

Future changes of the terrestrial water budget over twenty major European river catchments from CORDEX regional climate model projections

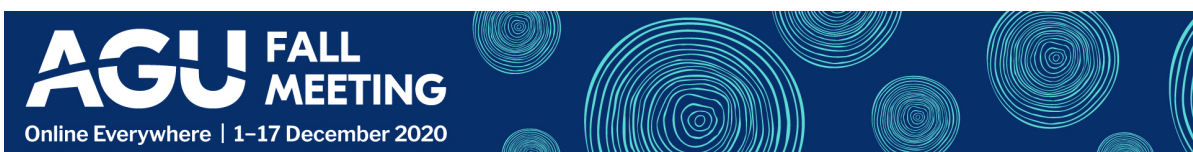


Mohamed Eltahan (1,2), Klaus Goergen (1,2), Stefan Kollet (1,2), Clemens Simmer (3)

(1) Institute of Bio- and Geosciences (Agrosphere, IBG-3), Research Centre Jülich, 52428 Jülich, Germany, (2) Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J, 52428 Jülich, Germany, (3) Division of Meteorology, Institute of Geosciences, University of Bonn, 53121 Bonn, Germany



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INTRODUCTION

Climate change-induced alternations of the hydrological cycle have impacts on natural and anthropogenic systems. Here we present an analysis of the changes of water cycle components, precipitation (P), evapotranspiration (ET), and runoff (R) over 20 major river catchments in Europe based on an ensemble of regional climate change projections from the European branch of the Coordinated Regional Downscaling Experiment (EURO-CORDEX) [1] [2].

PROJECTED FUTURE CHANGES OVER THE EBRO RIVER

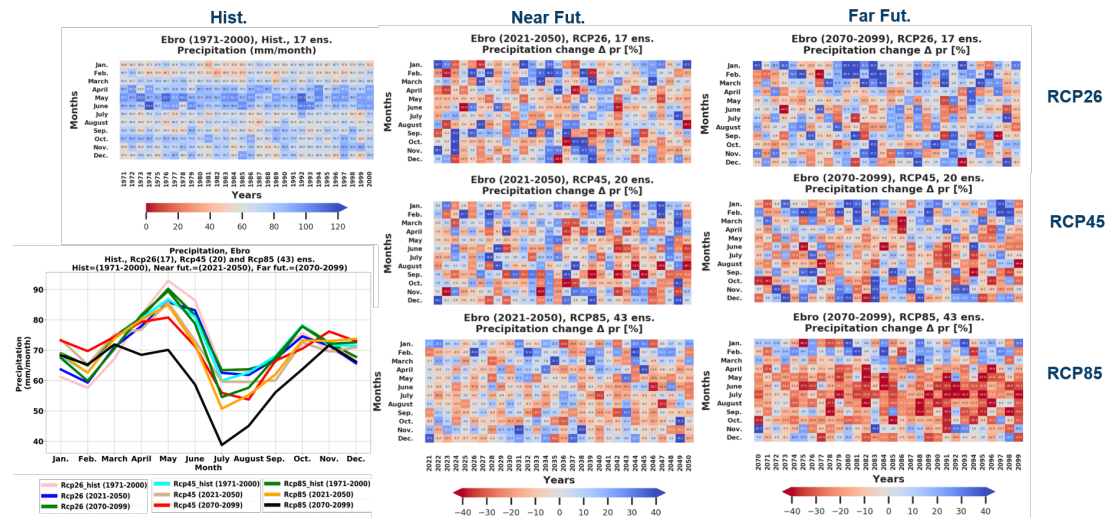


Fig. 2 Heat maps: Changes in multi-model means of precipitation (pr) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

