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

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### 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, Vistuala, 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.

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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 Coardinated Regional Downscaling Experiment (EURO-CORDEX) [1] [2].

# PROJECTED FUTURE CHANGES OVER THE EBRO RIVER

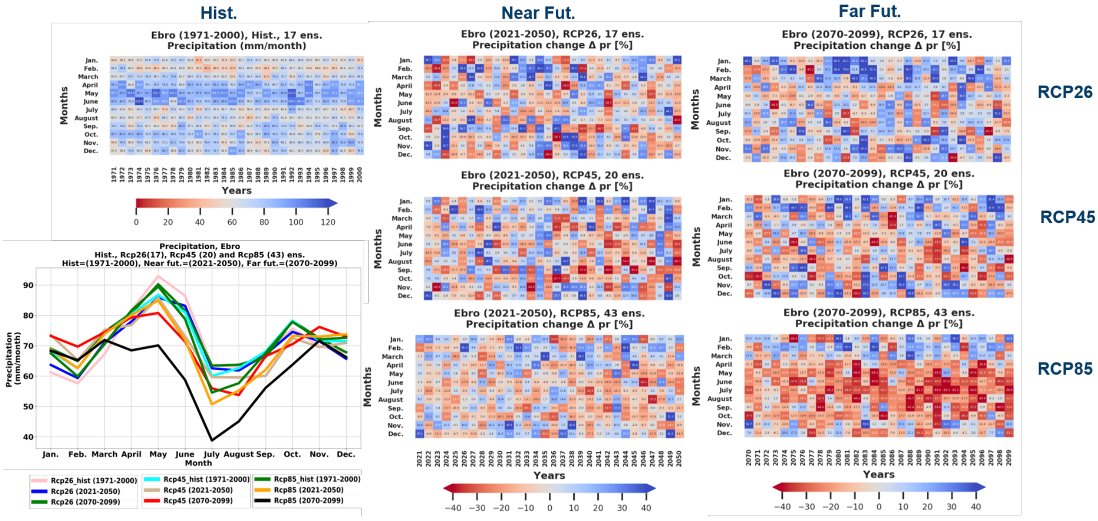


*Fig. 2 Heat maps: Changes in mutli-model means of  precipitation (pr) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

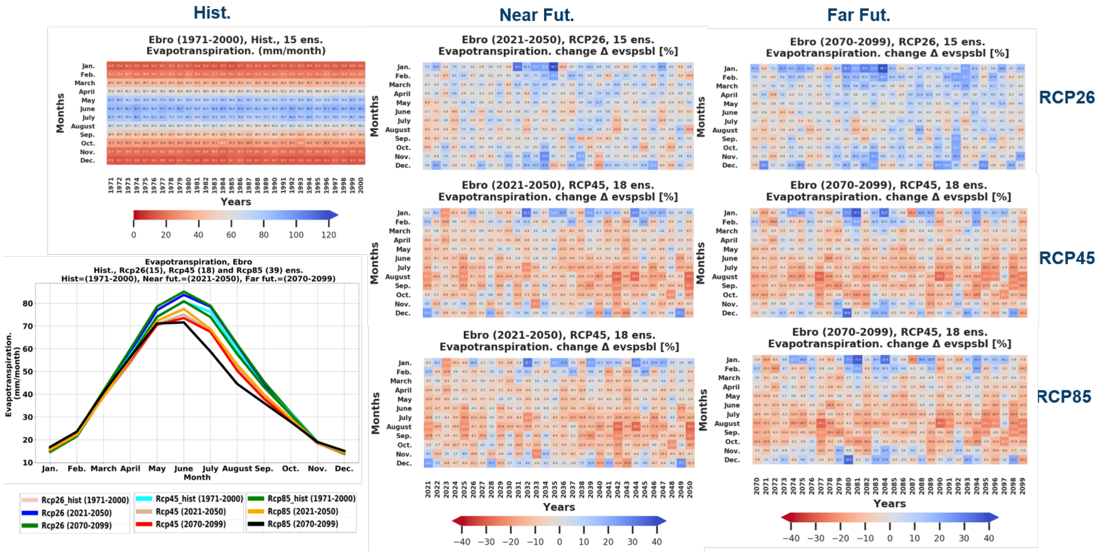


*Fig. 3 Heat maps: Changes in mutli-model means of evapotranspiration (evspsbl) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

