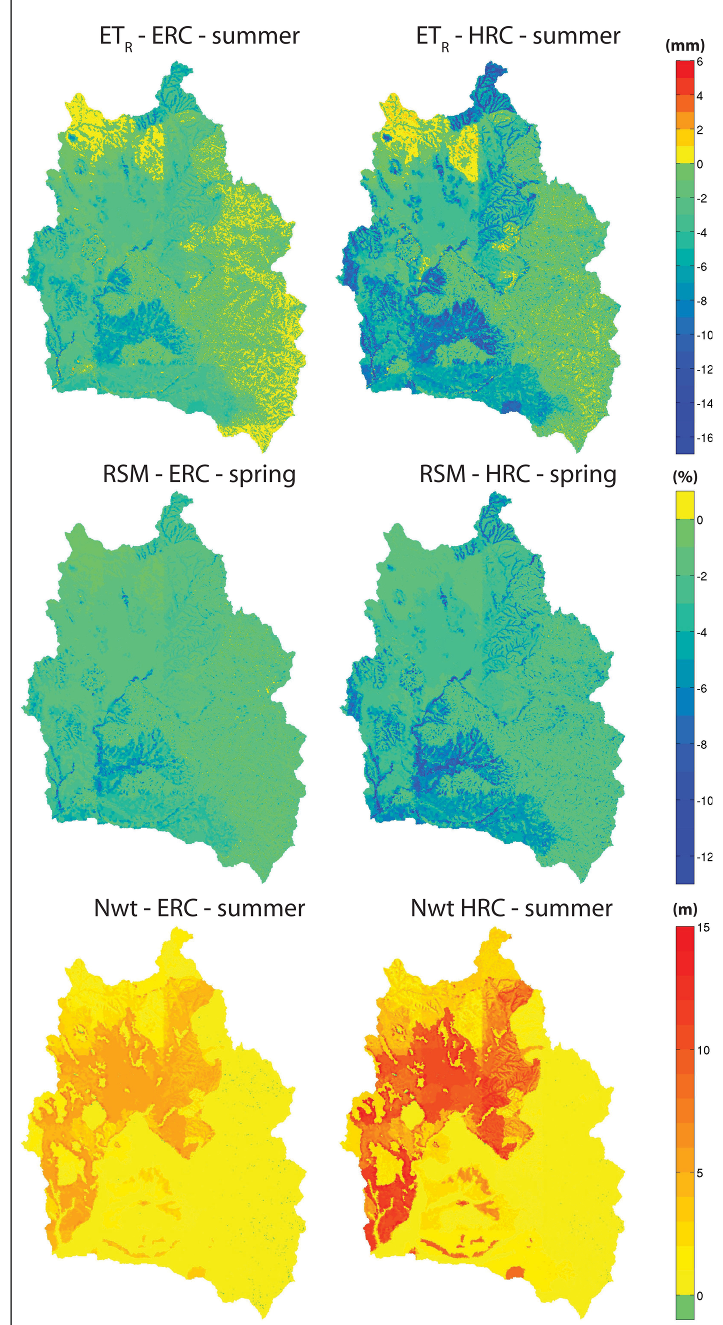


Fig. 11 - Change in annual (a) ET_R, (b) SSM, and (c) Nwt, as a function of λ.

- Hydrologic simulations predict an **increase in ET_0** and a **decrease in real evapotranspiration (ET_R)**, resulting in a reduction of their ratio (ET_R/ET_0) (Fig. 10a).
- Decrease in ET_R with higher ET_0 (due to higher T) is most likely caused by lower future precipitation, which, in turn, leads to **drier soils** (Fig. 10b).
- The variation in mean annual ET_R are related to terrain characteristics, with slight increments in areas with low topographic index λ (mountain areas) and reductions that increase in areas with higher λ (from hillslopes to floodplains) (Fig. 11a).
- The mean SSM is expected to decrease, especially in areas with intermediate λ (Fig. 11b).
- All simulations predict a **drop in the groundwater table depth** (Nwt) (Fig. 11c).
- The changes predicted with HRC forcing are the most extreme (highest decrease of ET_R and Nwt), due to lower precipitation and higher temperature in FUT (Fig. 7).

Spatial patterns of changes in hydrologic variables



- Fig. 12 shows maps of changes (mean on FUT - mean on REF) for:
  - Real Evapotranspiration, ET_R.
  - Root Soil Moisture, RSM.
  - Depth of the ground water table, Nwt.
- Results are shown for the models (Fig. 7c,d) and the seasons with the most marked changes.
- Variation in ET_R are influenced by terrain attributes (higher negative changes in areas of saturation), soil texture (higher negative changes in soils with sandy content), and patterns of gridded inputs.
- Variations in RSM are affected by terrain, with higher decreases in areas of saturation close to the drainage network.
- Variations in Nwt are related to soil texture, with higher drops of the water table in clay soils.

Fig. 12 - Spatial maps of changes in hydrologic variables.

Conclusions

- The impact of future climate change on the hydrologic response of a medium-sized Mediterranean basin in Sardinia (Italy) was quantified by combining a process-based distributed hydrologic model, known as tRIBS, with four RCMs.
- Two downscaling techniques were applied to generate the sub-daily forcing required to conduct high-resolution hydrologic simulations.
- All RCMs predict lower mean annual precipitation and higher mean temperatures in the future period 2041-2070.
- The hydrologic simulations under future climate forcing indicate:
  - Decreasing mean annual runoff, with modification of the generation mechanisms.
  - Decreasing mean real evapotranspiration, likely due to drier soil moisture conditions.
  - Decreasing mean level of the groundwater table.
- The future changes in the mean values of the hydrologic variables are influenced by the spatial patterns of topography and soil texture.

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