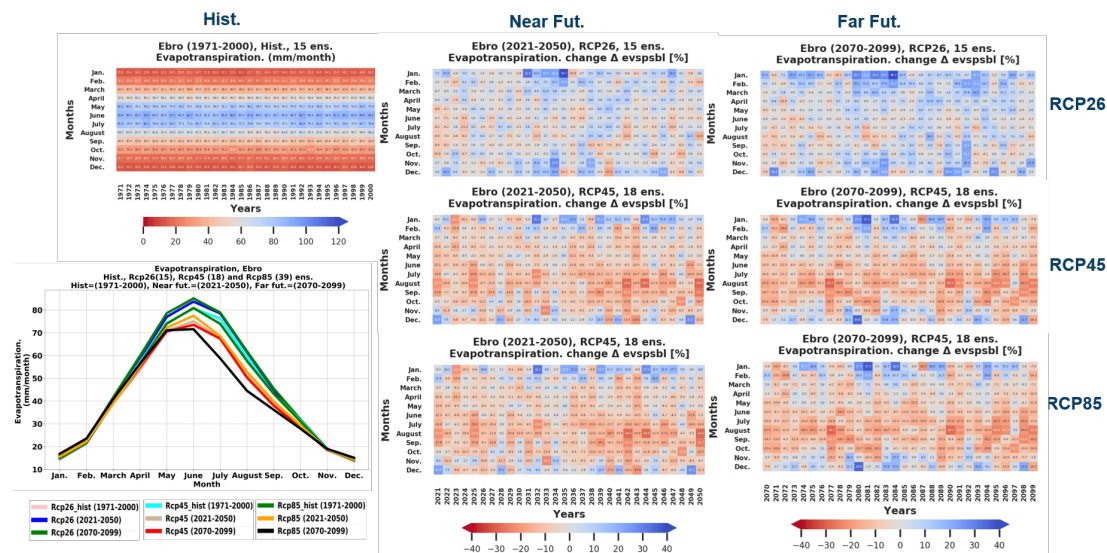


Fig. 3 Heat maps: Changes in multi-model means of evapotranspiration (evspsbl) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

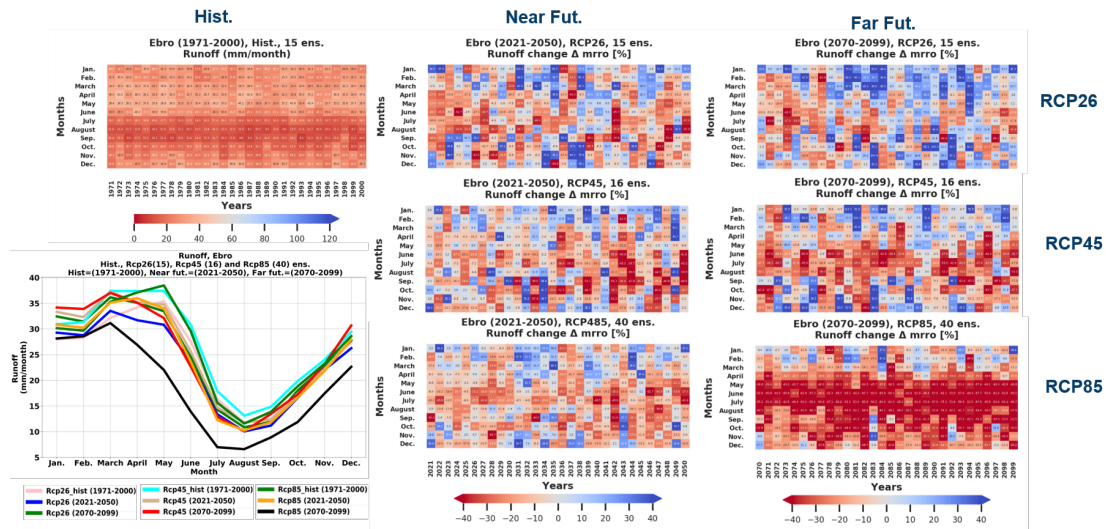


Fig. 4 Heat maps: Changes in multi-model means of runoff (mm/month) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

Over the Ebro River basin, for RCP8.5, there is a clear change signal with a downward shift (decrease) in the long-term average of multi-model means annual cycles of precipitation, evapotranspiration and runoff for both near and far future. There is a decrease in monthly precipitation especially during the Summer months.