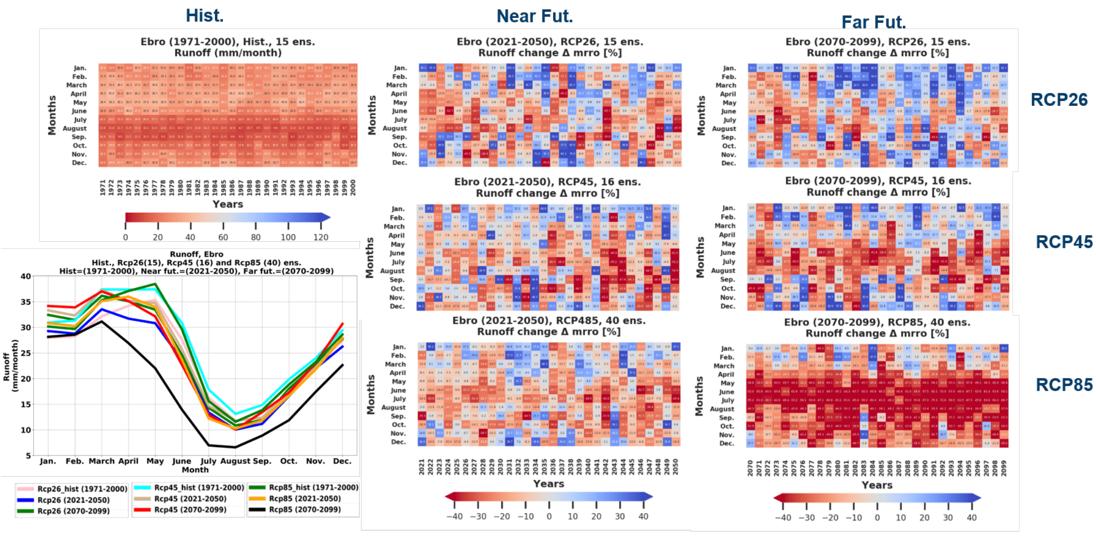


*Fig. 4 Heat maps: Changes in mutli-model means of runoff (mrro) over the Ebro River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

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

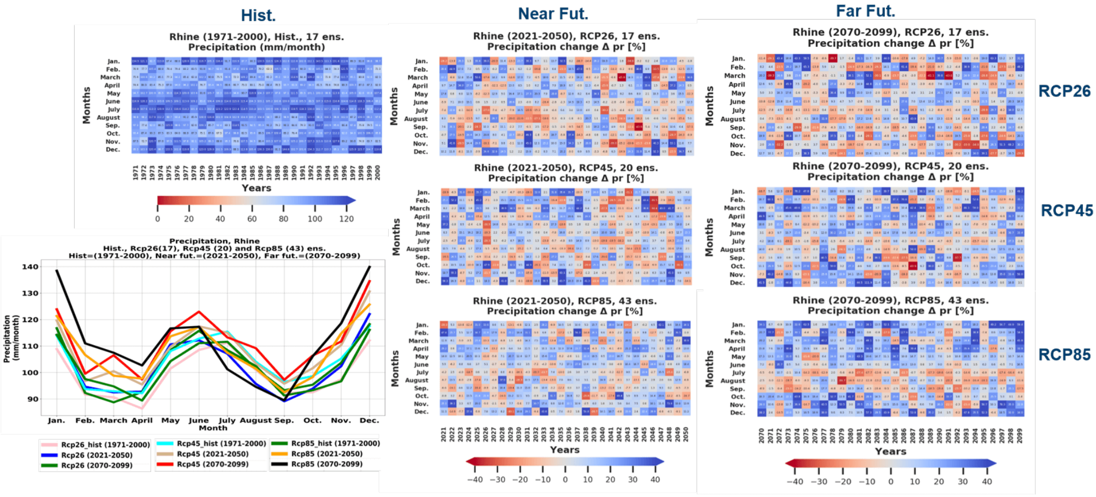


*Fig. 5 Heat maps: Changes in mutli-model means of precipitation (pr) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for three (RCPs), RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