PROJECTED FUTURE CHANGES OVER THE RHINE RIVER RIVER

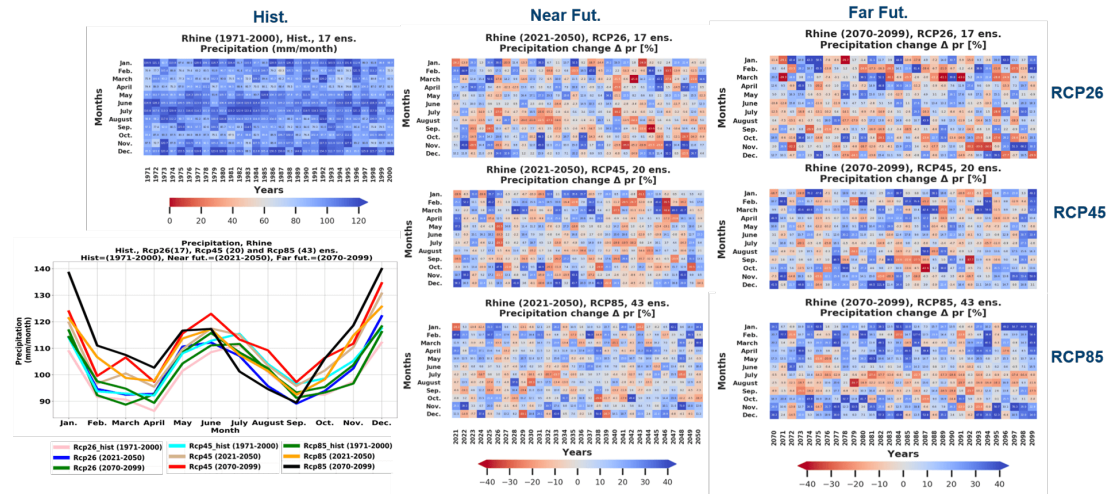


Fig. 5 Heat maps: Changes in multi-model means of precipitation (pr) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for three (RCPs), RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

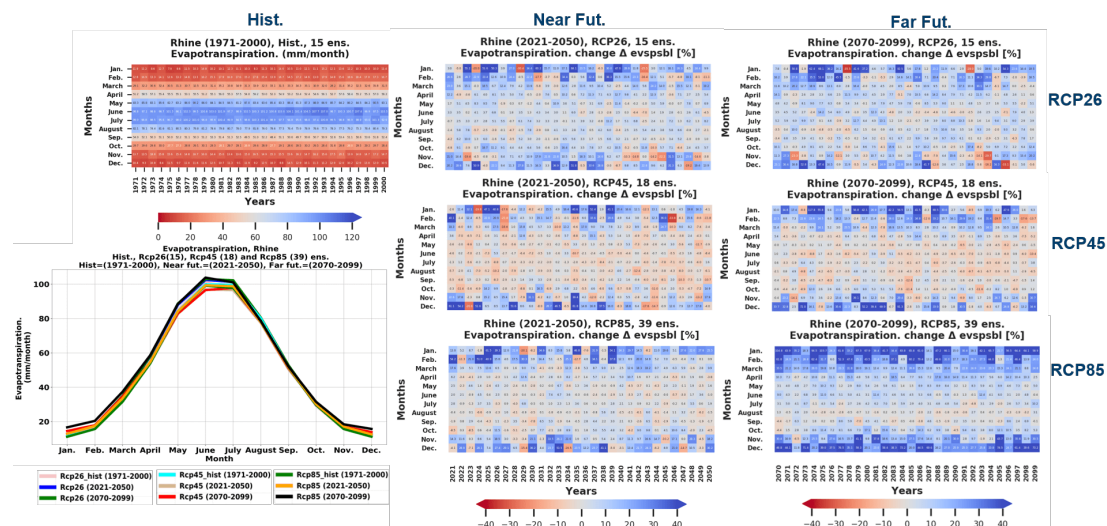


Fig. 6 Heat maps: Changes in multi-model means of evapotranspiration (evspsbl) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

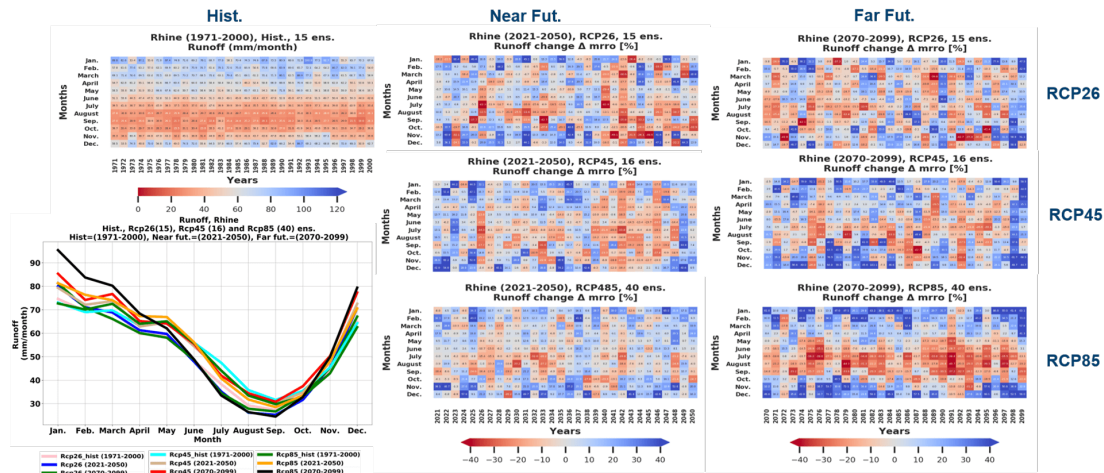


Fig. 7 Heat maps: Changes in multi-model means of runoff (mmro) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

Over the Rhine River basin, for RCP8.5, there is an upward shift (increase) in the Winter and downward shift (decrease) in Summer for the long-term average of multi-model mean annual cycles of precipitation and runoff for both near and far future. For evapotranspiration, there is an upward shift (increase) in the long-term average multi-model mean annual cycle. Over the Rhine River basin, there seems to be an intensification of the hydrological cycle in the RCP8.5 in the far future.

PROJECTED FUTURE CHANGES OVER THE DANUBE RIVER

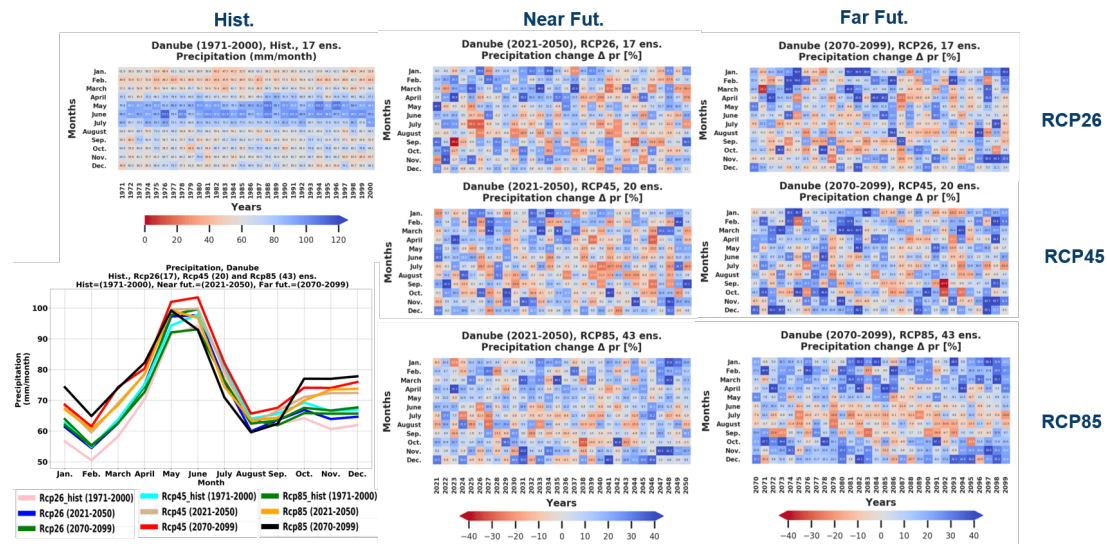


Fig. 8 Heat maps: Changes in multi-model means of precipitation (pr) over the Danube River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.