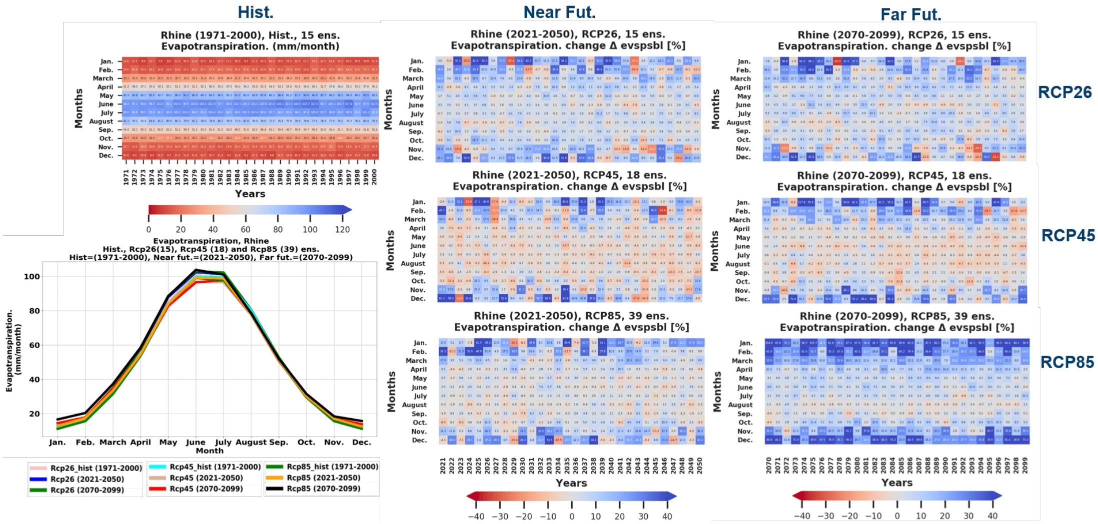


*Fig. 6 Heat maps: Changes in mutli-model means of evapotranspiration (evspsbl) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

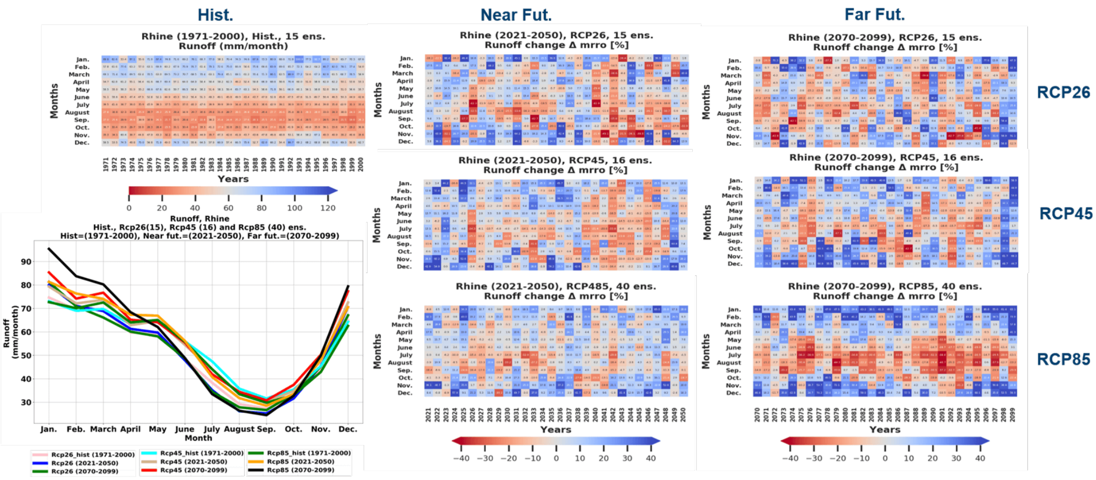


*Fig. 7 Heat maps: Changes in mutli-model means of runoff (mrro) over the Rhine River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

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 evapotransipration, 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

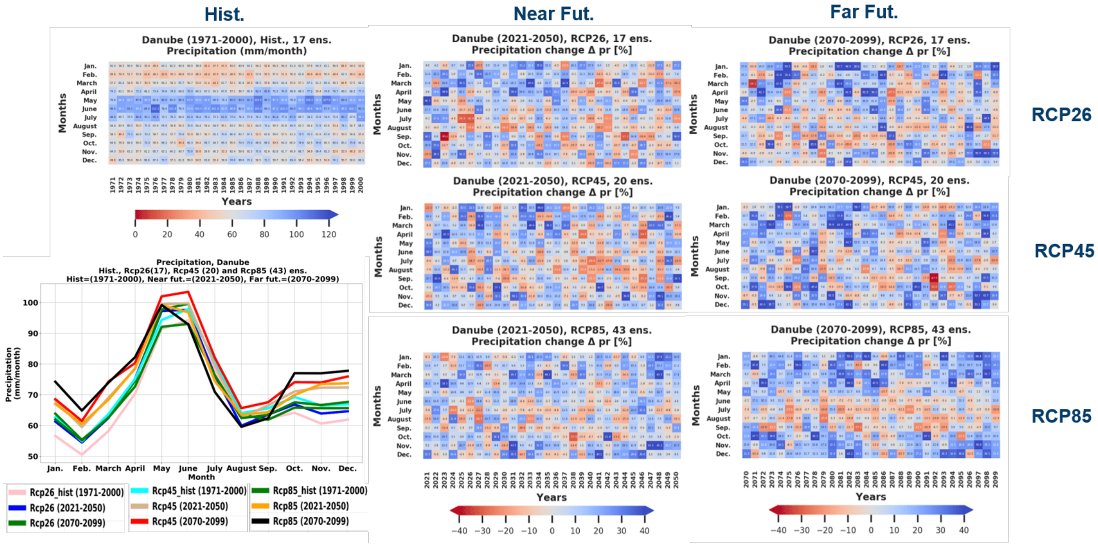


*Fig. 8 Heat maps: Changes in mutli-model means of precipitation (pr) over the Danube River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

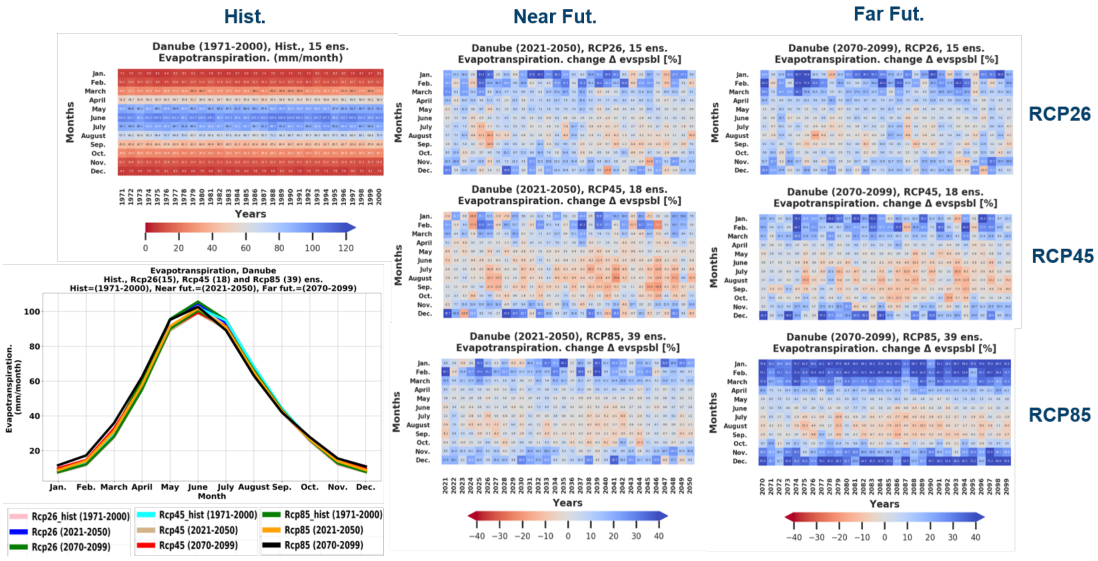


*Fig. 9 Heat maps: Changes in mutli-model means of evapotranspiration (evspsbl) over the Danube River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