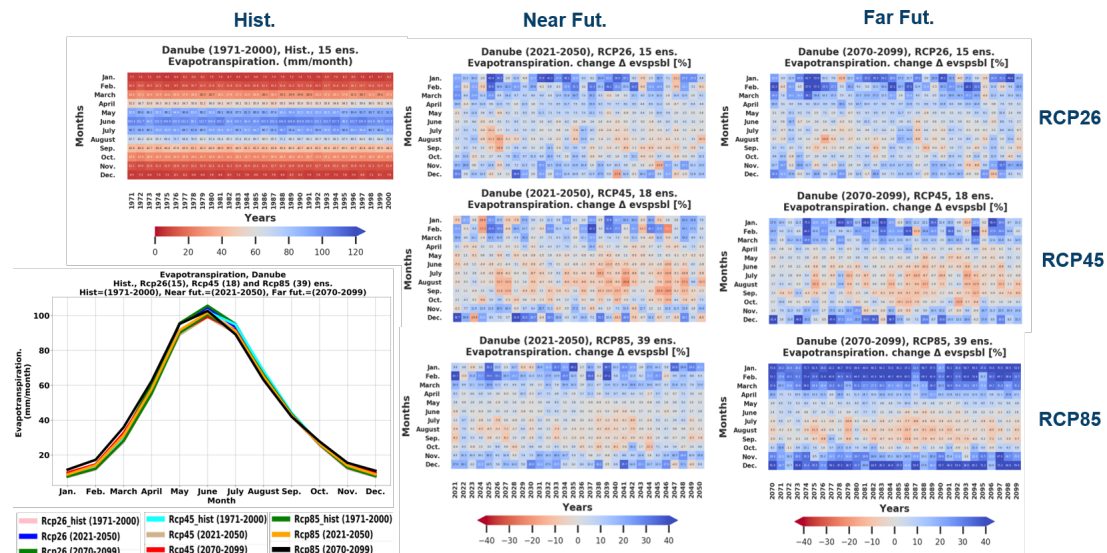
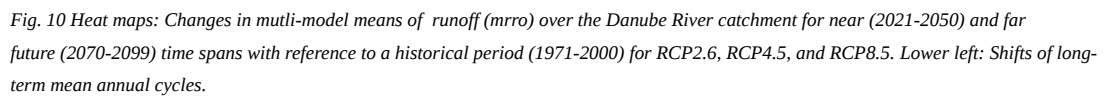


Fig. 9 Heat maps: Changes in multi-model means of evapotranspiration (evpsbl) over the Danube River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.



DATA AND METHODS

Terrestrial water budget [3]:

$$\Delta S = P - ET - R$$

ΔS = storage change

P = precipitation (CORDEX variable: pr)

ET = evapotranspiration (CORDEX variable: evspsbl)

R = runoff (CORDEX variable: mrro)

Analysis domain:

- Twenty major European river catchments
- Different climatic regions
- Base data for calculation: Catchment spatial means

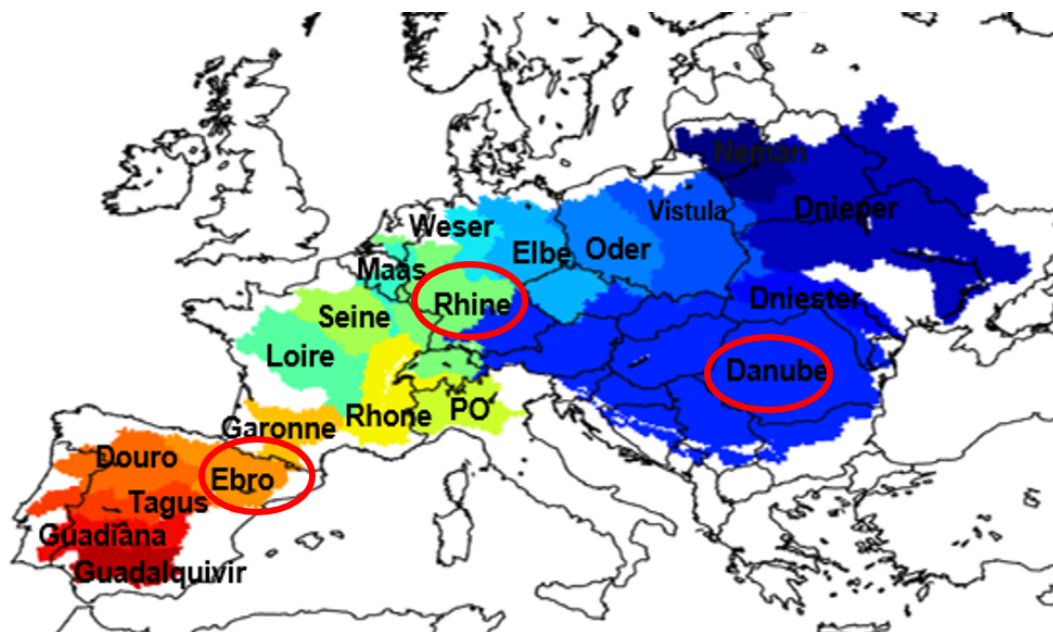


Fig. 1 River catchments considered in the analysis. Catchments considered in the a more detailed analysis: Red circles.

Regional climate model (RCM) ensemble:

- 47 ensemble members: Three Representative Concentration Pathways (RCPs): RCP2.6 (17), RCP4.5 (20), RCP8.5 (43)
- Pan-European domain (EUR-11 grid, about 12km)
- Temporal coverage: 1970-2100
- Data source: Earth System Grid Federation (ESGF)

Tab.1 List of EURO-CORDEX dataset used in this study.

Institute	RCM	GCM	Realization	Version	RCPs	Horizontal (Temporal) resolution)	Num. of Horizontal Grid points
CLM Community (CLMcom)	CCLM	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP4.5, RCP8.5	0.11 deg (daily)	412 * 424
		ICHEC-EC-EARTH	r121tp1		RCP2.6, RCP4.5, RCP8.5		413 * 424
		MOHC-HadGEM2-ES	r11tp1		RCP4.5, RCP8.5		415 * 424
		MPI-M-MPI-ESM-LR	r11tp1		RCP4.5, RCP8.5		416 * 424
Eidgenössische Technische Hochschule Zürich (ETH) CLMcom-ETH	CCLM	NCC-NorESM1-M	r11tp1		RCP8.5		416 * 424
Centre National de Recherches Meteorologiques (CNRM)	ALADINS3	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP2.6, RCP4.5, RCP8.5		453*453
	ALADIN63	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP2.6, RCP4.5, RCP8.5		453*453
		MOHC-HadGEM2-ES	r11tp1		RCP8.5		453*453
		MOHC-HadGEM2-ES	r11tp1		RCP8.5		453*453
Danish Meteorological Institute (DMI)	HIRHAM5	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP8.5		412 * 424
		ICHEC-EC-EARTH	r121tp1		RCP8.5		412 * 424
		ICHEC-EC-EARTH	r11tp1		RCP8.5		412 * 424
		ICHEC-EC-EARTH	r31tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		MOHC-HadGEM2-ES	r11tp1		RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1		RCP4.5, RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1	v2	RCP4.5, RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1	v3	RCP4.5, RCP8.5		412 * 424
Climate Service Center Germany (GERICS)	REMO	IPSL-IPSL-CM5A-LR	r11tp1		RCP2.6		412 * 424
		MIROC-MIROC5	r11tp1		RCP2.6		412 * 424
		MOHC-HadGEM2-ES	r11tp1		RCP2.6		412 * 424
		MPI-M-MPI-ESM-LR	r31tp1		RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1		RCP2.6, RCP8.5		412 * 424
		NOAA-GFDL-GFDL-ESM2G	r11tp1		RCP2.6		412 * 424
		CNRM-CERFACS-CNRM-CM5	r11tp1		RCP8.5		412 * 424
		IPSL-IPSL-CM5A-MR	r11tp1	v2	RCP4.5, RCP8.5		412 * 424
Institut Pierre-Simon Laplace/ Institut National de l'Environnement Industriel et des Risques (IPSL-ITERIS)	WRF	MOHC-HadGEM2-ES	r11tp1		RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1		RCP8.5		412 * 424

Tab.1 List of EURO-CORDEX dataset used in this study (continued).