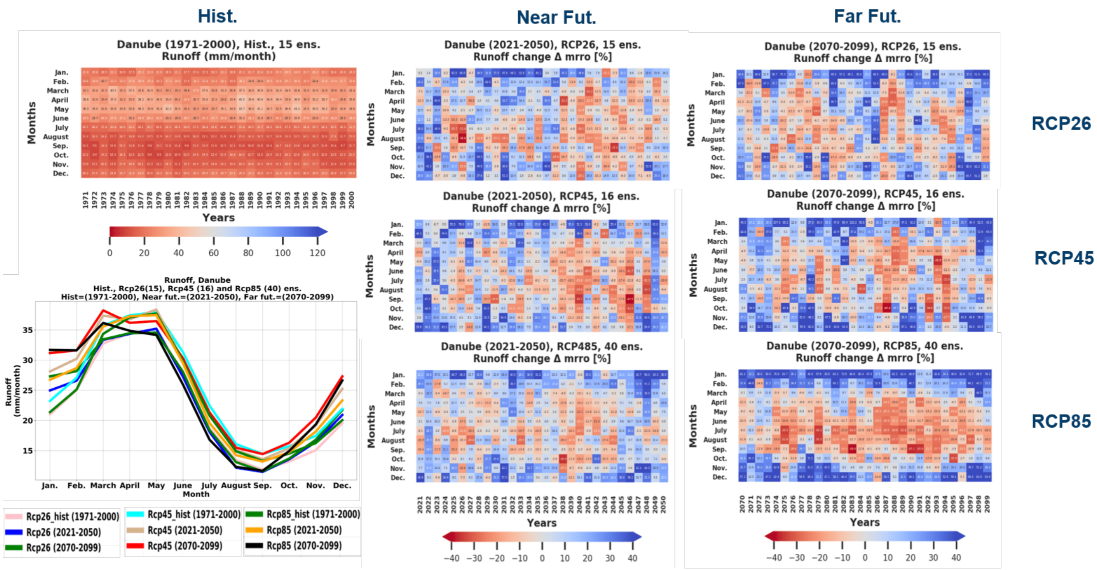


*Fig. 10 Heat maps: Changes in mutli-model means of runoff (mrro) over the Danube River catchment for near (2021-2050) and far future (2070-2099) time spans with reference to a historical period (1971-2000) for RCP2.6, RCP4.5, and RCP8.5. Lower left: Shifts of long-term mean annual cycles.*

Over the Danube River, for RCP8.5, there is an upward shift (increase) in the Winter and downward shift (decrease) in Summer for long-term average of multi-model mean the annual cycles of precipitation and runoff for both the near and far future.