Institute	RCM	GCM	Realization	Version	RCPs	Horizontal (Temporal) resolution)	Number of Horizontal Grid points
Royal Netherlands Meteorological Institute (KNMI)	RACMO22E	CNRM-CERFACS-CNRM-CM5	r11tp1	v2	RCP2.6, RCP4.5, RCP8.5	0.11 deg (daily)	412 * 424
		ICHEC-EC-EARTH	r121tp1	v1	RCP2.6, RCP4.5, RCP8.5		412 * 424
		ICHEC-EC-EARTH	r11tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		ICHEC-EC-EARTH	r31tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		IPSL-IPSL-CM5A-MR	r11tp1		RCP8.5		412 * 424
		MOHC-HadGEM2-ES	r11tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		MPI-M-MPI-ESM-LR	r11tp2		RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1		RCP8.5		412 * 424
Met Office Hadley Centre (MOHC)	HadREM3-GA7-05	MOHC-HadGEM2-ES	r11tp1		RCP8.5		413 * 425
Max-Planck-Institut für Meteorologie Climate Service Center (MPI-CSC)	REMO2009	MPI-M-MPI-ESM-LR	r11tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
			r21tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
Royal Meteorological Institute of Belgium and Ghent University (RMIB-Ugent)	ALARO-0	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP2.6, RCP4.5, RCP8.5		485 * 484
Swedish Meteorological and Hydrological Institute (SMHI)	RCA4	CNRM-CERFACS-CNRM-CM5	r11tp1		RCP4.5, RCP8.5		412 * 424
		ICHEC-EC-EARTH	r121tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		ICHEC-EC-EARTH	r11tp1		RCP8.5		412 * 424
		ICHEC-EC-EARTH	r31tp1		RCP8.5		412 * 424
		IPSL-IPSL-CM5A-MR	r11tp1		RCP4.5, RCP8.5		412 * 424
		MOHC-HadGEM2-ES	r11tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		MPI-M-MPI-ESM-LR	r11tp1		RCP2.6, RCP4.5, RCP8.5		412 * 424
		MPI-M-MPI-ESM-LR	r21tp1		RCP8.5		412 * 424
		MPI-M-MPI-ESM-LR	r31tp1		RCP8.5		412 * 424
		NCC-NorESM1-M	r11tp1		RCP2.6, RCP8.5		412 * 424

MULTI-MODEL MEANS OF LONG-TERM AVERAGES OF P, ET AND R ANNUAL SUMS, AND CHANGES IN THE NEAR (2021-2050) AND FAR (2070-2099) FUTURE