# 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

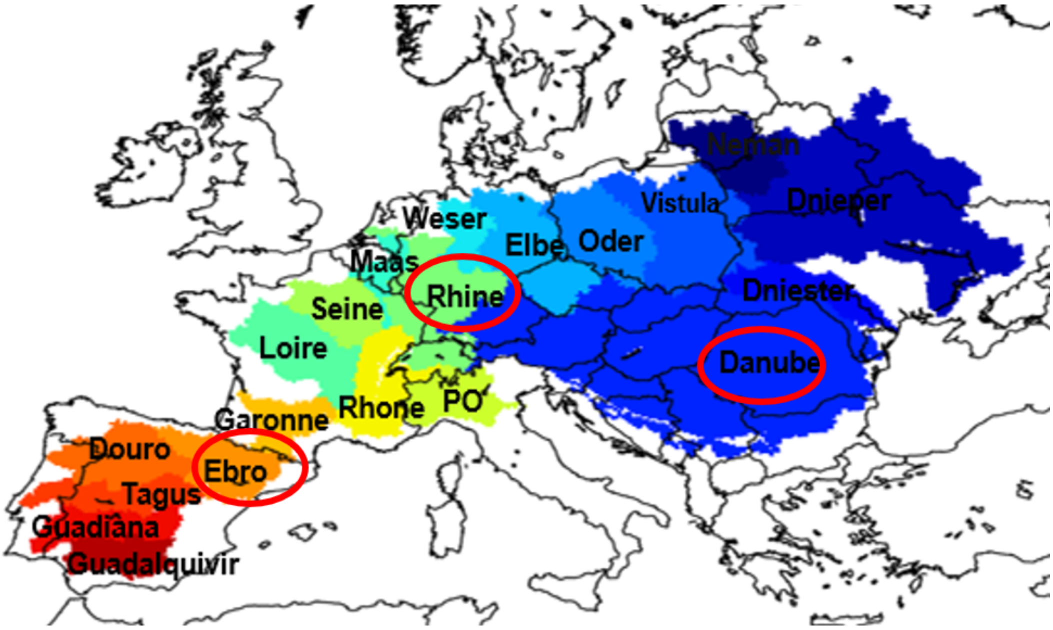


*Fig. 1 River catchments considered in the analysis. Catchments considered in the a more detailed analysis: Red circles.*

**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 | r1i1p1 | | RCP4.5, RCP8.5 | 0.11 deg (daily) | 412 * 424 |
| | | ICHEC-EC-EARTH | r12i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 413 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP4.5, RCP8.5 | | 415 * 424 |
| | | MPI-M-MPI-ESM-LR | r1i1p1 | | RCP4.5, RCP8.5 | | 416 * 424 |
| Eidgenössische TechnischeHochschule Zürich (ETH) CLMcom-ETH | CCLM | NCC-NorESM1-M | r1i1p1 | | RCP8.5 | | 416 * 424 |
| Centre National de Recherches Météorologiques (CNRM) | ALADIN53 | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 453*453 |
| | ALADIN63 | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 453*453 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP8.5 | | 453*453 |
| Danish Meteorological Institute (DMI) | HIRHAM5 | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r12i1p1 | | RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r3i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | v2 | RCP4.5, RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | v3 | RCP4.5, RCP8.5 | | 412 * 424 |
| Climate Service Center Germany (GERICS) | REMO | IPSL-IPSL-CM5A-LR | r1i1p1 | | RCP2.6 | | 412 * 424 |
| | | MIROC-MIROC5 | r1i1p1 | | RCP2.6 | | 412 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP2.6 | | 412 * 424 |
| | | MPI-M-MPI-ESM-LR | r3i1p1 | | RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | | RCP2.6, RCP8.5 | | 412 * 424 |
| | | NOAA-GFDL-GFDL-ESM2G | r1i1p1 | | RCP2.6 | | 412 * 424 |
| Institut PierreSimon Laplace/ Institut National de l'Environnement Industriel et de sRisques (IPSL-INERIS) | WRF | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | v2 | RCP8.5 | | 412 * 424 |
| | | IPSL-IPSL-CM5A-MR | r1i1p1 | | RCP4.5, RCP8.5 | | 412 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | | 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 | r1i1p1 | v2 | RCP2.6, RCP4.5, RCP8.5 | 0.11 deg (daily) | 412 * 424 |
| | | ICHEC-EC-EARTH | r12i1p1 | v1 | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r3i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | IPSL-IPSL-CM5A-MR | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | MPI-M-MPI-ESM-LR | r1i1p2 | | RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | | RCP8.5 | | 412 * 424 |
| Met Office Hadley Centre (MOHC) | HadREM3-GA7-05 | MOHC-HadGEM2-ES | r1i1p1 | | RCP8.5 | | 413 * 425 |
| Max-. Planck-Instituts für Meteorologie Climate Service Center (MPI-CSC) | REMO2009 | MPI-M-MPI-ESM-LR | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | | r2i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| Royal Meteorological Institute of Belgium and Ghent University (RMIB-UGent) | ALARO-0 | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 485 * 484 |
| Swedish Meteorologi-cal and HydrologicalInstitute (SMHI) | RCA4 | CNRM-CERFACS-CNRM-CM5 | r1i1p1 | | RCP4.5, RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r12i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r1i1p1 | | RCP8.5 | | 412 * 424 |
| | | ICHEC-EC-EARTH | r3i1p1 | | RCP8.5 | | 412 * 424 |
| | | IPSL-IPSL-CM5A-MR | r1i1p1 | | RCP4.5, RCP8.5 | | 412 * 424 |
| | | MOHC-HadGEM2-ES | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | MPI-M-MPI-ESM-LR | r1i1p1 | | RCP2.6, RCP4.5, RCP8.5 | | 412 * 424 |
| | | MPI-M-MPI-ESM-LR | r2i1p1 | | RCP8.5 | | 412 * 424 |
| | | MPI-M-MPI-ESM-LR | r3i1p1 | | RCP8.5 | | 412 * 424 |
| | | NCC-NorESM1-M | r1i1p1 | | 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