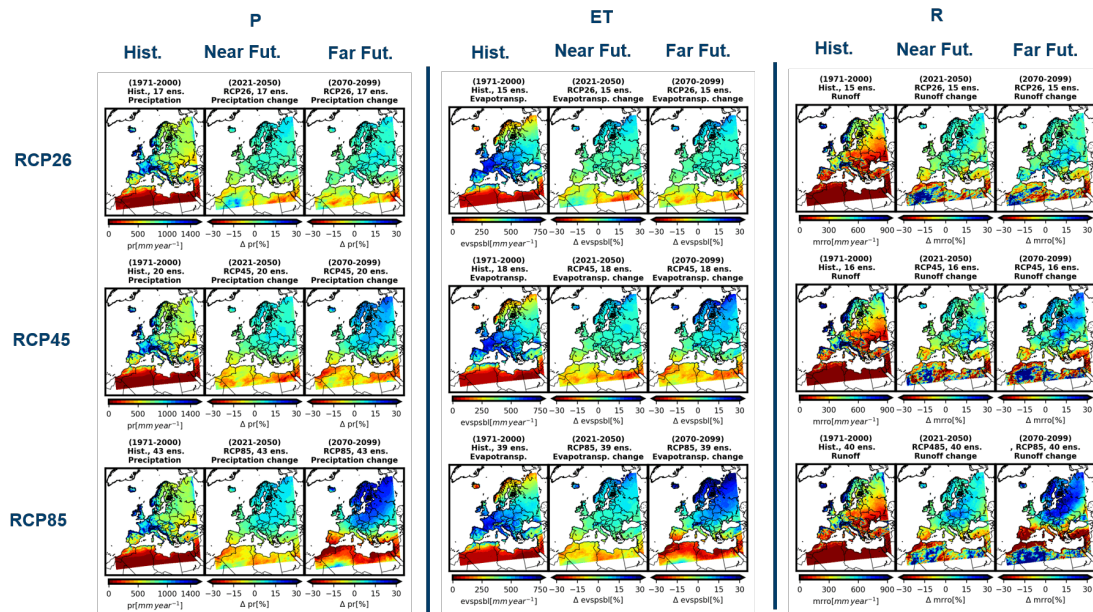


Fig. 11 Multi-model means of long-term averages of annual sums of water cycle components precipitation (P), evapotranspiration (ET), and runoff (R) and their changes for the near (2021-2050) and far future (2070-2099) time spans with reference to the climate normal period from 1971 to 2000 for RCP2.6, RCP4.5, and RCP8.5.

For the near future RCP8.5 scenario, the multi-model mean 30-year average annual precipitation increases by up to 10% over central European catchments; decreases up to 10% are found, e.g., over the Iberian Peninsula. For the far future, there is an increase in precipitation of about 30% for eastern, 15% for central, and 7% for western European catchments, and further decreases of up to 25% over the Iberian Peninsula, which would increase the likelihood for water stress situations.

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Contact:

Mohamd Eltahan, m.eltahan@fz-juelich.de
Institute of Bio- and Geosciences (IBG-3, Agrosphere)
Jülich Research Center (FZJ)
52425 Jülich, Germany

AUTHOR INFORMATION

Mohamed Eltahan (1,2), Klaus Goergen (1,2), Stefan Kollet (1,2), Clemens Simmer (3)

(1) Forschungszentrum Jülich GmbH, Institute of Bio- and Geosciences (Agrosphere, IBG-3), Jülich, Germany

(2) Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J, Jülich, Germany

(3) Division of Meteorology, Institute of Geosciences, University of Bonn, Bonn, Germany

ABSTRACT

Climate change may cause profound changes in the regional water cycle causing negative impacts in many sectors, such as agriculture or water resources. In this study, projected changes of the terrestrial water cycle are investigated based on the simulations from 47 regional climate model ensemble members of the COordinated Regional Downscaling EXperiment (CORDEX) project's EURO-CORDEX initiative, which downscale different global climate models of the CMIP5 experiment over a 12km resolution pan-European model domain. We analyze climate change impacts on the terrestrial water budget through changes in the long-term annual and seasonal cycles of precipitation, evapotranspiration, and runoff over 20 major European river catchments (Guadalquivir, Guadiana, Tagus, Douro, Ebro, Garonne, Rhone, Po, Seine, Rhine, Loire, Maas, Weser, Elbe, Oder, Vistula, Danube, Dniester, Dnieper, and Neman) for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for three Representative Concentration Pathways (RCPs), RCP2.6, RCP4.5, and RCP8.5. The analysis shows substantial differences between the projected changes in precipitation, evapotranspiration, and runoff for the twenty European catchments. For the near future RCP8.5 scenario, the long-term average of the annual sum precipitation increases over most of Europe by up to 10% in the ensemble mean over central European catchments; but also decreases up to 10 % are found, e.g. over the Iberian Peninsula. For the far future, the long-term average ensemble means of the annual precipitation sum increases from 30% for eastern, 15% for central to 7% for western European catchments, and further decreases up to 25% over the Iberian Peninsula, which will likely cause water stress situations. These first order changes in precipitation lead to ensuing changes in evapotranspiration and runoff, that cause altered hydrological regimes and feedback processes in the water cycle in the catchments.

REFERENCES

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- [2] Jacob, D., et al. (2020) Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Regional Environmental Change* 20, 51, 1436-378.
- [3] Oke, T. R. (1987) *Boundary Layer Climates*, 2nd Edition, Methuen, London, 435 pp.