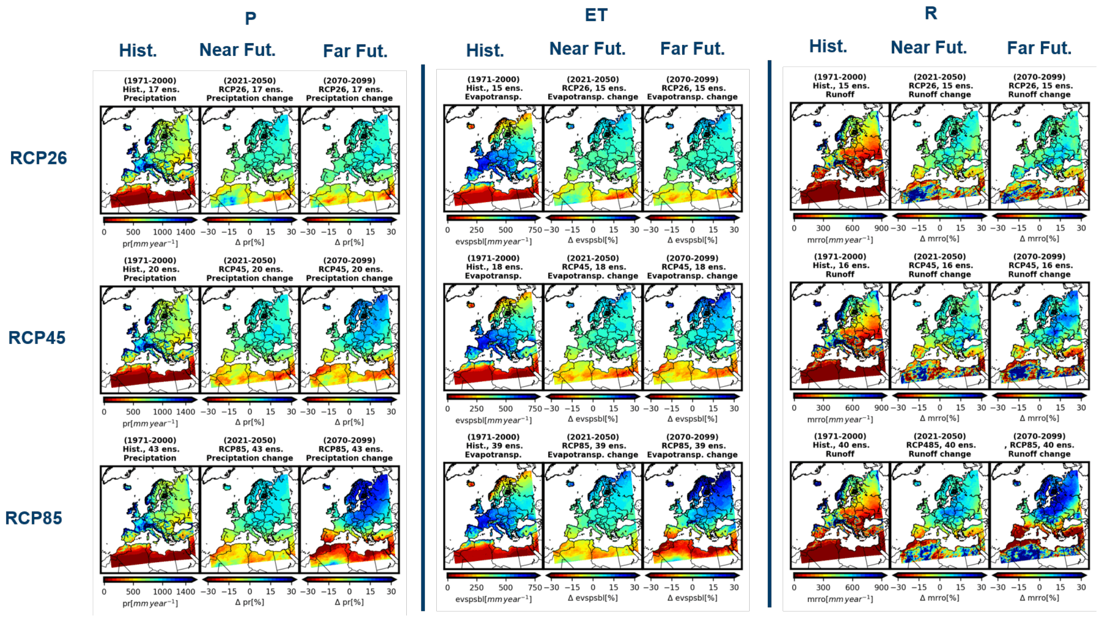


*Fig. 11 Multi-model means of long-term averages of annual sums of water cycle components precipitation (P), evapotranspiration (ET), and runoff (R) and their changes for the near (2021-2050) and far future (2070-2099) time spans with reference to the climate normal period from 1971 to 2000 for RCP2.6,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

# ACKNOWLEDGEMENTS AND CONTACT

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# 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, Vistuala, 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

[1] Jacob, D., et al. (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change*, 14, 563–578.

[2] Jacob, D., et al. (2020) Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Regional Enviromental Change* 20, 51, 1436-378.

[3] Oke, T. R. (1987) Boundary Layer Climates, 2nd Edition, Methuen, London, 435 pp.